Exposing the Complexity of GHG Reduction

Validation of a multi-criteria emission abatement curve built with the Y-factor to support sustainable energy strategies

Master Thesis

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Validation of a multi-criteria emission abatement curve constructed with the Y-factor to support sustainable energy strategies

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy and Management

by

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To be defended in public on October 31st, 2018

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Acknowledgements

This Master Thesis report concludes my master's degree in Complex System Engineering and Management at Delft University of Technology. Yet again, I find myself in disbelief reflecting on all that happened over the course of the last 26 months.

I first talked with my first supervisor Emile Chappin about this project in May 2017, when I approached him before my departure for South Korea. Besides proposing me a very exciting project, he surprised me telling me why he thought this project would suit me because of my character, background and personality.
I started working on the topic in February 2018, once back in Delft, to complete the *thesis prep* course which I followed in Quarter 3 of last academic year; once completed my internship at AkzoNobel, in June 2018 I started working fulltime on this Thesis project.
These last five months of research have been a very interesting and challenging time. While glad this intense time-period has come to an end, I am proud of the efforts I put into this work and of its results.

First of all, I would like to thank my three supervisors for their guidance over the last months: although extremely busy, they have always found time for accurate and precious comments which have helped me browsing through the many possible directions this research could follow. During my first year in Delft, I was impressed by how all three of them are caring and fun persons before skillful professors.
I feel lucky they all accepted my request for supervising this project.
Ivo, Emile and Daniel: For all you did as much as for how you did it, Van Harte Bedankt!

There are many other people without the support of whom everything would be less fun and much harder and that I would like to thank. It would take too long to thank you sufficiently, so I will just say this to my friends in Italy, in Groningen, in Delft and around the world:
I do not know if I am able to show it sufficiently, but knowing I can count on you no matter how far or close apart we might be and how often we are able to meet is an enormous source of joy and strength. And it has helped enormously also in the last months even if you do not know. Thank You!

I would like to thank Sophie, who has been with me every step in these months as much as in the last years. There are many reasons I can thank you for, but especially I thank you for truly caring about me in every moment, in a way that still surprises me every day; you are special. Danke Schön!

Finally, immense gratitude goes to my family. Papà, Mamma, Stefi e Matteo, I owe you everything: you saw me leaving the house 6 years ago, moving to an entirely unknown situation and country and have always supported me, not matter what. Now my life as a student is incredibly over, but I keep learning every day from you. I am forever thankful and cannot ask for a better family. Grazie!

I want to dedicate the last few words to the energy transition, to which this Master Thesis research can hopefully contribute:

The energy transition is a topic which I first discovered studying Smart Grids for my Bachelor thesis, and it has become my specific interest over the course of this two-year master's program. I believe it is one of the greatest challenges of the 21^{st} century, and its complex character mingling technical, financial, geo-political and social challenges fascinates me. The results of this research are obviously not a point of arrival, as many GHG abatement options are much discussed but not implemented, and multi-domain perspectives are not popular; hopefully, the results of this Thesis can highlight the importance to pursue change strategically and comprehensively. Thus, I encourage all readers to reflect on the approach proposed by the Y-factor method and its implications, and to strive so that the reduction of GHG emissions can become reality.
I am glad to have dedicated the biggest research effort of my life to developing a new approach to support and enable sustainable change; I have studied features of the energy transition for more than two years, and I have now a lifetime ahead of me to contribute to its implementation for a sustainable future.

Ad Maiora!

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Executive Summary

The abatement of CO_2 and other Green House Gasses (GHG) is one of the hottest topics in policy and society, and at the core of the energy transition. In 2009, McKinsey & Company presented its latest global cost curve (Nauclér & Enkvist, 2009), which has become a popular tool to draft energy strategies: it ranks more than 200 emission abatement options according to the marginal Abatement Cost of their implementation. Although relevant and elegant, McKinsey's cost curve is insufficient to in explaining which abatement options materialize, as many of the ones it ranks as financially convenient are not fully implemented. Chappin (2016) proposes a new method to construct emission abatement curves, called the Y-factor, further refined by Arensman (2018) and Cheung (2018).

The Y-factor method is composed by 12 ranking criteria ("factors") divided in four categories: *Cost and Financing*, *Multi-actor Complexity*, *Physical Interdependencies* and *Behavior*; its aim is to expose the relevance of multiple barriers in hampering the implementation of emission abatement options. Implementation barriers are not captured by cost curves such as McKinsey's, and thus the Y-factor method wants to propose new insights to be considered for effective and sustainable strategy-making. This master thesis research applies the Y-factor method to answer the following research questions: *What emission abatement curve can capture not only economic but also relevant non-economic implementation barriers?*

A new, validated emission abatement curve is first constructed and then discussed with some of the players responsible for drafting energy strategies in The Netherlands.

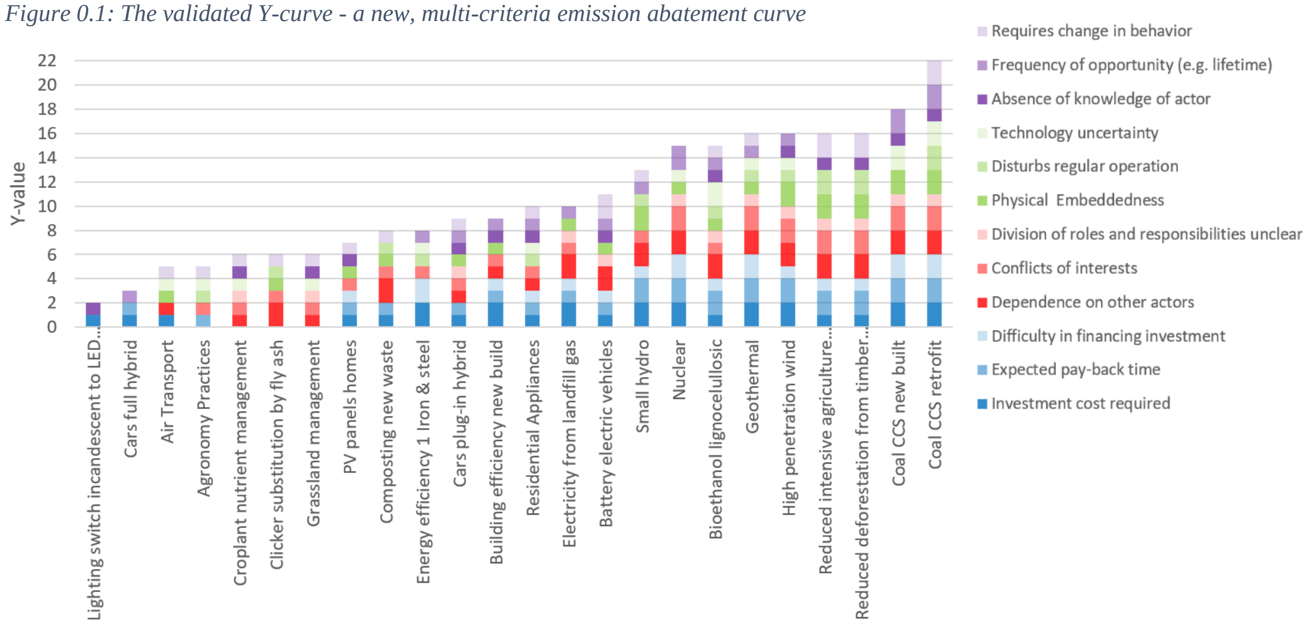
Table 0.1: The Y-factor method

Category	Factor	Value 0	Value 1	Value 2	Definition
(A) Costs and Financing	Investment cost required **(A1)**	Absent	Medium	Large	Degree to which the investment in an abatement measure is significant
	Expected pay-back time **(A2)**	< 5 years	5-12 years	> 12 years	Expected time required to earn back the investment for an abatement measure
	Difficulty in financing investment **(A3)**	Low	Medium	High	The degree to which it is difficult to finance the abatement or attract appropriate financial means
(B) Multi-actor Complexity	Dependence on other actors **(B1)**	No	Little	Much	Degree of dependence on actions of other actors to successfully implement and execute the abatement measure
	Diversity of actors involved incl. conflicts **(B2)**	Low	Medium	Large	Degree of diversity of interests, values, roles, skills and expectations of the actors involved. Degree of public acceptance. When opposing interests from the (local) public to the implementation of the abatement option are (expected to be) present, a high score should be given'
	Division of roles and responsibilities unclear **(B3)**	Clear	Slightly	Unclear	The extent to which the roles and responsibilities for the realization of the abatement option are clear
(C) Physical Interdependences	Physical embeddedness **(C1)**	No	Medium	High	Degree to which the abatement measure requires physical changes to the environment it is placed in
	Disturbs regular operation **(C2)**	No	Slightly	Strongly	Degree (duration, intensity) to which status quo/regular operation is disrupted to successfully apply the abatement measure
	Technology uncertainty **(C3)**	Fully proven	Small	Large	Degree to which the technological performance of the abatement measure is uncertain
(D) Behavior	Absence of knowledge of actor **(D1)**	High Knowledge	Low Knowledge	No Knowledge	Level of knowledge of the parties responsible for the abatement measure
	Frequency of opportunity **(D2)**	Often	Medium	Rarely	Number of opportunities for the responsible party to realize the abatement measure
	Requires change in behavior **(D3)**	No	Slight	Severe	Degree to which the actors involved need to change their day to day behavior

24 emission abatement options are selected from the pool of options ranked in McKinsey's curve, pursuing diversity of selection with a multi-criteria selection process. Relying on information in the existing literature, the Y-factor method is initially applied to assign preliminary scores to the 24 selected options and thus obtain a preliminary curve. The preliminary scores are then discussed with experts knowledgeable about the considered emission abatement options; following an explicitly pre-determined strategy, the opinions collected from the interviewed experts are synthetized to achieved final, validated scores.

Summing the individual scores assigned to each abatement option appoints an overall score to it, called Y-value; comparing the different Y-values enables the construction of an emission abatement curve, the Y-curve (*Figure 0.1*), ranking the considered abatement options. The displayed scores do not provide a quantitative comparison of the abatement options but highlight the relevance of the implementation barriers captured by the 12 factors, thus representing the difficulty of implementing an option in society.

Figure 0.1: The validated Y-curve - a new, multi-criteria emission abatement curve



The final, validated scores composing the Y-curve are displayed in *Table 0.2* (below), highlighted in a color referring to their degree of uncertainty: the green ones are considered "certain", as the interviewed experts had very similar opinions about them; the ones highlighted in yellow are "somewhat uncertain", as the collected experts' opinions were slightly conflicting; and red ones are "significantly uncertain", as the opinions of experts were conflicting and the reported score acts as medium. 5 abatement options were validated by only one expert (highlighted by an "*") are their scores also reported as "somewhat uncertain".

Table 0.2: Validated scores characterizing the abatement options investigated

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	sum
Lighting switch incandescent to LED (residential)	1	0	0	0	0	0	0	0	0	1	0	0	2
Cars full hybrid	1	1	0	0	0	0	0	0	0	0	1	0	3
Air Transport*	1	0	0	1	0	0	1	0	1	0	0	1	5
Agronomy Practices	0	1	0	0	1	0	0	1	1	0	0	1	5
Cropland nutrient management	0	0	0	1	1	1	0	0	1	1	0	1	6
Clinker substitution by fly ash*	0	0	0	2	1	0	1	1	0	0	0	1	6
Grassland management	0	0	0	1	1	1	0	0	1	1	0	1	6
PV panels homes	1	1	1	0	1	0	1	0	0	1	0	1	7
Composting new waste*	1	1	0	2	1	0	1	1	0	0	0	1	8
Energy efficiency 1 Iron & steel*	2	0	2	0	1	0	0	1	1	0	1	0	8
Cars plug-in hybrid	1	1	0	1	1	1	1	0	0	1	1	1	9
Building Efficiency New Build	2	1	1	1	1	0	1	0	0	1	1	0	9
Residential appliances	1	1	1	1	1	0	0	1	1	1	1	1	10
Electricity from landfill gas*	2	1	1	2	1	1	1	0	0	0	1	0	10
Battery Electric Vehicles	1	1	1	2	0	1	1	0	0	1	1	2	11
Small hydro	2	2	1	2	1	0	2	1	0	0	1	1	13
Nuclear	2	2	2	2	2	1	1	0	1	0	2	0	
Bioethanol lignocellulosic	1	2	1	1	1	1	1	1	2	1	1	1	15
Geothermal	2	2	2	2	2	1	1	1	1	0	1	1	16
High penetration wind	2	2	1	2	2	1	2	1	1	1	1	0	16
Reduced intensive agriculture conversion	1	2	1	2	2	1	2	2	0	1	0	2	16
Reduced deforestation from timber harvesting	1	2	1	2	2	1	2	2	0	1	0	2	16
Coal CCS new build	2	2	2	2	2	1	2	0	2	1	2	0	18
Coal CCS retrofit	2	2	2	2	2	1	2	2	2	1	2	2	22

The first important result achieved by this research is the construction of a validated emission abatement curve built applying the Y-factor method: in fact, the Y-curve is characterized for the clear majority (about three quarters) by scores which smoothly synthesize non-conflicting opinions of multiple experts. This makes the Y-curve not only validated but also significantly robust.
The Y-curve is robust over a longer time-period than a MAC curve, because it does not exclusively focus on financial figures: these are more likely to significantly evolve over time than some of the barriers considered by the Y-factor method, such as *B1 Dependence on other actors* and *C1 Physical embeddedness*; in fact, these barriers capture characterizing features of the abatement options rather than their market value. Nevertheless, the Y-curve also considers barriers such as costs and behaviors, and it is thus also robust on a limited time-horizon. Moreover, the Y-curve is location-dependent at least as much as a MAC curve.

The existing differences in opinions are reflected in the uncertainties of the validated scores, which thus highlight the most contentious abatement options and their most debated features, exposing relevant issues within the emission abatement debate. Considering the 19 abatement options validated by two or more experts, the most equivocal ones are found to be: High penetration wind, Nuclear, and Bioethanol lignocellulosic; considerably dubious abatement options are: Building efficiency new built, Geothermal, Small hydro, Cropland nutrient management, Agronomy practices, and Cars plug-in hybrid.
Similarly, *D1 Absence of knowledge of actors* is the factor over which the interviewed experts had the most conflicting opinions. The scores for the factors *A3 Difficulty in financing the investment*, *C2 Disturbs regular operations*, and *D3 Requires change in behavior* are also often uncertain. The uncertainty for the factors *D1* and *D3* was most often caused by the different geographical scopes to which the scores could refer.

The ranking of the abatement options in the validated Y-curve is then compared to McKinsey's global cost curve, to verify the new insights provided. Of the considered 24 abatement options, 9 are assigned a very similar ranking in the two curves (color green in *Table 0.3*), while 5 others have a very different one (color yellow). The remaining 10 abatement options are also ranked significantly differently in the Y-curve.

Table 0.3: Ranking comparison between McKinsey's MAC curve and the Y-curve

Abatement option	Abatement Cost [€/tCO_2e]	Y-value [out of 24]	Ranking MAC → Ranking Y-curve	Financial ranking Y-curve
Lighting switch incandescent to LEDs, residential	-253.1	2	1 → 1	4
Residential appliances	-195.8	10	2 → 13	10
Bioethanol lignocellulosic	-138.8	15	3 → 17	13
Cars full hybrid	-72.9	3	4 → 2	7
Cropland nutrient management	-68.8	6	5 → 5	1
Building efficiency new built	-40.2	9	6 → 11	13
Clinker substitution by fly ash	-32	6	7 → 5	1
Electricity from landfill gas	-23.4	10	8 → 13	13
Air Transport	-20.5	5	9 → 3	4
Small hydro	-8.9	13	10 → 16	19
Geothermal	-3.9	16	11 → 19	21
Grassland management	3.4	7	12 → 7	1
Reduced deforestation from timber harvesting	6.9	16	13 → 19	13
Energy efficiency 1 Iron & Steel	8.2	8	14 → 9	13
Composting new waste	9.9	8	15 → 9	7
Nuclear	10.4	15	16 → 17	21
Agronomy Practices	15.8	5	17 → 3	4
Cars plug-in hybrid	18.1	9	18 → 11	7
PV panels homes	27.9	7	19 → 7	10
High penetration wind	32.4	16	20 → 19	19
Reduced deforestation from intensive agriculture conversion	39.9	16	21 → 19	13
Coal CCS retrofit	62.2	22	22 → 24	21
Coal CCS new built	64.6	18	23 → 23	21
Battery electric vehicles	90	11	24 → 15	10

Substantial ranking differences also exist comparing McKinsey's cost curve to the ranking obtain only considering the "financial-factors" in the Y-curve, which are those belonging to the *Cost and Financing* category. The ranking differences can be caused by: the lower sensibility of the three financial factors considered by the Y-curve (7 possible values, from 0 to 6) which facilitates score-overlaps impactful for the ranking; outdated cost figures in McKinsey's 2009 cost curve; the inclusion of cost-savings in McKinsey's MAC curve, not captured by the Y-factor method.

Comparing the ranking and the characterizing figures the two curves provides new insights for each abatement option. The following ones are amongst the most evident:

- The abatement option Coal CCS new built and Coal CCS retrofit are classified by both curves as the most difficult to implement, as Lighting switch incandescent to LED (residential) is similarly considered the abatement option having the fewer implementation barriers. For the implementation of LEDs, the Y-curve highlights discouraging market prices and the existence of educational barriers, especially relevant for the purchase.
- PV panels home and Battery electric vehicles are ranked amongst the most expensive options by McKinsey's MAC curve, while they are located in the central section of the Y-curve. Considering the limited relevance of non-financial barriers, the large ranking difference is likely to be caused by outdated cost-figures: McKinsey's curve was published in 2009 and since then, costs of PV technology have dropped more than 70% (SEIA, 2018) and BEVs price-competitive with ICEs of their respective classes have been introduced on the market, such as the 2018 introduction of the Nissan LEAF.
  The Y-curve highlights the existence of a chicken and egg paradox: how to introduce the recharging infrastructure necessary to encourage the diffusion of BEVs, while few are circulating?
- Agronomy practices is considered much easier to implement in the Y-curve than expensive in McKinsey's cost curve. Such difference is explained by the low scores of the factors in the *Cost and Financing* category, and by different views about the effectiveness of the such practices, which were also evident in the performed interviews.
- The negative abatement costs assigned by McKinsey's MAC curve to the abatement options Bioethanol lignocellulosic and Residential appliances are surprising. For the former, the Y-curve remarks implementation barriers well-distributed across the four categories of the Y-factor method, and the interviewed experts reported complexities caused by high production costs, uncertainty of the market and similarities between secondary-biofuels and their disappointing predecessors. Instead, a partial reason for the ranking differences for Residential appliances is definitional: the interviewed experts remarked the inevitability of focusing on smart, energy-efficient appliances rather than solely efficient ones, making the management of energy-consumption data from appliances' owners the most relevant barrier, and imposing a reflection on the definition and management of behavioural changes.

Moreover, the scores in the Y-curve can explain the limited implementation of the 11 abatement options ranked with a negative abatement cost in McKinsey's global cost curve and considered in this investigation: for 10 of these 11 options, non-financial implementation barriers (factors belonging to the three non-financial categories: *Multi-actor Complexity, Physical Interdependencies,* and *Behavior*) account for 50% or more of their total relevant barriers. The missing option, Cars full hybrid, can be considered already largely diffused, as McKinsey's report includes in HEVs' definition also all vehicles with a start-and-stop system.

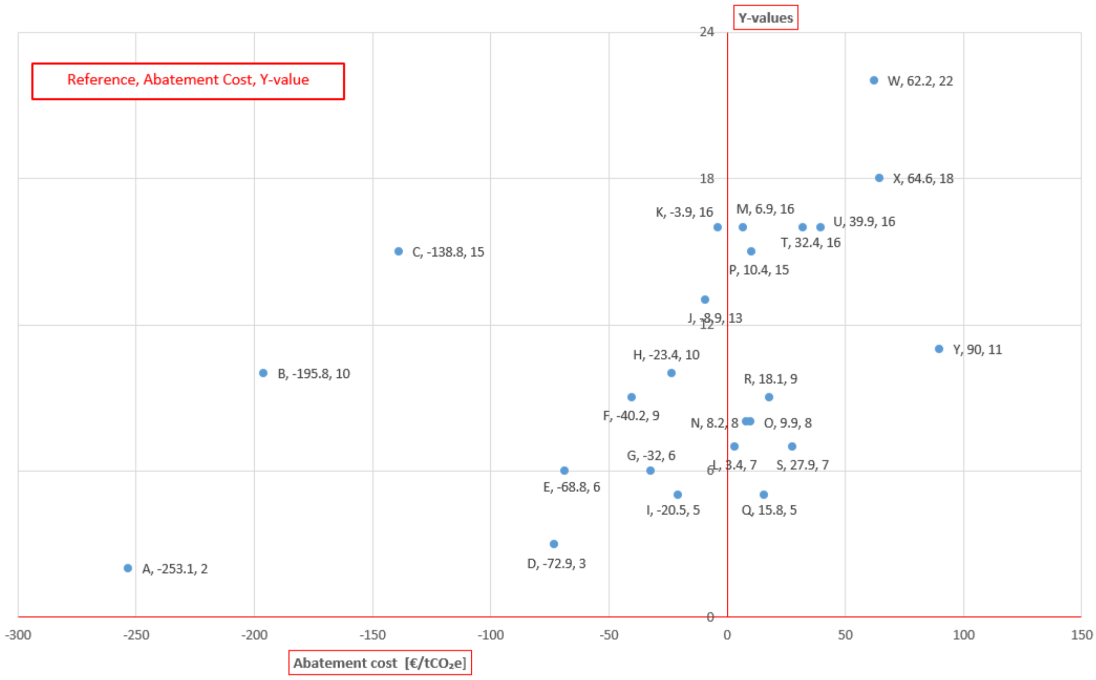
Following the procedure proposed by Hekkert and Negro (2009), remarking how it is possible to validate the importance of specific variables by observing their relevance across different case studies, it is possible to validate the relevance of each of the 12 factors, adding to the previously achieved theoretical embedding of the Y-factor method. In fact, each of the 12 factors was considered a relevant implementation barrier during the interviews with experts, as proved by *Table 0.4*, reporting the average contribution of each factor to the collected overall Y-values. These figures also highlight the importance of including non-financial analysis in decision-making, as the factors not belonging to the category *Cost and Financing* account on average for 70% of the discussed implementation barriers.

Table 0.4: Relevance of the 12 factors

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
AVERAGE CONTRIBUTION - per Y-factor	**12.4**	**10.4**	**7.3**	**12.5**	**10.6**	**4.9**	**8.7**	**5.7**	**6.1**	**6.4**	**6.7**	**8.4**
AVERAGE CONRIBUTION – per category		**30.1**			**27.9**			**20.5**			**21.4**	

Having confirmed the relevance of the barriers highlighted by the Y-curve, a first example of a tool integrating the approaches of McKinsey's cost curve and of the Y-factor method is developed (*Figure 0.2,*); in this version, the Abatement Potential is neglected and the Abatement Cost (in €/tCO_2e) of each abatement option is matched to its overall Y-values. Each dot represents an abatement option, characterized by a reference letter (assigned in *Table 0.2* above), its Abatement Cost, and its overall Y-value.

Figure 0.2: A new tool combining figures from McKinsey's MAC and the Y-curve



Finally, the validated Y-curve is discussed with three players responsible and/or consulted for drafting energy strategies in The Netherlands, to verify if and how employing the Y-factor method can aid in drafting effective energy strategies. Specifically, the discussions occurred with professionals working at the Ministerie van Economische Zaken en Klimaat, the Planbureau voor de Leefomgeving (PBL), and ECOFYS.

All the consulted energy strategists accepted the presented Y-curve, acknowledging the Y-factor method to be a valid and insightful approach to the emission abatement debate, able to support effective sustainable decision-making. All envisioned possible applications of the Y-factor method and the Y-curve, which very much differing in extent and intention. While some players highlighted the importance of a structured approach to implementation barriers such as the one proposed by the Y-factor method, others doubted the feasibility of a structured analysis, and highlighted how many politicians and parliamentarians are likely to prefer McKinsey's MAC curve to the Y-factor for its higher ease-of-use and reputation.

In particular, the Y-factor method can be employed for three different activities:

1. Support to policy-making: The Y-factor method fosters the discussion on the policies measures implemented to tackle specific implementation barriers and facilitates the comparison of policies belonging to different domains, which is usually challenging.
2. Support to research analyses: The Y-factor method facilitates the comparison of different opinions on implementation barriers, valuable for providing sound advices, and enables the construction of multiple new tools integrating quantitative and qualitative insights on emission abatement options.

3. Support to business strategy: The Y-factor method helps a business active in the energy market in the strategic allocation of available resources, highlighting the most promising products or services and supporting their design in tackling existing implementation barriers.

Of all methodological suggestions collected during the interviews with experts and energy strategists, the following ones can be beneficial for an increased accuracy and clarity of the Y-factor method:

Governance support should be included in the definition of factor *B3: Division of roles and responsibilities unclear*, to account for the clarity of the institutional environment; thus, the name of category B could be changed into *Multi-actor and institutional complexity*.

Emotional decisions should be added to the definition of faction *D1 Absence of knowledge of actors* to capture the prowess of actors to face immediate higher cost for future savings.

Moreover, it is suggested to expand the current tripartite value scale into a four-value scale: next to the current three values, this could contain a negative score accounting for the co-benefits caused by the implementation of an emission abatement option, increasing its attractiveness; these are likely experienced over an extended time-period and situations-range and are thus difficult to capture for each factor.

Other themes for further investigations include: the development of a global and local Y-curves, and of a software guiding the application of the Y-factor method, increasing its ease of use and of employments' accuracy; the development of new tools integrating the approaches to the emission abatement debate from existing tools: integrative tools can further clarify the emission abatement debate and, alongside the endorsement from leading organizations and individuals, increase the reputation and popularity of the Y-factor; modelling the implementation barriers and the impact different policies might have on them in an Agent Based Model, to simulate the possible consequences of specific decisions and provide an additional, dynamic tool to the emission abatement debate.

The tradeoff between the employment of the Y-factor method and a MAC curve in the emission abatement debate is evident: on one hand, a MAC curve has a higher ease-of-use than a Y-curve, because it is characterized by less, more quantitative information; on the other hand, a Y-curve enriches the discussion, which is currently inconclusive and accepting multiple debatable assumptions.

Concluding, this investigation has proven the Y-factor method is fit-for-purpose, as it can at least partially satisfy the existing need and interest for another approach to the theme of emission abatement. Using the framework of Smith et al. (2005), the Y-factor method can be identified as a *heuristic tool* for the *purposive transition* of cost-efficient strategy-making towards effective sustainable societal development.

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Chapter 1: Introduction

Motivation and structure of this master thesis research

On October 30th, 2017, the World Meteorological Organization (WMO) launched a new warning: a record-breaking atmospheric CO_2 concentration of 403.3 ppm was measured for 2016, increasing from the 400 ppm of 2015 and the average annual increase of 2.0 ppm/year, establishing the largest increase over 30 years (WMO, 2017). Air pollution is at the core of the environmental debate, impacting societies across the globe: an increasing amount of people is considered dying because of poor air quality (IHME, 2016), and there is a large agreement in the international political and scientific community on the impelling need to reduce atmospheric concentration of Green House Gasses (GHG): pre-industrial emissions (1990) of GHG are estimated at 36-38 $GtCO_2e$/year, of which 26-28 $GtCO_2e$/year consisted of CO_2 (IPCC, 2014); global emission figures raised to 49 $GtCO_2e$/year in 2010, year of the fifth and latest assessment of the UN Intergovernmental Panel on Climate Change (IPCC). CO_2 emission are estimated to have recently exceeded 40 $GtCO_2$/year (IPCC, 2018), and global energy-related CO_2 emissions grew by 1.4% in 2017, reaching a historic high of 32.5 $GtCO_2$/year (IEA, 2017).

Countermeasures such as banning oil-consuming vehicles from metropoles (BBC, 2016), and new regulations are being drafted and implemented, progressively affecting the outlooks of societies. While with the Paris Agreements (UNFCCC, 2015), the 195 signatory nations have committed for the first time in history to lowering national emissions of GHG, national and international strategies to reduce such emissions have yet to be developed and implemented. A vast debate is ongoing to ascertain the most promising options to reduce emissions of CO_2 and other GHG and how to introduce them in society.

Marginal Abatement Cost curves (MAC or MACCs) are a prominent tool used for ranking emission abatement options in, which highlight their abatement potential and implementation cost, and are thus a tool frequently employed in the air pollution debate. While helpful and elegant, MAC curves have received different critiques for their inability to capture the process-complexity of implementing emission abatement options. Chappin (2016) proposes a different approach to emission abatement curves, the Y-factor method, which aims to highlight the relevance of multiple socio-technical barriers in hampering the implementation of emission abatement options. This research is dedicated to constructing the first, validated emission abatement curve with the Y-factor method, and to the exploration of some of its possible applications to support the drafting of effective energy strategies. The problem at hand is described in more detail below.

1.1 Problem Description: Approaches to Emission Abatement

This section provides more details on the mission of this master thesis, discussing the strengths and limitations of MAC curves highlighted in the literature, and introducing the approach to emission abatement curves proposed by the Y-factor method. Successively, the results of antecedent researches on the Y-factor are summarized to identify the knowledge gap filled by this research. Ultimately, the scientific and societal relevance of this master thesis research are discussed, as well as its fit with the objectives of the MSc. in Complex System Engineering and Management at Delft University of Technology.

1.1.1 MAC Curves

A MAC curve is a bar-graph ranking emission abatement options according to their marginal abatement cost, which is the cost of eliminating the last-achievable unit of CO_2 by the specific abatement option given its incurred investment (Kesicki & Ekins, 2012). The abatement costs are measured in Euro per ton of CO_2 equivalent (€/tCO_2e) reduced and are the dominant ranking criterion; the abatement potentials are measured in tCO_2e and are depicted as the width of the individual bars composing the graph (Kesicki & Strachan, 2011).
Between 2007 and 2009 McKinsey & Company published 16 MAC curves specific for individual countries, and a global cost curve (Nauclér & Enkvist, 2009), which quickly became most popular; the curve ranks more than 200 emission abatement options, belonging to 10 very different economic sectors. More information on MAC curves and on McKinsey's global cost curve can be found in the info-box below. In the remainder of the report, "McKinsey's MAC curve" and "McKinsey's global cost curve" always refers to Nauclér and Enkvist (2009).

Marginal Abatement Cost (MAC) curves

A MAC curve is a bar-graph ranking different options to reduce, or abate, GHG emissions. The graph is characterized by two independent variables: the X-axis displays the Abatement Potential of the ranked abatement options, measured in ton of CO_2 equivalent (tCO_2e) and referring to the emissions avoided by implementing each of the ranked options. Summing the individual abatement potential on the X-axis, MAC curves display the full emission-reduction potential. The Y-axis instead shows the costs incurred to achieve the maximum emission-reduction potential of the ranked options; this is called (marginal) "Abatement Cost" and is measured in € per ton of CO_2 equivalent reduced (€/tCO_2e). Thus, each of the depicted bars refers to an analyzed abatement option, its width represents the emissions-reduction potential of the option and height of the bar its implementation cost.
The Abatement Cost is the dominant variable for graphically composing the graph, and the abatement options are thus ranked from left to right according to their increasing Abatement Cost.
From the displayed marginal abatement costs, the average and total abatement cost can also be easily determined, calculating the integrals of the marginal costs (Kesicki & Strachan, 2011).
The first carbon-focused curves date back to the early 1990s (Jackson, 1991), developing from Conservation Supply Curves (CSC), and have become popular tools as over the years economic criteria have progressively established their dominance in the policy discussion. MAC curves are not only applicable to CO_2 abatement options, but "can be applied more generally as they essentially pull together the reduction (or supply) potential of an economic bad (or good) with its associated marginal" (Kesicki & Strachan, 2011, p 1195); in fact, MAC curves have also been applied to assess waste reduction (Beaumont & Tinch, 2004) and water availability (Kesicki, 2010). The popularity of MAC curves in the emission abatement debate, for instance evident in (DECC, 2009b) and (HM Government, 2009), is explained by their ability to simplify the complexity of cost-efficient emissions reduction into an elegant graph of quick reading and straightforward understanding.

McKinsey's global cost curve

In 2007, McKinsey & Company published a collection of 17 MAC curves, consisting of 16 curves specifically referring to the GHG emissions of single countries (namely Australia, Belgium, Brazil, China, Czech Republic, Germany, Greece, India, Israel, Poland, Russia, Sweden, Switzerland, UK, and USA), and one curve estimating global abatement potentials and costs. This "Global Greenhouse Gas Abatement Cost Curve" was revised in 2009 (Nauclér & Enkvist, 2009), when an updated version was published; and this has become a very famous and popular tool in the emission abatement debate.
Basing on the climate science presented in Fourth IPCC Assessment Report (IPCC, 2007), the curve assesses 218 GHG abatement opportunities across 10 major economic sectors and 21 world regions between 2010 and 2030. 2030 is thus used as reference year because reflects "our belief that mitigation-action requires a long-term outlook to prioritize different opportunities effectively" (Nauclér & Enkvist, 2009, p. 30) along with 1990, reference as pre-industrial year and characterized by estimated emissions of 36 $GtCO_2e$. To project a Business-As-Usual (BAU) scenario-development, combined projections from the International Energy Agency's (IEA) World Energy Outlook 2007, the US Environmental Protection Agency (EPA) and others are used. All costs refer to the 2005 value of Euro, exclude taxes, subsidies, and account for capital costs close to "real risk-free rate of 4%" (Nauclér & Enkvist, 2009, p. 2). [CONTINUES ON THE NEXT PAGE]

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Many of the abatement options are ranked with a negative Abatement Cost, as they entail and account for energy savings, which thus lower incurred implementation costs. The curve calculates a potential of emission reduction by 2030 of 35% compared to 1990 levels, reaching a minimum of 18-29 with a total worldwide annual cost of € 200-350 billion (< 1% of forecasted global GDP in 20130). This is estimated to lead to a GHG atmospheric concentration of 480 ppm and would entail an average increase of global temperature just below the 2 degrees Celsius targeted by the EU and in 2015 by the Paris Agreements.

The data used to construct the curve was provided by McKinsey for the research of Chappin (2016) and was made available for this investigation in the form of an Excel worksheet, containing the Abatement Cost and Abatement Potential for each of the 218 abatement options considered.

1.1.2 Limitations of MAC Curves

Different researches (e.g.: Kesicki & Ekins, 2012) have specifically elaborated on the strengths and weaknesses of MAC curves. Three main limitations are attributed to MAC curves by the existing literature:

Lack of transparency

Kesicki and Ekins (2012) and Chappin (2016) criticize the lack of transparency characterizing the diffusion of MAC curves, often presented and utilized without a precise description of their many, fundamental underlying assumptions; hence, results are interpretable, and more value than justified risks to be assigned to the displayed rankings. Particularly problematic in this regard is the fact that in the past 20 years a numerous MAC curves have been constructed in very different ways (Kesicki & Strachan 2011).

Inconclusive financial analysis

The barriers hampering the implementation of emission abatement options do not seem to be adequately captured by MAC curves (Chappin, 2016; Kesicki, 2010). In fact, abatement measures ranked as financially convenient in McKinsey's MAC curve have still not been implemented (Chappin, 2016), such as the installation of LED lights, the thermal-insulation of buildings, and sustainable air transport, still causing a large CO_2 production. This suggests there shall be are other factors besides implementation costs influencing decision-making; these should be considered when constructing emission abatement curves for more realistic analyses, better able to support effective decision-making.

Interdependent abatement

MAC curves like McKinsey's do not account for interactions between emission abatement measures, nor for the dynamic character of decarbonizing the economy (Kesicki & Ekins, 2012). Thus, MAC curves represent the abatement cost for a single moment of time, and they cannot capture differences in the emission pathway (Kesicki, 2010), with the implementation of an abatement option affecting others. This is damaging for decision-making, as it provides a rather abstract description of the consequences of emission abatement measures, which in reality have interconnected, time-sensitive effects.

1.1.3 The Y-factor method

The "Y-factor" is a new method to construct emission abatement curves, firstly presented by Chappin (2016) and further analyzed by Arensman (2018) and Cheung (2018). Instead of focusing on the abatement cost of emission abatement options, the Y-factor method aims to qualitatively expose the relevance of 12 socio-technical criteria, called "factors", in hampering the implementation of emission abatement options. The 12 factors are grouped in four categories: *Cost and Financing*, *Multi-actor Complexity*, *Physical Interdependencies*, and *Behavior*. Each of the factors is characterized over an ad-hoc, tripartite scale; used to quantify how relevantly is each factor in hampering the implementation of a specific abatement measure. To enable comparisons across factors, all the 12 factor-specific scales refer to a general scale, characterized by three values: Value 0, Value 1, and Value 2. Successively, the 12 scores assigned to each abatement option can be combined to rank and compare multiple abatement options, thus constructing a multi-factorial emission abatement curve. The Y-factor method is presented in the table below *(Table 1)*.

The assigned scores should not be understood as having any absolute meaning; in fact, considering the intrinsic differences among the respective factors, the scores do not pursue a numerical quantification of the implementation barriers. Rather, they enable a qualitative comparison of abatement options, highlighting the relevance of the implementation barriers captured by the 12 factors: a high score signifies a high relevance of the barrier, and suggests the importance of discussing it to achieve the implementation of the considered abatement option. For example: assuming the scores of *B2* = 2, *C1*=1, *D2* = 1 for any given abatement option, it is possible to affirm that for the factor *B2* is more problematic for the considered abatement option than the factor *C1*, but the difficulty of overcoming *C1* and *D1* are hardly comparable, even if they are characterized by the same score, because of the intrinsic differences between the factors. Rather, the Y-factor can be considered an "ordinal" method, aiming to qualitatively compare abatement options along different factors.

Table 1: The Y-factor method

Category	Factor	Value 0	Value 1	Value 2	Definition
(A) Costs and Financing	Investment cost required **(A1)**	Absent	Medium	Large	Degree to which the investment in an abatement measure is significant
	Expected pay-back time **(A2)**	< 5 years	5-12 years	> 12 years	Expected time required to earn back the investment for an abatement measure
	Difficulty in financing investment **(A3)**	Low	Medium	High	The degree to which it is difficult to finance the abatement or attract appropriate financial means
(B) Multi-actor Complexity	Dependence on other actors **(B1)**	No	Little	Much	Degree of dependence on actions of other actors to successfully implement and execute the abatement measure
	Diversity of actors involved incl. conflicts **(B2)**	Low	Medium	Large	Degree of diversity of interests, values, roles, skills and expectations of the actors involved. Degree of public acceptance. When opposing interests from the (local) public to the implementation of the abatement option are (expected to be) present, a high score should be given'
	Division of roles and responsibilities unclear **(B3)**	Clear	Slightly	Unclear	The extent to which the roles and responsibilities for the realization of the abatement option are clear
(C) Physical Interdependences	Physical embeddedness **(C1)**	No	Medium	High	Degree to which the abatement measure requires physical changes to the environment it is placed in
	Disturbs regular operation **(C2)**	No	Slightly	Strongly	Degree (duration, intensity) to which status quo/regular operation is disrupted to successfully apply the abatement measure
	Technology uncertainty **(C3)**	Fully proven	Small	Large	Degree to which the technological performance of the abatement measure is uncertain
(D) Behavior	Absence of knowledge of actor **(D1)**	High Knowledge	Low Knowledge	No Knowledge	Level of knowledge of the parties responsible for the abatement measure
	Frequency of opportunity **(D2)**	Often	Medium	Rarely	Number of opportunities for the responsible party to realize the abatement measure
	Requires change in behavior **(D3)**	No	Slight	Severe	Degree to which the actors involved need to change their day to day behavior

Chappin (2016) proposes its results by summing the individual scores assigned to each factor and comparing the overall score characterizing each abatement option; this allows to qualitatively and comparatively highlight the overall difficulty of implementing different emission abatement options and presents a bar-graph of structure and graphical appeal comparable to MAC curves like McKinsey's.

1.1.4 Theoretical background of the Y-factor method

The structure of the Y-factor method presented in *Table 1* results from the combination of different researches, which have progressively developed it. These researches have refined its structure and the definitions of the 12 factors and have embedded it in the existing body of literature, thus providing the theoretical grounds to this investigation, as discussed below.

The Y-factor method was introduced by Chappin (2016), which proposed it consisting of 13 factors, and provided some preliminary results: in a self-conducted test, the Y-factor method was applied to rank the 50 abatement options ranked by McKinsey's MAC curve with the highest abatement potential (*Appendix B)*. The high scores assigned to all the 12 factors led to ranking the considered 50 options substantially differently from what displayed in McKinsey's MAC curve. Given their subjectivity, such preliminary results were not able to provide reliability to the obtained curve, which thus needed further verifications and testing. The investigations of Arensman (2018) and Cheung (2018) focus on underpinning the 12 factors in the existing literature, discussing the debated implementation barriers and referring to *Transition theory* to explain the logical approach of the Y-factor method.

In particular, Cheung (2018) connects the approach of the Y-factor method to *Transition theory*: abatement options can be understood "as subsystems in the wider climate system in transition. The policy challenge then is to move the climate system from a high carbon-based economy to a low carbon-based economy" (p. 99). The *Multi-actor Complexity* category of the Y-factor method could be paralleled to concepts Transition Management (TM), as the Multiple-Level Perspective (MLP) and Transition Arena, while the *Cost and Financing*, *Physical Interdependencies*, and *Behavior* categories could only be loosely linked to perspectives typical of TM. Successively, the Y-factor method was tested applying it to six case studies to verify its ability to help gathering and comparing empirical data. This testing led to the following conclusions: "the Y-factor may be applied to abatement options in the sector heavy industry, built environment, energy production, forestry, agriculture, and waste, because useful case studies can be constructed with the retrieved data and because the Y-factor was found to be an empowering tool for creating constructive dialogues in the interviews" (Cheung, 2018, p. 101).

The research performed by Arensman (2018) can be dissected in two main parts:
Firstly, it focuses on underpinning the barriers captured by the 13 Y-factors presented by Chappin (2016) in the existing literature on emission abatement, mainly reviewing the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) and different frameworks from *Transition theory*: MLP, Technological Innovation Systems (TIS), and Transition Management (TM). The performed investigation led to conclude that "The Y-factor can be classified as a research method, since it is more concise and concrete than the frameworks it was compared to. The reviewed literature was formulated on a more conceptual level. Hence, the relevance of the four Y-factor categories could be supported by the reviewed literature. The thirteen barriers could not be supported individually" (Arensma, 2018, p. 17).
Successively, it tested the Y-factor method as proposed by Chappin (2016) discussing four abatement options (Carbon Capture Storage for coal plants, Geothermal energy, Insulation retrofit residential, and Bioethanol lignocellulosic) with experts, with The Netherlands as fixed geographic scope.
Combining the insights obtained in the reviewed literature on *barriers to emission abatement* and *Transition theory*, the investigation concludes with the suggestion of some methodological adjustments for the Y-factor method. These mainly consist of modification to the definition of the factors proposed by Chappin (2016) and the elimination of one of the 13 factors, thus leading to the most-updated Y-factor method, presented in *Table 1* and used in this research.

While further research is needed to individually and exclusively justify the relevance of each of the 12 factors, the researches of Arensman (2018) and Cheung (2018), concluded after the start of this investigation, provide a first theoretical framing for the Y-factor method, and justify the focus of this investigation, explained below.

1.1.5 Knowledge Gap and Main research question

Having been introduced by Chappin (2016), theoretically investigated and tested on a small-scale by Arensman (2018) and Cheung (2018), the Y-factor method can now be employed for its purpose: construct a reliable emission abatement curve. This allows the verification of its ability to provide new insights to the emission abatement debate, which can hopefully support the development effective energy strategies for the reduction of GHG emissions.

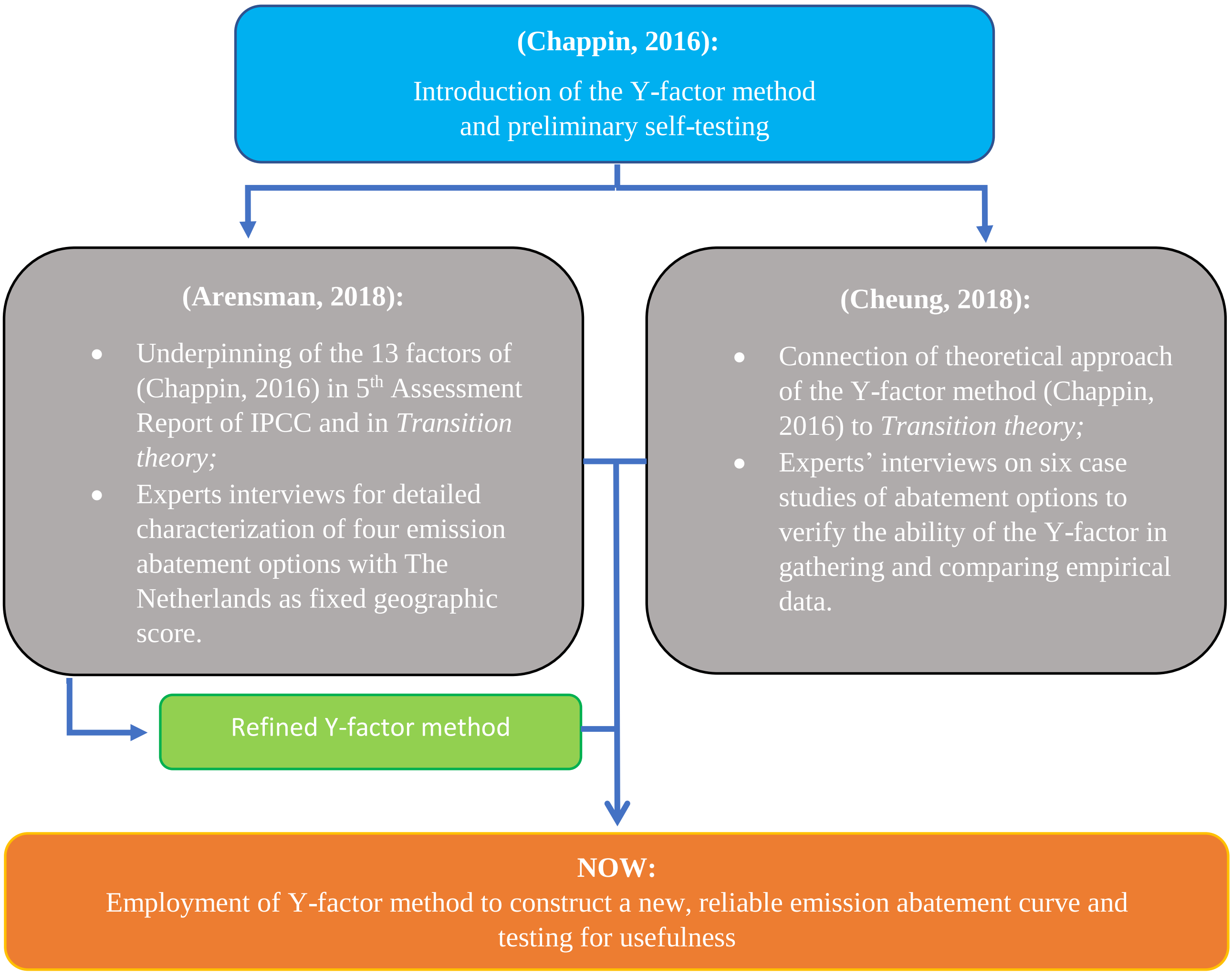
Thus, the construction of a reliable emission abatement curve using the Y-factor method is the knowledge gap tackled by this investigation. A reliable emission abatement curve is a curve composed by reliable figures, which in this case are the individual scores assigned to each factor for every considered abatement option. The reliability of the individual scores cannot be achieved by performing extensive quantitative research, as only some of the factors are quantifiable, (for instance, the factors *A1: Investment cost required* and *A2: Expected payback time*), and the scores are not quantitively comparable across factors given their typological differences. Hence, the reliability of the desired curve shall be achieved by obtaining scores qualitatively synthesizing the opinions of multiple experts, knowledgeable on the abatement option topic. Experts' opinions reduce the subjectivity of the displayed ranking, thus enabling the construction of an emission abatement curve reliably highlighting the relevance of the proposed implementation barriers.

Successively, the obtained emission abatement curve and the Y-factor method can be discussed with different players responsible and/consulted for drafting energy strategies, as policy makers and strategy-consultants, regularly working with emission abatement curves like McKinsey's MAC curve. These players can verify if Y-factor and the emission abatement curve constructed with it provide information which help the drafting of effective and cost-efficient energy strategies.

Thus, the following main research question guides this investigation:

RQ: *What emission abatement curve can reliably capture not only economic but also relevant non-economic implementation barriers?*

Figure 1: Knowledge gap tackled by this master thesis research



1.1.6 Theoretical framing, Scientific & Societal relevance

While validating and discussing the applications of a new emission abatement curve, this investigation aims also to provide scientifically relevant results, able to expand the existing scientific body of knowledge and to contribute to the betterment of society.

Two main themes are addressed by goal of this research: the development of emission abatement curves, and the development of sustainable energy strategies.

<u>Scientific contribution to the development of emission abatement curves and of the Y-factor method</u>

MAC curves are currently the most common tool used to compare and debate emission abatement options. For instance, MAC curves have been used by the UK government to draft its Low Carbon Transition Plan (HM Government, 2009) and to construct "the Global Carbon Finance model (Committee on Climate Change, 2008) based on MAC curves to forecast financial flows between various world region" (Kesicki & Ekins, 2012, p. 220). Other countries have also used MAC curves to elaborate their energy strategies, confirming the predominance of MAC curves in the emission abatement debate.
The Y-factor method proposes a radically different approach to emission abatement curves. Using the terminology of the Multi-Level Perspective and considering emission abatement curves as the technical system in object, the Y-factor can be described as a niche-innovation which aims to complement MAC curves, currently owning the regime status. The works of Arensman (2018) and Cheung (2018) have aimed to underpin the relevance of the criteria composing the Y-factor method, to confirm their theoretical relevance and thus reinforce the validity of the Y-factor method as a framework for comparing emission abatement options. As already highlighted in *section 1.1.4*, the relevance of the individual 12 factors could not be verified by previous researches.

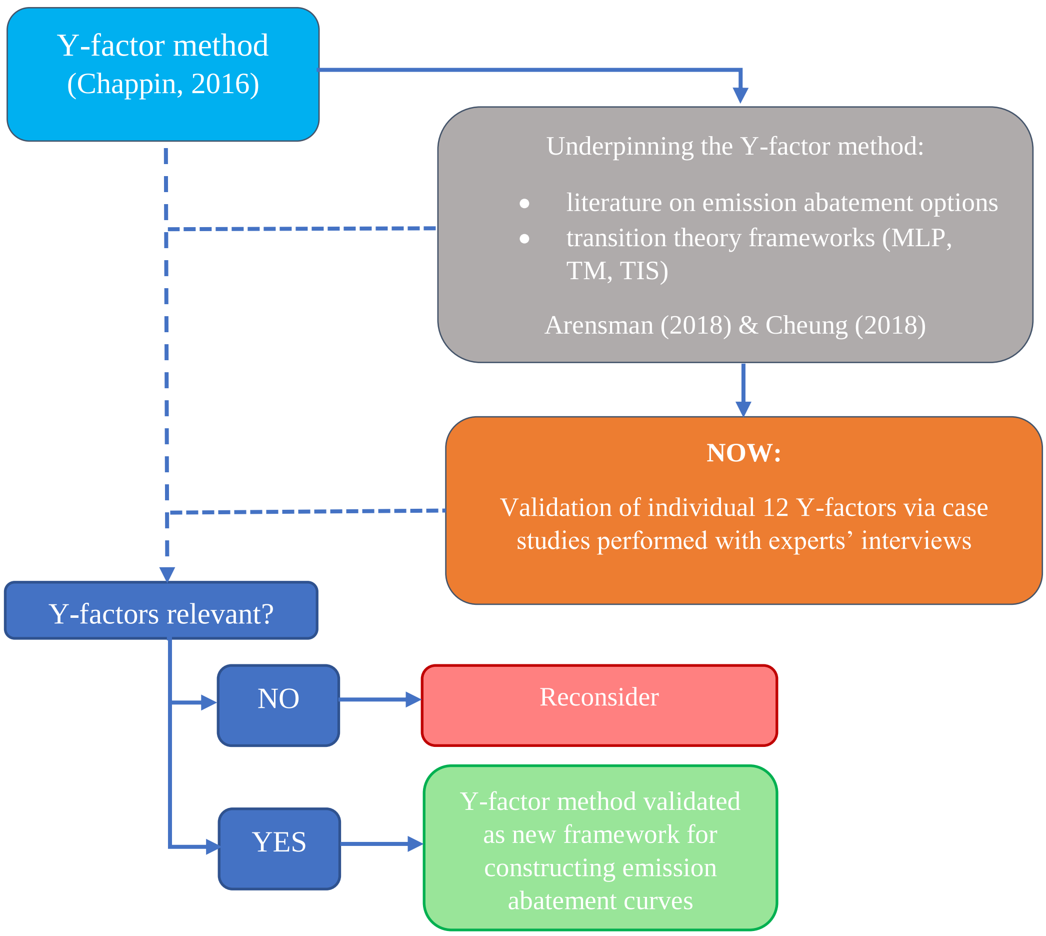
Hekkert et al. (2007) propose 7 fundamental functions to be considered when describing the development of an innovation system. To verify the individual relevance of the 7 functions, Hekkert and Negro (2009) apply them in a collection of case studies and conclude how "First, based on the different event databases we can count how many events are allocated to each system function and calculate the share of each system function per case study and in total. Second, based on the earlier described cases, we argue what the relative importance is of the different system functions" (p. 590), by looking at the narratives of the case studies.

Inspired by this procedure, this investigation aims to further validate the Y-factor method by verifying the relevance of its 12 factors, relying on experts' opinions. If each of the 12 factors were to be considered by experts as a relevant barrier hampering the implementation of the abatement options, the relevance of the 12 factors would be verified; consequently, the Y-factor method would be further recognized as a reliable framework to compare emission abatement options. Instead, if some of the factors were to be disregarded by experts, the accuracy of the Y-factor method would be questioned.

Verifying the relevance of the 12 factors with the procedure of Hekkert and Negro (2009) does not nevertheless exclude the relevance of additional factors, not considered in the Y-factor method.

Thus, the scientific relevance of this master thesis research is two-fold: on one hand, it constructs a new, for the first time a validated emission abatement curve applying the Y-factor method, and on the other hand it aims to verify the relevance of the 12 factors, to strengthen the theoretical validity of the Y-factor method. The scientific contributions of this research are illustrated in *Figure 2*.

Figure 2: Scientific contribution

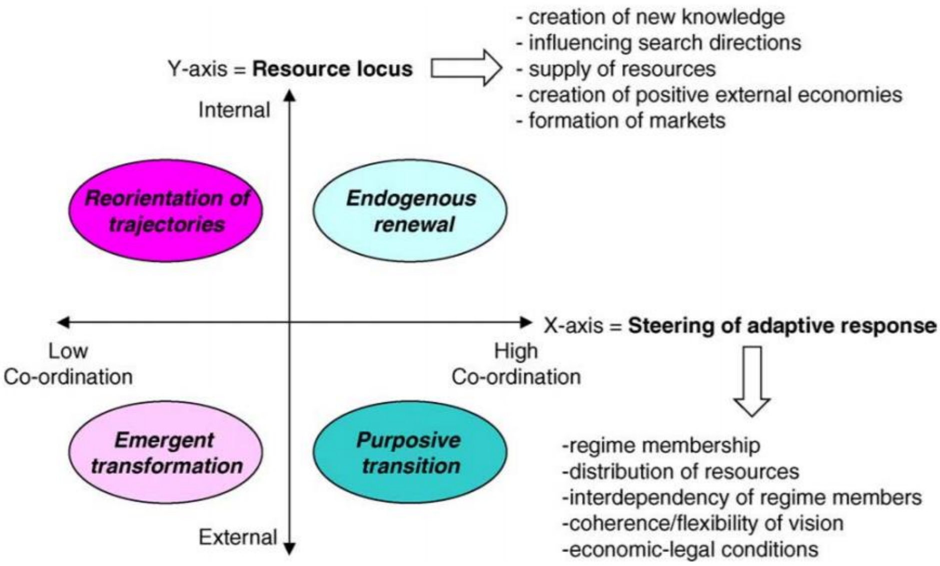


Societal implications: Contribution to sustainable policy and decision making

There is a vast political and scientific agreement on the urgent need of decreasing GHG emissions to reduce air pollution; most nations of the world are committing to reducing pollutions via international agreements like the Paris Agreements (UNFCCC, 2015) and the EU Renewable Energy Directive (Directive 2009/28/EC) and subsequent national policies. The societal urgency is reinforced by an increasing amount of people considered dying because of poor air quality (IHME, 2016), and by rising global temperatures, to which an increasing air pollution contributes. Nevertheless, the debate on the means to achieve emission reduction is still open, as the abatement potential and costs of each option are continuously discussed to decide which abatement options are the most effective and cost-efficient, and what strategy can best support their implementation.

McKinsey's MAC curve is the prominent tool used in this debate, but its sole focus on implementation cost is insufficient to explain the introduction of emission abatement options in society. Thus, the emission abatement debate risks to be lacking the comprehensive approach necessary to provide decision-makers with the information needed to draft effective, sustainable energy strategies. The importance of new tools is highlighted by Smith et al. (2005) who mention how "if we are to engage both analytically and normatively with the complexities of governing sustainable systems innovation, there is a need for more explicit and detailed conceptual tools" (p. 1492). In this perspective, governance processes are considered tasked to independently modulate the regime transformation for socio-technical systems, and a framework is proposed to highlight four different types of governance-steered sustainable innovation. The framework proposed by Smith et al. (2005) is presented below in *Figure 3*.

Figure 3: Transition contexts from Smith et al. (2005, p. 1499)



Considering societies as the systems needing sustainable innovation, and MAC curves as the tools currently used to analyze and compare different concepts (i.e.: abatement options) which can help achieving such innovation, the suggestions provided by the framework of Smith et al. (2005) can be applied to this investigation: policy and decision makers responsible and/or consulted for the sustainable governance of societies bear the responsibilities of governing sustainable innovation, using the available conceptual tools.
MAC curves, the currently employed tools, are not able to independently support sustainable innovation, and thus other tools are needed. New conceptual tools, or visions, can assume many different shapes; one of this is a *heuristic*, which "acts as a problem-defining tool by pointing to the technical, institutional and behavioral problems that need to be resolved" (Smith et al., 2005, p. 1506). Its goal is to reveal the features of the debated choices, and thus help facing provocative questions and shaping possible responses.

The Y-factor method wants to expose the complex diversity of the barriers hampering the implementation of emission abatement options. Its application via experts' interviews can show the relevance of the 12 factors and thus proof its ability to construct an alternative, validated emission abatement curve. Then, the Y-factor method can be considered as a new, *heuristic tool*: by pinpointing the many diverse challenges of implementation, the Y-factor increases the richness of the debate on air pollution, highlighting financial, managerial, technical and behavioral problems which should be addressed. Thus, it can support the sustainable evolution of societies, facilitating the debate on the implementation of currently lacking, and thus innovative, emission abatement options.
In particular, the Y-factor method is a *heuristic* which aims to create a *purposive transition*: the energy transition and the reduction of GHG emissions are topics extensively debated with an increasing awareness of their impelling urgency, and thus with the intention of implementing sustainable changes. This research wants to propose a new tool to those involved in the governance of the sustainable transformation of society, a tool which is thus outside the current regime.

Smith et al. (2005) argue how "it is not a feature of the vision itself whether it becomes recognized as an image around which agents with effective power choose to organize, but on the cultural and political context in which it is propounded" (p. 1507). Thus, after applying the Y-factor method to construct a validated curve, this research focuses on discussing it with players differently involved in the governance of the sustainable transformation of society to introduce the Y-factor method and its results to the relevant agents.

Thus, the proposed research has societal relevance as it provides a new *heuristic tool* to energy strategists, able to expose implementation-complexities; these should be considered in the emission abatement debate to draft strategies able to effectively reduce GHG emissions, one of the grand-challenges of the 21st century.

1.1.7 Fit with CoSEM Objectives

Abatement options have a strong socio-technical character: they are most often enabled by technology, impact people's habits requiring behavioral adaptation, and must be supported by ad-hoc policies for financial and/or operational convenience. The Y-factor method aims to analyze emission abatement options by comprehensively considering diverse themes, reflected in its four categories: *Cost and Financing*, *Multi-actor Complexity*, *Physical Interdependencies* and *Behavior*. By constructing a new emission abatement curve employing the Y-factor method, this investigation embraces and applies the multi-domain, socio-technical perspective typical of CoSEM's problem-solving style.

The topic of air pollution and the consequent need to reduce GHG emissions is at the core of the energy transition debate and of national and international energy strategies and agreements, thus aligning this research with the Energy specialization track of the CoSEM MSc. The different abatement options analyzed cover values belonging to both the private and public sector, as they are relevant for national and international policy making, require and encourage private investments, and are oriented to the well-being of all people. Moreover, the outcomes of this investigation can also be used by energy-service firms to support and/or advise strategic decision-making.

The Y-factor is a new method to construct emission abatement curves which aims to provide new insights to the air pollution debate and to the interdependent energy transition. Thus, constructing a new emission abatement curve, this master thesis research contributes to the process of designing future, sustainable energy systems.

As presented in the following section, this master thesis research is performed firstly relying on experts' opinions to construct a reliable, validated emission abatement curve, and successively discussing it with energy strategists; moreover, time is an important variable, as this research is performed over the course if the summer period (June-October 2018), thus clashing with most peoples' holidays. On one hand, this requires a clear understanding of research and experts' requirements, to adequately manage interdependent research steps having their own needs and requirements, elements typical of the system engineering approach. On the other hand, the process of involving experts, managing their expectations and their specific time and privacy needs will also be essential, and can be tackled exploiting a process management approach, which helps involving experts in the whole research effort, also fostering methodological suggestions.

1.2 Methodology

This section is dedicated to exposing the logic guiding this investigation and the detailed explanation of its subsequent research steps, graphically summarized in the Research Flow Diagram. Ultimately, the strengths and weaknesses of the proposed research approach are discussed.

1.2.1 Research approach

The goal of the research is to construct a reliable emission abatement curve using the Y-factor method, relying on experts' opinions to decrease the subjectivity of the displayed scores. Successively, the newly obtained curve can be discussed with energy-strategists, to verify the benefits the curve and the Y-factor method can provide to policy and decision makers. This research pursues the comprehensiveness of analysis characterizing McKinsey's MAC curve, witnessed by the 10 economic sectors to which the 218 ranked abatement options belong; nevertheless, considering the five months' timeframe available for this master thesis research, a more limited pool of abatement options to include in this analysis ought to be selected; for the same reason, a limited number of experts' interviews can be performed.

To facilitate the interactions with experts and accelerate the discussion, it is decided to provide the interviewed experts with preliminary scores, assigned by the researcher, and to successively ask them to validate these preliminary assigned scores. For assigning the preliminary scores, an overview of the information on the selected abatement options available in the existing literature is performed. Moreover, the retrieved information shall aid the researcher in conversating with experts much more knowledgeable about the specific abatement options.

By comparing and synthesizing the collected opinions of experts, validated scores for each of the considered abatement options can be obtained, and with these the desired emission abatement curve can be constructed.

The obtained emission abatement curve can successively be discussed with players responsible and/or consulted for drafting energy strategies, thus knowledgeable about emission abatement curves like McKinsey's MAC curve, to discuss potential applications for the Y-factor method.

1.2.2 Research methodology

The research logic introduced in the previous section is translated into the sequential research steps presented below, which introduce the sub-research questions guiding the research towards answering the main research question.

<u>Step 1: Construction of the preliminary Y-curve</u>

To facilitate and accelerate experts' interviews, the preliminary scores are self-assigned to the selected abatement options; this enables asking experts to validate rather than assign the scores themselves. This decision is discussed after the results of the interviews with experts are presented (*Chapter 4*) evaluating its possible impacts on the outcomes. By combining the preliminary score assigned applying the Y-factor method, an emission abatement curve is constructed, called "preliminary Y-curve". To construct this curve, three fundamental actions need to be performed: a) Selection of the abatement options to analyze,
b) Overview of the most characterizing features of the selected abatement options, and c) Assignment of preliminary scores to the selected abatement options. These actions are presented in more detail below:

a) *<u>Selection of the Abatement Options</u>*

Initially, the emission abatement options to consider in this investigation are selected. Their number should be sufficient to construct an emission abatement curve enabling comparisons, while fitting in the limited time available for this investigation. McKinsey's MAC curve is one of the possible, and the most obvious reference to which the desired emission abatement curve shall be compared; in fact, its ambition is to tackle some of the limitations of MAC curves, of which McKinsey's is arguably the most representative exemplary. McKinsey's MAC curve ranks more than 200 emission abatement options, belonging to 10 different economic sectors. To facilitate the selection process, the options investigated in this research are selected from the pool of options considered by Chappin (2016), which consists of the 50 abatement options ranked in McKinsey's MAC curve with higher abatement potential; these 50 options belong to 9 different economic sectors. The selection of options shall pursue the principle of diversity, to match the diversity of options ranked in McKinsey's MAC curve.

b) *<u>Overview of selected abatement options</u>*

Once the selection is complete, the main features of the selected abatement options discussed in the existing literature are reviewed. This enables highlighting the options' most characterizing and relevant features, thus allowing the successive assignation of preliminary scores. Moreover, reviewing the main features of the considered abatement options facilitates the conversations with experts, having different expertise, and all being much more knowledgeable in their research field than the researcher.

c) *<u>Scoring of Abatement Options</u>*

Basing on the information retrieved in the literature, the selected abatement options are preliminary scored by the researcher. Following the example of Chappin (2016), the assigned scores can be summed to create a preliminary, non-validated version of the intended emission abatement curve, called the "preliminary Y-curve". This is conceptually comparable to the subjective curve presented in the research of Chappin (2016) and can be used to better communicate to the interviewed experts the intent of the research and of the interviews.

The following sub-research question guides this first research step:

Q1: *What scores can be assigned to the considered abatement options basing on information in the existing literature?*

Step 2: Validation of the Y-curve

To transform the preliminary Y-curve into the desired, validated and thus reliable Y-curve, interviews with experts are conducted. The goal of the interviews is to ask the experts to validate the preliminarily assigned scores, encouraging them to provide an alternative score and a motivation in cases of disagreement. It is decided to aim for a minimum of two expert-interviews per abatement option, to effectively reduce the subjectivity of each score. As experts do not necessarily share the same opinion or similar opinions might lead to the proposal of two different scores, a process to synthesize experts' opinions needs to be developed. Once experts' opinions over each individual score are synthesized and all scores can be considered validated, the final score (or "Y-value") of each abatement option can be obtain. Checking the contributions of each factor to the total Y-value characterizing each abatement option enables to verify if all the 12 factors are relevant, following the process proposed by Hekkert and Negro (2009). Finally, ranking all Y-values in increasing order enables the creation of the intended, validated Y-curve.

Thus, the following sub-research question guides the second research step:

Q2: *How are the preliminary scores validated by interviews with experts?*

Step 3: Application of the Y-curve

Having constructed the intended Y-curve, it is successively possible to discuss it with energy strategists, responsible and/or consulted for drafting energy strategies.

The goal of this research step is to verify if also those responsible for sustainable decision-making recognize the validity of the Y-factor method and its ability to provide new insights to the emission abatement debate which can aid drafting effective energy strategies. Moreover, it is interesting to verify different possible applications for the Y-factor, as these can also inspire future research.

The following sub-research question shall guide this investigation step:

Q3: *How do players responsible and/or consulted for the development of energy strategies envision applications of the Y-curve and of the Y-factor method?*

The thesis research terminates with a Conclusion chapter, which contains reflections on the obtained results and their impact on the air pollution and energy transition debate, and which highlights some limitations and ideas for further research.

The research methodology just introduced is illustrated graphically in the Research Flow Diagram on the next page (*Figure 4).*

1.2.3 Research Flow Diagram

Figure 4: Research Flow Diagram

1.2.4 Strengths and weaknesses

This investigation has an ambitious character: it proposes a new, validated emission abatement curves employing a method, the Y-factor, whose ultimate purpose has never been tested before; it aims to verify the relevance of 12 factors which compose it, and finally investigates the potential applications of the obtained Y-curve for drafting effective energy strategies.

The Y-factor is not only a new method to construct emission abatement curves, but it also proposes a radically different approach to the broader emission abatement debate. This new approach adds a modern perspective to the debate, as it embraces and exposes the multi-domain complexity characterizing and stalling the ongoing emission abatement debate. Hopefully, this research can provide the Y-factor method with the reliability needed to become a popular framework for sustainable decision-making.

To construct a reliable Y-curve which can be compared to MAC curves such as McKinsey's, this research analyzes multiple, explicitly diverse emission abatement options, so far mainly compared on implementation costs, and ranks them according to their Y-values. For constructing a qualitative ranking, different experts are involved in the scoring phase, and these add quality to the results decreasing their subjectivity. A partial, but direct comparison of the obtained Y-curve with the ranking in McKinsey's MAC curve, and the discussion of the applications envisioned for the Y-factor and the Y-curve by players with decision-making power for emission abatement strengthens the ambitious character of this master thesis and its societal and scientific relevance.

The Y-curve has a graphical appeal similar to MAC curves', as the difficulty of implementing an emission abatement option is explicitly displayed in the graph, enabling a quick comparison between multiple, very diverse abatement options. Additionally, the Y-factor and the proposed research approach place an explicit focus on information transparency, the lack of which makes MAC curves hard to reproduce and interpret.

While reduced compared to the self-tests of Chappin (2016), an evident risk in this investigation is the subjectivity of experts' judgement, which needs to be tackled by an ad-hoc interview structure and by carefully comparing the scores assigned by different experts. This is limited by the possibility of finding enough experts and sufficient time for conducting the interviews. Moreover, only a subset of the abatement options ranked in McKinsey's MAC curve is considered, and for each of these only a few experts interviews are conducted; thus, the obtained ranking is partial compared to the one displayed in McKinsey's' MAC curve and still suffers of some degrees of subjectivity. Further research seems promisingly able to tackle these problematic research limitations.

Finally, the proposed Y-curve can tackle only due of the three limitations of MAC curves highlighted in the literature and introduced in *section 1.1.2*. In fact, the Y-curve does not only consider financial parameters and tries to present its results transparently highlighting how they are obtained; nevertheless, it does not capture the path-dependency of emission reduction, as it does not depict how the implementation of an emission abatement option increases or reduces the difficulty of implementing other abatement options.

Chapter 2: Abatement Options

Selection and overview of the abatement options to analyze

This chapter presents the selection procedure leading to the list of mission abatement options included in the analysis (2.1) and proposes an overview of their most characterizing features highlighted in the existing literature (2.2). The options are selected pursuing diversity for representativeness purposes, and for each of them the following information is used to form an overview: definition (from Chappin, 2016), highlight features, estimated costs, abatement potential, and main implementation barriers in the literature.

2.1 Case Selection

Considering the five-month time available for the investigation, a limited pool of abatement options needs to be selected for the analysis. Hence, the challenge is to select an amount of abatement options sufficient to construct the desired emission abatement curve and reflecting the diversity of the abatement options ranked in McKinsey's MAC curve, one of its main strong points. Thus, to enable the desired selection, a multi-criteria selection process is constructed.

2.1.1 Selection criteria

As explained in *section 1.2.2*, McKinsey's MAC curve is a reference for this research; thus, the abatement options to analyze in this research are selected from the pool of 218 abatement options included in McKinsey's global cost curve. To facilitate the selection process, the pool from which to initially select the abatement options is reduced from McKinsey's to the one considered by Chappin in his research (2016), which consists of the 50 options ranked by McKinsey's MAC curve with the highest emission abatement potential.

Considering the time constraints for this research, it is decided to preliminary select 20 abatement options to include in the investigation, as the amount is considered sufficient to construct a curve which enables multiple comparisons of abatement options and highlights their relative ranking. To select the 20 abatement options, a multi-criteria selection procedure is constructed, which has the goal of providing diversity to the selection, to pursue the information richness mentioned by Patton (1990) and the diversity characterizing the abatement options included in McKinsey's MAC curve.

Two main sources of diversity can be highlighted in the pool of options considered by Chappin (2016):

1) Reflecting the classification in McKinsey's MAC curve, the abatement options considered belong the 9 different economic sectors: Building, CCS, Energy, Household Changes, Industrial Processes, Forestry & Agriculture, Fuels, Vehicles, and Waste ("*Filter 1*").
2) McKinsey's MAC curve ranks abatement options in terms of their marginal abatement cost; thus, the options can be diversified basing on their positive or negative marginal abatement costs indicated in McKinsey's MAC curve ("*Filter 2*").

The two sources of diversity mentioned above, in combination with the scores assigned to the 50 abatement options by the research of Chappin (2016), are used to construct the multi-criteria selection process.

Step 1: Most Similar and Most Different overall Y-value per sector

Per sector, select the abatement options with the Most Similar and Most Different overall Y-value assigned by Chappin (2016). The Y-value of each abatement option is obtained summing its characterizing 12 scores.

Step 2: Marginal Abatement Cost in McKinsey's MAC curve

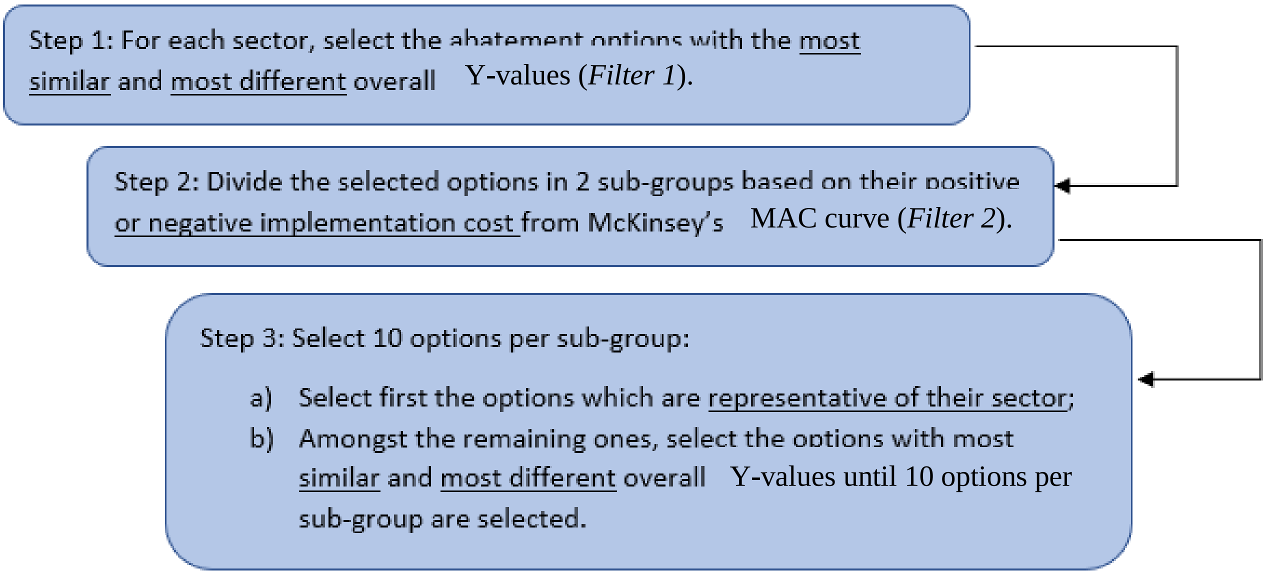
Divide the options selected in *Step* 1 in two sub-groups: one contains the abatement options with Marginal Abatement Cost [€/tCO_2e] < 0, and the other containing the abatement options with Marginal Abatement Cost [€/tCO_2e] > 0, as ranked by McKinsey's MAC curve.

Step 3: Sectorial diversity and Most Similar and Most Different overall Y-values

Select 10 abatement options from each of the two sub-groups:

a) Select first the abatement options which are the only representative of their economic sector;
b) Select the options remaining for reaching a pool of 10 considering the Most Similar and Most Different Y-values. Differently from *Step 1*, these abatement options are not selected per-sector.

Figure 5: Procedure for the selection of diverse emission abatement options to analyze



The Abatement Costs figures provided by McKinsey's MAC are only considered in *Step 2*: while the scores assigned by Chappin (2016) are subjective, the costs reported in McKinsey's MAC are likely to be outdated. Thus, the multi-factor ranking proposed by Chappin (2016) is preferred as main source of diversity. Moreover, Abatement Cost is not a selection criterion, as it does not impose a condition; thus, it is only used to create sub-groups in which to impose additional selection conditions.
Important to note is how the scores proposed in Chappin (2016) are assigned with a 13-factor Y-factor method, as this was successively refined into the 12-factor version used in this investigation by Arensman (2018).

After having selected 20 abatement options with the multi-criteria selection process presented above, four addition abatement options are added for their specific societal relevance and popularity. In the remainder of this elaborate, the abatement options will be presented as follow: [Sector]: Abatement option.

2.1.2 Selected abatement options

For the sake of brevity, the performance of the selection process is not reported in the main text but in *Appendix C*. Thus, in this section only the abatement options selected with the selection procedure described above are introduced.

The multi-criteria selection process described in *section 2.1.1* led to selecting a pool of 20 abatement options, displayed below and able to guarantee the pursued diversity of analysis.

Table 2: Preliminarily selected abatement options

#	Sector	Option	#	Sector	Option
1	Building	Building Efficiency New Build	**11**	Forestry & Agriculture	Reduced intensive agriculture conversion
2	CCS	Coal CCS new build	**12**	Forestry & Agriculture	Reduced deforestation from timber harvesting
3	CCS	Coal CCS retrofit	**13**	Fuel	Bioethanol lignocellulosic
4	Energy	Geothermal	**14**	Household Changes	Lighting switch incandescent to LED (residential
5	Energy	High penetration wind	**15**	Household Changes	Residential appliances
6	Energy	Small hydro	**16**	Industrial Processes	Energy efficiency 1 Iron & steel
7	Energy	PV panels homes	**17**	Industrial Processes	Clinker substitution by fly ash
8	Forestry & Agriculture	Agronomy Practices	**18**	Vehicles	Air Transport
9	Forestry & Agriculture	Cropland nutrient management	**19**	Waste	Composting new waste
10	Forestry & Agriculture	Grassland management	**20**	Waste	Electricity from landfill gas

It is then decided to include four additional abatement options to this pool of 20, for their current popularity in the societal debate. Three of them are included in the list of options from the research of Chappin (2016):

- [Energy]: Nuclear.

- [Vehicles]: Cars full hybrid, Cars plug-in hybrid.

Additionally, [Vehicle]: Battery electric vehicles (BEVs) are included, as they are considered to have the potential to revolutionize the transport sector and drastically reduce its substantial CO_2 emission. Battery electric vehicles are not considered by Chappin (2016), as they are not one of the 50 options with the highest abatement potential in McKinsey's MAC curve. McKinsey's report (Nauclér & Enkvist, 2009) does nevertheless include them in the analysis, and defines them as vehicles that "are powered by an electric motor that receives power, via a controller, from a battery of significant capacity" (p. 95).

The list of options to include in this investigation is then finalized and consists of 24 abatement measures, reported in the *Table 3* below.

Table 3: Abatement options selected for analysis

#	Sector	Option	#	Sector	Option
1	Building	Building Efficiency New Build	**13**	Forestry & Agriculture	Agronomy Practices
2	CCS	Coal CCS new build	**14**	Fuel	Bioethanol lignocellulosic
3	CCS	Coal CCS retrofit	**15**	Household Changes	Lighting switch incandescent to LED (residential)
4	Energy	Geothermal	**16**	Household Changes	Residential appliances
5	Energy	Small hydro	**17**	Industrial Processes	Energy efficiency 1 Iron & steel
6	Energy	PV panels homes	**18**	Industrial Processes	Clinker substitution by fly ash
7	Energy	High penetration wind	**19**	Vehicles	Air Transport

8	Energy	Nuclear	**20**	Vehicles	Cars full hybrid
9	Forestry & Agriculture	Cropland nutrient management	**21**	Vehicles	Cars plug-in hybrid
10	Forestry & Agriculture	Reduced intensive agriculture conversion	**22**	Vehicles	Battery electric vehicles
11	Forestry & Agriculture	Reduced deforestation from timber harvesting	**23**	Waste	Electricity from landfill gas
12	Forestry & Agriculture	Grassland management	**24**	Waste	Composting new waste

2.2 Overview of selected abatement options

This section aims to provide a brief overview of the selected abatement options, with the goal of highlighting their most characterizing features. The retrieved information facilitates the successive scoring process, allowing the researcher to assign the preliminary scores to be validated via experts' interviews, and enabling a more informed discussion with them.

It is important to stress how the goal of the overview is not to obtain a detailed characterization for each of the selected options, but rather to indicate their most important characteristics. Thus, the focus was placed on finding the same information for all the selected options, particularly challenging considering their sector-differences and the peculiar perspective of each research. In the following overview, the sources from which the information on each abatement option has been retrieved are reported, alongside the option's definition used by Chappin (2016) and collected from McKinsey's report (Nauclér & Enkvist, 2009); the definition list of the selected abatement options (Chappin, 2016) is provided in *Appendix D*. Successively, the highlight-features found in the literature are presented, combining the perspectives provided by the consulted articles, which are specifically cited only in the case of exact information and figure. The potential for GHG emissions reduction and their cost estimate reported in the literature follow, before mentioning the most important barriers hampering implementation discussed in the reviewed literature.

The abatement options are presented below in alphabetical order according to their sector: Building, CCS, Energy, Forestry & Agriculture, Fuel, Household Changes, Industrial Processes, Vehicles, Waste.

2.2.1 Building

<u>Building efficiency new built</u>

Sources: Allouhi et al. (2015), Tettey, Dodoo and Gustavsson (2014), Ruparathna, Hewage & Sadiq (2016), Uğur & Leblebici (2017).

Definition: Achieve energy consumption levels comparable to passive housing: Reduce demand for energy consumption through improved building design and orientation; improve building insulation and airtightness; improve materials and construction of walls, roof, floor and windows; ensure usage of high efficiency HVAC and water heating systems.

Highlights: There are many different strategies being researched to decrease buildings' emissions; while most focus on increasing their energy efficiency, the means to achieve the improvements are very diverse. Leadership in Energy and Environmental Design (LEED) is one of the most popular green-building programs, which researches have shown to be capable of achieving 30% of energy consumption reduction compared to conventional buildings, and $1.38/ft^2 savings per annum.

Emissions: LEED= 16% GHG reduction; using cellulose fiber as insulation material= 6-8% GHG reduction.

Costs: LEED= 7.43-9.43% higher than normal buildings, with an additional payback time of 0.41-2.56 years.

Main barriers: High equipment costs, poor micro-credit support schemes, long process and requires the involvement of several actors, social energy waste behaviors and unconsciousness.

2.2.2 CCS

<u>Coal CCS New built & Retrofit</u>

Sources: Haszeldine (2009), Leung, Caramanna and Maroto-Valer (2014), Lohwasser and Madlener (2012), Rubin, Davison and Herzog (2015).

Highlights: CCS technologies involve four main processes: Capture, Separation, Transport and Storage of CO_2. Of the four, carbon capture is the most expensive. Most common technologies implement the capturing of CO_2 Post-combustion or during an Oxyfuel combustion. While both are possible for new-built plants, only Post-combustion is possible when CCS technologies are retrofitted on an existing coal plant. Efficiency for CCS-retrofit is much lower than for new built, and prices much higher. While theoretical efficiencies are calculated to be 65-80 % for new-built plants, implemented CCS technologies on coal plants have achieved only 37-44% efficiency.

Main barriers: Investment, transport and storage infrastructure, policies limiting waste transport, social demonstrations, new for carbon pricing.

<u>Coal CCS New Built</u>

Definition: Using CCS in the same way as in retrofit, but now it is incorporated in the design and building of a new coal power plant.

Emissions: Total emission saving (capture + avoidance) = 1.480-1.8 tCO_2/MWh.

Costs: at least $1.5 billion for an average size plant.

<u>Coal CCS Retrofit</u>

Definition: Using CCS (Carbon Capture and Sequestration) on existing coal power plants by capturing the CO_2 from the point source of exhaust gases. The CO_2 is then permanently stored in deep geological formations.

Emissions: Lower emission-reductions than when CCS system is designed for a new-built plant.

Costs: Levelized cost of electricity (LCOE) for a new coal plant without CCS technology is estimated to be 64–87 $/MWh, while with CCS technology installed the price rises to 94-163$/MWh. Investment cost for new coal plants with CCS technologies is in the range of 1,400-3,000€/kW.

Additional specific barriers: Compatibility and spacing issues, cost of additional equipment, lower economies of scales due to smaller plant dimensions.

2.2.3 Energy

<u>Geothermal energy</u>

Source: IPCC (2012).

Definition: Large scale geothermal energy generation.

Highlights: Important to distinguish between large-size geothermal plants for power generation (deep drilling) or smaller-size plants for heat production, requiring only a superficial drilling. Most technologies for power generation employ a geothermal fluid, which passes through a heat exchanger heating another working fluid with a low boiling point, which in turn vaporizes and drives a turbine. In 2008, global geothermal energy use represented only about 0.1% of the global primary energy supply.

Emissions: 50 gCO_2e/kWh.

Costs: Upfront investment of $ 1,800-5,200/kW (capacity 500-1000 MW).

Main barriers: High upfront investment costs (but low operational cost); social opposition due to minor earthquakes and steam eruptions.

High penetration wind

Source: IPCC (2012).

Definitions: Wind energy, with a penetration of the energy mix higher than 10%.

Highlights: In 2009, it was estimated that the then-1.8% contribution to match worldwide electricity demand of wind energy could grow to 20% by 2050. One of the greatest challenges of wind energy is its variability and location dependence, even if studies have shown that it is unlikely that multi-year annual mean wind speeds will change by more than a maximum of ±25-50 %. Different researches have suggested that up to 20% of wind energy penetration in the energy mix does not present impossible technical or economic challenges.

Emissions: 8-20 gCO_2/kWh.

Costs: Worldwide average onshore turbines investment = $ 1,750/kW, resulting in an average market price of $cent 0.7-3/kWh. Worldwide average offshore turbines investment= $ 3,200-5,000/kW, resulting in an average market price of $cent 7.5-23/kWh.

Main barriers: Wind variability, Not-In-My-Backyard (NIMB) phenomena, impact on wildlife (e.g.: bird collisions) and landscape modifications.

Nuclear

Sources: Deutch et al. (2003), Dittmar (2012), Georgiapower (2018), IPCC (2012), Nuclear Power Insights (2018), World Nuclear Association (2018).

Definition: Energy generation in nuclear power plants.

Highlights: Nuclear energy is one of the most discussed energy sources; the discussion has been ongoing since its origins in the 1950s and it is still bitter nowadays. There are four main characterizing issues: cost, safety, waste, and proliferation. Supporters of nuclear energy stress the increasing operational performances and safety of nuclear plants. Opponents of nuclear energy stress the unavoidable maximum-capacity operations of nuclear plants, waste management and limited uranium-availability, and they criticize the large funds dedicated since the 1950s to nuclear energy with the unaccomplished promise of solving energy supply problems.

Emissions: 90-140 gCO_2e/kWh.

Costs: Difficult to estimate the total costs because of very long construction lead-times (> 50 months), influencing the required capital costs, land concessions, and technical and social requirements. E.g.: Vogtle 3&4 project in June 2014 cost $ 14 billion for an installed capacity of 2,234 MW. Average market costs are estimated at $cent 6.6-8.4/kWh.

Main barriers: Waste management, market uncertainties, proliferation of nuclear weapons.

PV panels homes

Sources: IPCC (2012), The Renewable Energy Hub UK (2018).

Definition: Solar energy installed on homes of individual home owners.

Highlights: Mono-and polycrystalline silicon-wafer are the dominating technologies on the PV market. Peak efficiencies vary from 10% to 50%, depending on the cells type, but market PVs have efficiencies normally varying between 16-23%; the modules' performance is usually guaranteed by manufactures for 20-30 years. More than 90% of the current PV capacity is installed in three leading markets: the EU (73%), Japan (12%) and the USA (8%).

Emissions: None, besides the use of some toxic, explosive gases and corrosive liquid (30-80 gCO_2e/kWh).

Costs: $ 2,000 (1 kW module), $ 6,000 (4 kW module). Current levelized cost of electricity (LCOE) is around $0.15-0.4/kWh.

Main barriers: Permits, financing challenges, and access to transmission lines.

Small Hydro

Sources: IPCC (2012), Jäger et al. (2017).

Definition: Small scale hydro energy generation

Highlights: Hydropower plants come in three main project types: run-of-river (RoR), storage and pumped storage. Storage hydropower stations deliver a broad range of energy services such as base load, peak, and energy storage, and act as a regulator for other sources. Additionally, they often deliver services that go beyond the energy sector, including flood control, water supply, navigation, tourism and irrigation. Only 25% of the worldwide potential has been already developed. Small hydro power plants are usually built on rivers and have an installed capacity of around 20-50 MW.

Emissions: None, besides CO_2 and methane in the decomposition of organic materials (4-14 gCO_2e/kWh).

Costs: Upfront investment between $ 1,000/kW and $3,000/kW.

Main barriers: High upfront investment costs (but low O&M cost), problems with suspended loads (e.g.: branches) which require frequent flushing, lack of interconnections with power-distribution grid, little private-sector confidence, lack of cross-countries interconnections, substantial social impact as relocation of local communities and compensation of downstream communities are often required.

2.2.4 Forestry & Agriculture

Agronomy Practices

Sources: Conservative Agriculture (2018), World Bank (2017).

Definition: Improved agriculture mechanisms, such as: crop varieties; extended crop rotations, less intensive cropping systems, extended use of cover crops. This is a more long-term measure for soil treatment.

Highlights: Pool of practices developed in Brazil and Argentina in the 1970s, focusing on: 1) minimizing soil disturbance (absent tilling, farmers seed directly into the soil), 2) maintaining soil cover (farmers leave crop residues after harvesting or grow cover crops), and 3) managing crop rotation (farmers change what is grown and where).

Emissions: Estimated emission-reduction of approximately 0.2 tCO_2e/hectare per year.

Costs: No first-cost assumed for already cultivated lands. Experimental testing and simulations have estimated a net profit of $650.65 per hectare per year, compared to $407.47 for the conventional practice.

Main barriers: Education, behavioral changes.

Cropland nutrient management

Sources: Drawdown.org, Nutrient Management (2018), World Bank (2017).

Definition: Management of croplands to reduce GHG emissions consists of improved nutrient management (such as slow-release fertilizer forms, nitrification inhibitors, and improved application rates and timing).

Highlights: Nutrient management consists in reducing fertilizer-waste and the nitrous-oxide (N_2O) emissions associated with agriculture, via an increased land efficiency, and implementing rotational, regenerative land practices.

Emissions: A reduction of 0.14 tCO_2e/hectare per year is estimated from the reduction of nitrous-oxide (N_2O) emissions due to a decrease in nitrogen fertilizers manufacturing and over-application.

Costs: First cost of nutrient management is $0/hectare, as reducing the over-application of fertilizer costs farmers nothing. Net profit margin is estimated at $7.48/hectare per year.

Main barriers: Need to test all cropland fields to understand the best fertilizer recommendation, education, behavioral changes.

Grassland Management

Sources: Regenerative Agriculture (2018), World Bank (2017)).

Definition: Increased grazing intensity, increased productivity (excluding fertilization), irrigating grasslands, fire management and species introduction.

Highlights: Focuses on the elimination of any pesticide or fertilizer, and includes strategies like no-tillage, diverse cover crops, in-farm fertility (no external nutrients), and multiple crop rotations. As a consequence, vital microbes proliferate, roots go deeper, nutrient-uptake improves, water-retention increases, plants are more pest-resistant, and soil fertility improves.

Emissions: Estimated reduction of approximately 0.23 tCO_2e/hectare per year.

Costs: No first-cost assumed for already cultivated lands. Experimental testing and simulations have estimated a net profit of $650.65 per year, compared to $376.98 per year for the conventional practice.

Main barriers: Education, behavioral changes.

Deforestation and Forest Degradation

Sources: Damette and Delacote (2011), Forest Protection (2018), Kindermann et al. (2008), Kissinger et al. (2018), Wageningen University and Research Centre (2012), WWF (2018).

Emissions: 5.1-8.4 $GtCO_2$/year caused by deforestation.

Cost: "10% reduction in deforestation from 2005 to 2030 could provide 0.3–0.6 $GtCO_2$/year in emission reductions and would require from $0.4 billion to $1.7 billion/year for 30 years. A 50% reduction in deforestation from 2005 to 2030 could provide 1.5–2.7 $GtCO_2$/year in emission reductions and would require $17.2 billion to $28.0 billion/year" (Kindermann et. al., 2008, p. 10302).

Main barriers: Corruption and low institutional quality, global trends (e.g.: urbanization, increasing international demand), local development.

Reduced deforestation from timber harvesting

Definition: Reduction of emissions from deforestation due to unsustainable timber extraction through compensation to landholders for lost timber revenue.

Highlights: 70% of forest degradation is caused by timber harvesting. Forest protection primarily happens at the government and NGO level, which bear the costs rather than dividing them over local communities.

Reduced intensive agriculture conversion

Definition: The decrease of deforestation for agricultural use. This is done through compensation of landholders for the lost revenue from one-time timber extraction and future cash flow from agriculture.

Highlights: Every year, about 13 million hectares of forest are converted to other land uses, leading to biodiversity losses, soil erosion, and massive CO_2 emissions. Of these, 70% of deforestation is related to agricultural expansion at the forest frontiers

2.2.5 Fuel

Bioethanol lignocellulosic

Sources: Carriquiry Duand Timilsina (2011), Lemos & Mesquita (2016), Naik et al. (2010), Wydra (2015).

Definition: A second generation biofuel: Modelled as lignocellulosic ethanol (25gCO_2e per MJ). Other second-generation biofuels are: lignocellulosic (LC) ethanol, Fisher-Troph (FT) diesel, and dimethyl ether (DME)). It is derived from feedstock such as bagasse, wheat straw, corn stover, or dedicated energy plants such as switch grass, and have a CO_2 reduction potential of up to 90 percent.

Highlights: Second generation biofuels, of which bioethanol lignocellulosic is the most popular representative, have been developed with the intention of reducing the undesired effects of primary biofuels production. The feedstock with the highest potential for producing second generation biofuel are lignocellulosic (agricultural residues, forest residues, herbaceous and woody energy crops) and biodiesel feedstock; second generation biofuels can be created from feedstock vial hydrolysis and fermentation processes.

Emissions: Net GHG emission from land usage decreasing from 35,000-39,000 $MtCO_2e$ from first generation biofuels to 14,000-23,000 $MtCO_2e$ with second generation biofuels.

Cost: The costs of lignocellulosic feedstock is in the range of $ 19-84/ton, leading to a production costs of second-generation ethanol in the range of $0.60–$1.30/L. Fuel cost expected to grow to 1.38$/L from the current baseline (1.18 $/L) and first-generation biofuels (1.14 $/L) levels, while crop price is expected to increase only marginally, from a current range of 1.21-1.29 $/kg, to 1.23-1.30 $/kg.

Main barriers: Technological developments to expand list of input materials, contrasting opinion, lack of clear policy support.

2.2.6 Household Changes

Lighting switch incandescent to LED (residential)

Sources: Cowan & Daim (2011), Hicks & Theis (2014), Mills & Jacobson (2011), Pimputkar, et al. (2009).

Definition: Switching incandescent lighting for LEDs in residences. Conversion to LEDs complete by 2030.

Highlights: LED produce between 60-100 Lm/W (luminosity efficacy), but there already exist prototypes reaching over 200-280 Lm/W. These figures ridicule the average 20 Lm/W of the most common incandescent lights. Moreover, the lifetime for a LED ranges between 25,000-100,000 hours, comparing to the 1,000-2,000 hours for incandescent.

Emissions: CO_2 emissions from fuel-based lightning are estimated to be 190 million tCO_2/ year. LED lights are estimated to be 40% more efficient than fluorescent lights and 80% more efficient than common incandescent lights. converting all conventional white light sources in the world to LED lights sources would reduce GHG emission by about 200 mil. tons.

Cost: $ 34, while the cost of an incandescent bulb is just above $ 1.

Main barriers: Installation costs, skepticism about cost savings, unsatisfactory light color, the longer start-up time, compatibility standards, inconsistent local policies, education.

Residential Appliances

Sources: Balta-Ozkan et al. (2013), Elma et al. (2013), IEA (2011), Stragier, Hauttekeete and De Marez (2010), Wada et al. (2012).

Definition: Replacing residential appliances with high efficiency models (when former expired): refrigerator/freezer, washer/dryer, dishwasher and fans.

Highlights: To enable a more efficient and flexible energy use at home, residential appliances like heaters, air conditioners, and washing machines must become "smart", meaning they should be characterized by a higher technological-sophistication and real-time access to energy-usage data, facilitated by a network of sensors and computers. One of the means to increase energy consumption awareness and encourage efficient and flexible energy use is to increase the visibility of energy utilization and cost, through interactive displays providing real-time usage and price data monitoring.

Emissions: 2.4 tCO_2/home per year (pilot from Elma et al., 2013), potential saving of 1.4 $GtCO_2$.

Cost: $500,000 for new, fully-smart home (pilot from Elma et al., 2013).

Main barriers: Technical interdependencies with information network/smart grid, purchase and maintenance cost of appliances, data privacy, social exclusivity (not for low-income and elder population), behavioral adaptation, Perceived Ease of Use and Perceived Usefulness.

2.2.7 Industrial Processes

Clinker substitution by fly ash

Sources: Hemalatha and Ramaswamy (2017), Rivera et al. (2015), Vargas and Halog, (2015), Worrellet et al. (2001).

Definition: Reducing the clinker content in cement, by substituting clinker with slag, fly ash, and other mineral industrial components, reduces process and fuel combustion emissions as well as electric power from clinker production.

Highlights: Fly ash (FA) is the major solid waste generated by coal-firing power stations and one of the most popular supplementary cementitious materials (SCM) which, having similar cementitious properties, can be employed instead of clinker as binders in the cement production process. FA is currently used to replace clinker in cement only up to 15-35% of the concrete total mass. One of the main causes of the wasted volumes of FA is the frequent inability of FA to meet the quality requirements but can be "upgraded"; if the energy required to modify FA is above 3.98 GJ/ton, emissions generated in the upgrading process surpass the savings produced by the replacement of clinker. Available technologies for upgrading FA are reported having a maximum energy need of 1 GJ/ton FA.

Emissions: 5-20% reduction (56-224 $MtCO_2$).

Cost: $ 15-30/ton ($ 24/ton for slag), considerably lower than the cost of cement, estimated (1990) at $ 36/ton.

Main barriers: low quality control systems available, long-term durability issues related to sulfate attack, initial investment, longer setting time, poor communication across the supply chain, need for extra processing.

Energy efficiency 1 Iron & steel

Sources: Brunke, Johansson and Thollander (2014), Consultation on Proposals regarding Smart Appliances (2018), Karali, Xu and Sathaye (2014), Quader, et al. (2015), Zhang, et al. (2014).

Definition: Higher energy efficiency in the iron and steel industry due to mechanisms such as: structural production shifts, better preventive maintenance, improved process flow (management, logistics, IT-systems), better motor systems, new efficient burners, pumping systems, capacity utilization management, heat recovery, coal moisture control, sinter plant heat recovery, or pulverized coal injection.

Highlights: The Iron and Steel Industry (ISI) is responsible for emitting 4–5% of the total anthropogenic CO_2. emissions. Technical focus is on the recovery of high-temperature waste heat energy from various industrial processes as gas streams. The blast furnace is the largest source of direct CO_2 emissions, thus, it is fundamental to utilize higher quality raw materials and to switch from coal-based fuels to a fuel mix with a lower carbon emission factor, as biomasses. Future developments aim at the incorporation of renewables, CCS technology for the furnace, hydrogen-based steelmaking, and iron-ore electrolysis.

Emissions: China = 463$MtCO_2e$, 253 Kt of Particulate Material (PM), and 1,392 Kt of Sulfur-dioxide (SO_2).

Cost: Cost of policies favoring energy-efficient processes estimated to be $ 0.8 billion in the US and $ 2.1 billion in China.

Main barriers: Access to capital, average payback times of 3 years in ISI, lack of long-term policy agreements.

2.2.8 Vehicles

Air Transport

Sources: Åkerman (2005), Bicer and Dincer (2017), Gössling and Cohen (2014), Quant (2015), Higham et al. (2016).

Definition: Technology solutions including alternative fuels, Operations-efficiency improvements and Infrastructure and air-traffic management.

Highlights: in 2013 air transport produced 705 million tons of CO_2, which approximately corresponds to 2% of the global total emissions; 65% of these are caused by civil aviation, the rest by cargo and military. Air traffic is projected to grow by 4-5% per annum in the period 2010-2050. Main attempts to reduce emissions have focused on improvements in fuel efficiency, and reducing cruising speed from 900-950 Km/h to 640-700 Km/h. In terms of alternative fuels, hydrogen and liquefied natural gas are more environmentally benign alternatives compared to ammonia, kerosene and methanol in terms of social and environmental costs, but fuels costs are higher. Governments are now focusing on regulatory-binding targets and market mechanisms; as no worldwide agreement has been reached yet, the EU has incorporated all flights within EEA in the ETS from 2017, re-instating Directive 2008/101/EC and continuing the debate with the International Civil Aviation Organization (ICAO).

Emissions: Improvement in fuel efficiency: nullified by increasing air traffic; Reduced cruise speed: 25% reduction per year. Alternative Fuels: hydropower-based ammonia = 0.24 $KgCO_2e$ per traveled tons-km, hydrogen= 0.03 $KgCO_2e$. per traveled tons-km, kerosene = 1 $KgCO_2e$. per traveled tons-km.

Cost: Improvement in fuel efficiency: additional $ 11 million for single-aisle and $ 40 million for twin-aisle aircrafts; Reduced cruise speed: no financial costs; Alternative fuels: Kerosene = 0.409 $/kg, Hydrogen= 2.3 $/kg, Ammonia = 0.280 $/kg.

Main barriers: Alternative fuels cost, Common but Differentiated Responsibilities and Respective Capabilities, stakeholders' skepticism, perceptions of attempts to restricting individual freedoms to travel.

Battery electric vehicles & Cars full hybrid & Cars Plug-in hybrid

Sources: Alternative Fuels Data Center (2018), Cbs (2015), Cbs (2018), Chan (2007), (Egbue and Long (2012), Statista (2018), USA Today (2015), Tesla (2018).

Main barriers (common): High price, short range.

Battery Electric Vehicles

Definition: "A battery electric vehicle (BEV, e.g.: Testa 3 and Tesla S) is an electric vehicle that utilizes chemical energy that is stored in rechargeable battery packs" (ScienceDaily, 2018). McKinsey's report defines BEVs as vehicles that "are powered by an electric motor that receives power, via a controller, from a battery of significant capacity" (Nauclér & Enkvist, 2009, p. 95).

Highlights: Expected to have a great emission-reduction potential but their market introduction is slow due to their high prices and low autonomy-ranges. Currently verified ranges using lithium-ion batteries can achieve about 250 Km with reasonable size packs, while the new Tesla S model promises to ensure a battery range of more than 415 Km. Questionable is the additional financial and energetic costs of producing batteries.

Emissions: 2 tCO_2e/year compared to the 5.4 tCO_2e/year of gasoline ICE vehicles.

Cost: start from around $ 35,000 (in 2015 ICE vehicles had an average price of $ 33,560 in the U.S. and about € 28,000 in the EU).

Main barriers: High costs, dependence on charging infrastructure, low autonomy range.

Cars full hybrid

Definition: Hybrids on the road today range from mild, simply incorporating some form of a stop-start system, to full, where an electrical drive system is packaged in parallel to the ICE drive system and is calibrated to run when conditions best suit electrical driving. In addition, full hybrids are typically engineered in such a way that aerodynamic drag, rolling resistance, and weight are all reduced to varying degrees.

Highlights: Hybrid Electric Vehicles (HEVs, e.g.: Toyota Prius) have both an ICE and an electric motor onboard; the ICE converts the fuel gas to mechanical energy, which in turns drives the electric motor. Because of the improvement of the ICE operations, the maintenance of the vehicle can be significantly reduced. Moreover, the electric motor allows for more flexibility and controllability to the vehicle control, enabling systems as antilock braking (ABS) and vehicle stability control (VSC). In The Netherlands "On 1 January 2018, there were over 150 thousand regular hybrid electric vehicles (HEVs) without plug-in capability; an increase of 12 percent year-on-year" (Cbs, 2018), HEVs already accounting in 2015 for 2% of the overall Dutch car fleet, rapidly increasing from the 0.5 % of 2010 (Cbs, 2015).

Emissions: 2.7 tCO_2e/year compared to the 5.4 tCO_2e/year of gasoline ICE vehicles

Cost: Additional $ 2,500-14,000 compared to ICE vehicles, which in 2015 had an average price of $ 33,560 in the U.S. and about € 28,000 in the EU.

Main barriers: Gas price, small all-electric-ranges.

Cars plug-in hybrid

Definition: Full-hybrids that can be recharged both by the vehicle-driving cycle and by external sources, enabling the vehicle to run more frequently on electrical power.

Highlights: While HEVs are refueled at normal gas stations, PHEVs are usually refueled by electricity grid. Thus, the efficiency of PHEVs is higher and allows for all-electric ranges of 30–60 Km using lithium-ion batteries, performance not possible for standard HEVs.

Emissions: 2.7 tCO_2e/year compared to the 5.4 tCO_2e/year of gasoline ICE vehicles.

Cost: Additional $ 2,500-14,000 compared to ICE vehicles, which in 2015 had an average price of $ 33,560 in the U.S. and about € 28,000 in the EU.

Main barriers: Limited all-electric-ranges

2.1.9 Waste

Composting New Waste

Sources: Cerda et al. (2017), Hoornweg Bhada-Tata and Perinaz (2012), Lou & Nair (2009), Sánchez et al. (2015).

Definition: Solid waste can be sorted for the recycling of glass, paper/cardboard, plastic, and metal waste, and the composting of organic waste. Recycling and composting reduce the introduction of new waste to landfills, thereby avoiding landfill and industry emissions. Composting avoids methane emissions from new organic waste.

Highlights: Aerobic digestion ("composting") is a biological process which leaves compost as final product (plus CO_2 and water, but CH4 emissions are negligible). Composting often requires pretreatment, to separate the different types of waste and thus guarantee a final compost quality which allows for further applications.

Emissions: 0.183-0.323 tCO_2e/ton of mixed waste. These figures are much lower than the calculated 1.287 tCO_2e/ton of waste emitted by a from landfill without material treatment.

Cost: 5 $/ton for low income countries to 90 $/ton for high income countries.

Main barriers: Odor emissions of landfills, side production of GHG emissions (no methane) as it is an energy and fuel intensive process employing heavy machineries.

Electricity from landfill gas

Sources: Broun and Sattler (2016), Chen and Lo (2016), Morgan and Yang (2001), Luz et al. (2015), Jaramillo and Matthews (2005).

Definition: Capture landfill gas to generate electricity.

Highlights: Landfill gas is composed for 50% by methane (CH4), 45% by CO_2, and the remaining 5% is a mix of nitrogen (N2) and other gases. The generation of landfill gas starts soon after the landfill becomes operational, and it can last for up to 30 years after its closure. Besides consuming some of the methane produced by the organic waste, electricity from landfill gas can indirectly further reduce air pollution by decreasing the standard electricity production, for the majority still achieved by burning more polluting fossil fuels.

Emissions: (direct) 803 $KgCO_2e$/ton of waste, compared to 668 $KgCO_2e$/ton of waste of conventional landfills. Though to account for emission reductions from reduced electricity generation.

Cost: 900-1500 $/KW, with 900 KW/ton produced.

Main barriers: Interconnection costs and regulations, buy-back rates, access to capital for the initial investment, absence of a worldwide market pricing emission.

Chapter 3: Preliminary Y-Curve

Assignation of preliminary scores basing on the literature overview

This chapter is dedicated to scoring the abatement options selected applying the Y-factor method and basing on the information presented in *section 2.2 Overview of Selected Abatement Options*. Once the preliminary scores are assigned, they can be summed per-abatement option to obtain a preliminary, non-validated version of the intended Y-curve, which can be used to facilitate successive interviews with experts.

3.1 Preliminary scores

This paragraph presents the scores preliminarily assigned to the analyzed emission abatement options, and their supporting arguments. The arguments about the same factor across different abatement options are more similar than the arguments for the same abatement options across different factors; thus, for the sake of brevity, the assigned scores are reported per factor rather than per abatement options, to group similar arguments. The information used to assign the scores is the one provided in *section 2.2* for each abatement option, which is not cited unless additional information is used. While score-accuracy is pursued, it is not fundamental for the scores to be certain, as they are means to facilitate experts' interviews which will validate them or propose an alternative. As in *Chapter 2*, the abatement options are mentioned highlighting the [Sector]: Abatement option to aid the reading, while the factors are mentioned with their reference-letters, highlighted at the beginning of each of the successive sections.

3.1.1 A. Cost and Financing

Cost and Financing is the first (named "A") of the four categories composing the Y-factor method, and it contains three factors: *A1: Investment cost required*, *A2: Expected payback time*, and *A3: Difficulty in financing investment.* The scores assigned to all the 24 analyzed emission abatement options for these three factors are discussed below, combining similar argumentations valid for different abatement options.

Energy & Waste

Some of the analyzed abatement options require the construction of power plants, namely [Energy]: Geothermal, Nuclear, and Small hydro. Regardless of the type of technology employed, the construction of power plants requires large capital investment: geothermal power has an estimated installed-capacity cost of $ 1,800-5,200/KW, nuclear power over $ 6,000/KW, and hydropower of $ 1,000-3,000/KW (argument valid even if the investment is halved by decreasing the size), which multiplied by the plant size explains the large investments required. Thus, all these options are assigned a score of 2 for the factor *A1*.

A power plant has a rather long life-time, as the 40+ years lifetime of nuclear plants (Scientific American, 2009), also needed to recover their substantial investment costs. Thus, these three abatement options are assigned a score of 2 for the factor *A2.*

Geothermal plants can be size-compact and reliably provide renewable baseload power, something other renewables such as wind and solar power are not able to do; thus, geothermal energy is considered having a competitive-advantage in the policy-environment, and it is scored with a 1 for the factor *A3.*

Instead, nuclear and hydropower are more controversial: public opinion and some governmental policies (e.g.: in Germany) are rather negative towards nuclear power, while it is becoming increasingly difficult to find adequate spot for hydropower plants (at least in Western countries) considering natural requirements and social opposition. Thus, a score of 2 is assigned to both abatement options for the factor *A3*.

Quite a different argument is valid for the other two abatement options of the energy sector, focusing on wind and solar power. The investment cost for wind power are very high ($ 1,750/KW onshore, and $ 3,200-5,000/KW for offshore), especially considering a 10% penetration in the energy mix, as in definition of the abatement option. Much lower is the investment for PV panels, which can be installed by privates with an investment of a couple of thousand dollars (The Renewable Energy Hub UK, 2018). Thus, for the factor *A1* a score of 2 is assigned to the abatement option [Energy]: High penetration wind and a score of 1 for [Energy]: PV panels homes.

Wind and solar power are arguably the most popular renewable energies; governments around the world are trying to encourage their installation with national subsidies (e.g.: Feed-in-Tariffs (FIT) and Feed-in-Premium (FIP) in the EU, Renewable Portfolio standard (RPS) in the USA), able to shorten the payback time (about 7 years but recently increasing for PV panels homes, more variable but decreasing for wind turbines) and facilitate the financing of the investment. Hence, both options are assigned a score of 1 for the factors *A2* and *A3*.

The reasoning for scoring the option [Waste]: Electricity for landfill gas is similar to the what discussed above for power plants. A large investment is needed for installing power production facilities at landfill sites, but even more challenging are the high interconnection costs, necessary for supplying the power produced burning municipal waste to the local power distribution grid (900-1500 $/KW). Thus, given the large investment and long lifetime of landfills, a score of 2 is assigned to the factors *A1* and *A2*.

Nevertheless, collecting and burning landfill gas is a process with permits avoiding almost entirely the highly problematic methane (CH4) emissions caused if municipal waste solely disposed in landfills, and it additionally contributes to power supply; thus, governments positively welcome this abatement options. Only a few incentives and regulations have so-far been drafted (e.g.: EU Directive 2008/98/EC), but more can be expected, thus facilitating the financing of the large investment. Thus, a score of 1 is assigned to the factor *A3*.

Much lower, but still present ($ 5-90/ton) are the costs for an alternative waste treatment process, namely [Waste]: Composting new waste, for which no power generation costs nor interconnecting infrastructure are needed. Thus, in a comparative fashion to Electricity from landfill gas, a score of 1 is assigned to both the factors *A1* and *A2*. While less expensive, waste composting also provides lower reductions of GHG emissions than Electricity from landfill gas and is considered to be likely less favored by government and investors (score of 1 assigned to the factor *A3*).

CCS

The implementation of the abatement option [CCS]: Coal CCS new built also involves the construction of new coal power plants, which have high investment costs (1,400-3,000€/KW); thus, a score of 2 is assigned to the factor *A1*. Even higher costs, although without requiring the construction of new power plant, are necessary for installing CCS systems on existing coal plants, because of complicated compatibility and space issues; thus, a score of 2 is assigned to the factor *A1* also for the option [CCS]: Coal CCS retrofit.

In the coming years a reduction in the operations of fossil fuel plants is expected, in favor of renewable power. Renewables energy is already preferred on the market having close-to-null variable costs, and conventional power-plants are dispatched by the various energy-market authorities only to cover the energy-demand unmatched by renewables. Hence, the pay-back time for investments in coal plants will enlarge, due to the fewer operational hours; this is likely also if currently-absent market mechanism (e.g.: capacity payments, capacity subscriptions, etc.) were to be implemented. Consequently, both abatement options are assigned a score of 2 for both factors *A2* and *A3*.

Forestry and Agriculture

Both [Forestry & Agriculture]: Cropland nutrient management and Grassland management practices focus on banning fertilizers, thus saving a considerable amount of money; this can be re-use to finance eventual new costs incurred with increasing land-rotations. Thus, to both options is assigned a score of 0 for factors *A1*, *A2*, and *A3*. The same scores are assigned to [Forestry & Agriculture]: Agronomy practices, but for different reasons: fertilizers are not banned, but no additional cost should be incurred, as changes relate to different crop variety and to the implementation of different cropping systems.

Some investment is needed to implement the abatement options [Forestry & Agriculture]: Reduced intensive agriculture conversion and Reduced deforestation from timber harvesting, although this consists more of annual payments than an initial investment. The overall investment needed to decrease deforestation on a global scale is very large (> $ 1 billion /year), but the cost of local forest protection programs is limited and easy to finance considering the many NGOs working and lobbying for them, as Green Peace and WWF. Thus, a score of 1 is assigned to both options for the factors *A1* and *A3*. Although limited, the investment will never be paid back, as payment to local farmers or landowners are annual. Thus, to both options a score of 2 is assigned for the factor *A2*.

Household Changes & Buildings

Emissions caused by households and other buildings can be reduced in different fashions, as demonstrated by the diversity of the scores assigned to the three abatement options below. The construction of any building is expensive and explains the high market-costs people often complain about, especially in The Netherlands. The construction of an energy-efficient building is estimated to add an 8% mark-up to common costs, quickly mirrored on the market price. Thus, a score of 2 is assigned to the options [Building]: Building efficiency new built for factor *A1*.

There might be extra investments needed for constructors to deliver more efficient products, but pay-back time is expected to increase of 2 years maximum, and government incentives should encourage buyers' purchases. Thus, a score of 1 is assigned to this abatement option for both *A2* and *A3* factors.

[Household changes]: Residential appliances and Lighting switch incandescent to LED (residential) require a substantially lower investment than constructing an energy-efficient building and are thus a score of 1 is assigned to the factor *A1*. The cost of a LED lights is $34 (and expected to drop fast), much higher than a regular incandescent bulb ($1) but still accessible to most of the population; moreover, LED lights are proven to be able to pay back their additional cost in their 2 years lifetime (score of 0 for the factor *A2*); hence a score of 0 is given to it for the factor *A3*.

Smart residential appliances are already on the market but not price-competitive and, given the limited experience and the still highly demand-pulled energy market, no savings are identified for smart residential appliances yet. Wanda et al. (2012) estimate an average pay-back time of 6 years, and thus a score of 1 is assigned to the factor *A2*. Some incentives are needed to encourage a rapid adoption, fact mirrored in assigning a score of 1 for the factor *A3*.

Industrial Processes

[Industrial Processes]: Energy efficiency 1 Iron & Steel focuses on one of the largest and oldest industries worldwide. To encourage changes aiming to improved energy-efficiency, policies are needed, and their costs are estimated to be around $ 0.8 billion in the US and $ 1.2 billion in China. Thus, considering the size of the investment rather than how accessible it is national-governments, a score of 2 is assigned to the factor *A1*. Companies active in the ISI industry would mirror possibly higher production cost on the market, and thus recover the investment in a short time; the governments which might fund ad-hoc policies would not receive any financial ROI but a decrease in GHG emissions. Moreover, the current lack of clear policies on industrial efficiency is not encouraging private investments in efficient technologies, creating uncertainties reflected in a very short (< 2 years) average pay-back time for investment in the ISI. Thus, a score of 0 is assigned to the Y-factor *A2*, and a score of 2 to the Y-factor *A3*.

Instead, the cost of substituting the clinker ($ 36/ton) in cement production with other supplementary cementitious materials (SCM) as fly ash ($ 15/ton) or slag ($ 24/ton) requires no investment, given the lower material cost and the material compatibility (substitution up to 60% at least). Hence, a score of 0 is assigned to all three factors (*A1*, *A2* and *A3)* for the option [Industrial Processes]: Clinker substitution by fly ash.

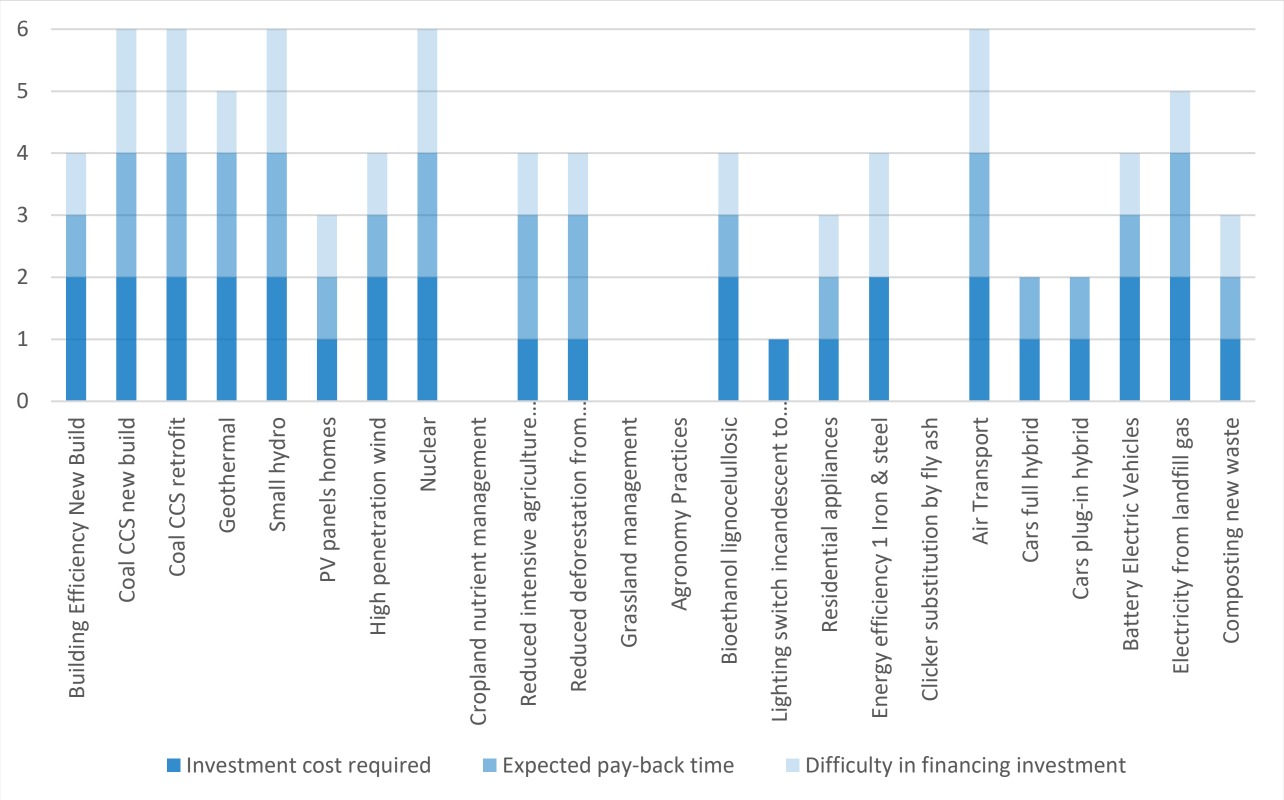
Vehicles & Fuels

Two of the three analyzed EV types have already been on the automobile market for some time and are, at least partially, price competitive. In fact, both full and plug-in hybrid vehicles cost on average an additional $ 2,000-14,000 over the cost of a normal ICE vehicle, much less than the few available full-electric cars ($ 40,000 for a Tesla guaranteeing a competitive range-autonomy). Thus, [Vehicles]: Cars full hybrid and [Vehicles]: Cars plug-in hybrid are assigned a score of 1 for the factor *A1* and a score of 0 for the factor *A3*, as the investment is accessible to most people. Instead, [Vehicles]: Battery electric vehicles is assigned a score of 2 for the factor *A1* and a score of 1 for the factor *A3*, given the higher capital required. For all three types of vehicles, the additional investment is expected to be recovered over their lifetime, which is on average 5-12 years; thus, a score of 1 is assigned to the factor *A2*.

It is not yet clear which of the many possible strategies would eventually lead [Vehicles]: Air transport to reduce its GHG emissions. Whether the preferred strategy will pursue improved fuel-efficiency, the introduction of alternative fuels, or optimized infrastructure-operations, the overall necessary investment is large; hence, a score of 2 is assigned to the factor *A1*. Given the high investment which can only partially be mirrored onto users, an aircraft lifetime (11-30 years) will be barely sufficient to recover the costs (score of 2 assigned to the factor *A2*). Moreover, given the lack of a preferred solution for the GHG reduction caused by air traffic and the lack of consistent policies (e.g.: ICAO v. EU), it is difficult to attract investment; hence, a score of 2 is assigned to the factor *A3*.

The production cost of second-generation biofuels like [Fuels]: Bioethanol lignocellulosic are still very high, estimated to be 5 times higher the cost of regular diesel ($0.60–$1.30/L of ethanol); considering also the investment needed to updated production processes, a score of 2 is assigned to the factor *A1*. Since there exists an abstract vague, but explicit sponsorship of biofuels from governmental-bodies (EU Directive 2009/28/EC), which consider them one of the best chances for reducing GHG emissions from the transport sector, it is expected financing the investment with subsidies not to be too difficult, thus reducing the pay-back time. Hence, a score of 1 is assigned to both factors *A2* and *A3*.

Figure 6: Preliminary scores - Cost & Financing



3.1.2 B. Multi-actor Complexity

Multi-actor complexity is the second category (named "B") of the Y-factor method, containing three factors: *B1: Dependence on other actors*, *B2: Conflicts of interests*, and *B3: Division of roles and responsibilities unclear*.

Energy & Waste

PV panels and wind turbines are new popular technologies, characterized by very different stakeholders. [Energy]: PV panels homes are widely available on the market and have already been installed on many households; citizens are able to independently purchase and install them and thus a score of 0 is assigned to the factors *B1* and *B3*. No major disputes should arise with other actors, but there are sometimes discussions with neighbors who might feel disturbed by the view (score of 1 for the factor *B2)*.

Instead, the construction of wind turbines is more technologically challenging, and requires the cooperation of more parties, both for their construction and for societal acceptance: frequent, so-called Not-In-My-Backyard (NIMB) protests from bird-protection associations require long, tough negotiations; thus, a score of 2 is assigned to the option [Energy]: High penetration wind for factors *B1* and *B2*). While the installation of onshore turbines is nowadays common procedure, more procedural uncertainties characterize offshore turbines, for instance interfering with ships' routes (score of 1 assigned to the factor *B3*.)

The construction of new power plants always requires the collaboration of many different stakeholders, as owners, constructors, permits-provider from the municipality, managers of the power grid interface and coordinate for enabling regular-operations, and the local population can interfere. Thus, a score of 2 is assigned to the factor *B1* of the abatement options [Energy]: Small hydro, Geothermal, and Nuclear, and of [Waste]: Electricity from landfill gas, where interconnections to the power grid represent the main challenge.

Considering the many parties involved and the size of the investments (factor *A1*), many negotiations are necessary to overcome disagreements regarding the construction of power plants, especially considering the often-contrary opinions of local populations: in extreme cases, these might have to be relocated or compensated, and as they feel disturbed or threatened by the power plant presence. Thus, a score of 2 is assigned to the factor *B2* of the options small-hydro, geothermal and nuclear power generation*;* instead a score of 1 to the factor *B2* of Electricity from landfill gas, considering the more favorable attitude of the population (no frightening incidents with the technology).

While there are decades of experience with nuclear, hydro and geothermal power generation (score of 0 for the factor *B3)*, generating electricity from landfill gas is rather new; thus, a score of 1 is assigned to it for the factor *B3.*

Instead, fewer actors are involved in the implementation of the option [Waste]: Composting new waste, (municipality, landfill owners and waste recycling companies) because no electricity is produced and thus interconnections are not needed (score of 1 for the factor *B1)*. This reduces conflicts, and the division of responsibilities should be clear as only the waste disposal processes changes (separation, treatment). Hence, a score of 0 is assigned to the factors *B2* and *B3).*

CCS

The reasoning for implementing [CCS]: Coal CCS new built is very similar to what described above for nuclear, geothermal and hydro power, as an entirely new power plant needs to be constructed, and thus many players are involved. Additional, powerful stakeholders are the ones responsible for CO_2 waste transportation and storage. Thus, a score of 2 is assigned to the factors *B1* and *B2*. The implementation of the abatement option [CCS]: Coal CCS retrofit is also dependent on many actors, even solely considering the additional ones needing to cooperate for waste transportation and storage; although lower than for new plants, the interdependence is still high and substantial negotiation is required (e.g.: international waste transportation and disposal). Thus, a score of 2 is assign for both factors *B1* and *B2.*

CCS technologies are rather new; hence, the division of responsibilities is not yet clear. Nevertheless, achieving an agreement on the implementation of the technical and financial issues seem currently the most problematic issues (score of 1 assigned to the factor *B3* for both CCS options).

Forestry and Agriculture

The argument for [Forestry & Agriculture]: Reduced intensive agriculture conversion and Reduced deforestation from timber harvesting is identical: both abatement options try to prevent events from happening rather than implementing them, and these events have been common practices for decades. Many actors are involved, as national governments and other funders, NGOs, the local population, local landowners and timber corporations and thus substantial conflicts need to be solved, especially considering the source-of-income role of forests. Thus, a score of 2 is assigned to both options for both factors *B1* and *B2*. Instead, a score of 1 is given to the factor *B3* of both options, as once the forest-protection program has been agreed, the necessary operations should be rather easy to implement.

Both [Forestry & Agriculture]: Cropland nutrient management and Grassland management are practices which local landowners can initiate independently, but they often need to rely on experts who can teach them the practices overtime, given the involvement of multiple crop rotations. Thus, for both options a score of 1 is assigned to the factor *B1*. While no conflicts are foreseen for changing grassland management practices (score of 0 for the factor *B2)*, implementing changes might be more problematic for cropland, as local farmers are at times bound to commercial contracts with pre-set crop output, and these might be, at least initially, affected (score of 1 for factor *B2*). As such practices are popular in Western countries but not in developing ones where they could be most largely implemented, division of roles and responsibilities is considered unclear and context-dependent; thus, a score of 1 is given to both options for the factor *B3.*

Instead, [Forestry & Agriculture]: Agronomy practices have been developing from locals' activities in Brazil and Argentina in the 1970s, so they should be well-known and somewhat already implemented, with roles and responsibilities which seem to be clearer than for the other practices. As they are more conservative, long-term practices, only minor conflicts are expected to occur. Thus, a score of 0 is assigned to all three factors *B1*, *B2* and *B3*.

Household Changes & Buildings

Increasing the efficiency of newly constructed buildings does not require the involvement of many more parties than for a normal building, for which many actors are regularly involved (engineers, constructors, architects, municipality, etc.), but agreements on the many project-specifications need to be reached before constructions start. Thus, a score of 2 is assigned to the option [Building]: Building efficiency new built for the factor *B1*, and a score of 1 for the factor *B2*. While buildings have been constructed for millennia, energy-efficient buildings such as "green" and "passive" buildings are a new concept, for which roles and responsibilities still have to be clarified (score of 1 for the factor *B3).*

The abatement options [Household Changes]: Residential appliances and Lighting switch incandescent to LED (residential) belong to the same sector but are characterized by a very different pool of actors. LEDs are present on the market, and any person can independently purchase them and install them at home; thus, a score of 0 is assigned to all three factors *B1*, *B2* and *B3.*

Only a few smart residential appliances are on the market, and additionally a supporting data network is also necessary to enable their operations; thus, their effective functioning is dependent on many actors (score of 2 for factor *B1*). A vast debate is ongoing regarding the privacy risks associated with the data-collection necessary to operate smart appliances, with one of the main issues being the responsibilities of data-collection and protection; moreover, the higher prices of smart appliances caused by their increased technological complexity have raised issues of social exclusion. Thus, while there are multiple proposals to deal with such problems (Consultation on Proposals regarding Smart Appliances, 2018), no satisfactory solution has been reached (score of 1 for factor *B2* and *B3*).

Industrial Processes

Iron & Steel (IS) companies are old, large and global corporations, which have the experience and the capital to independently adapt production processes, implementing energy-efficient practices; hence, a score of 0 is assigned to the factors *B1* and *B3* of the abatement option [Industrial Processes]: Energy efficiency 1 iron & steel. Nevertheless, while there might not be external actors able to effectively hamper energy-efficiency initiatives, the long tradition of industrial processes and the large size of ISI companies can result in internal, log-lasting conflicts. Thus, a score of 1 is assigned to the factor *B2*.

Instead, much more cooperation is needed to implement [Industrial Processes]: Clinker substitution by fly ash, as cement-companies need the supply of fly ash or slag, for which some long-term contracts are likely needed; nevertheless, given the lower costs of SCM compared to clinker, and the additional increased-revenues for SCM suppliers (SCMs are normally waste material for coal plants), an agreement should be rather easily achievable. Hence, a score of 2 is assigned to the factor *B1*, and a score of 0 to the factor *B2*. Considering the long experience of companies with supplementary cementitious materials (SCM), the division of roles and responsibility is expected to be clear, thus a score of 0 is assigned to the factor *B3*.

Vehicles & Fuels

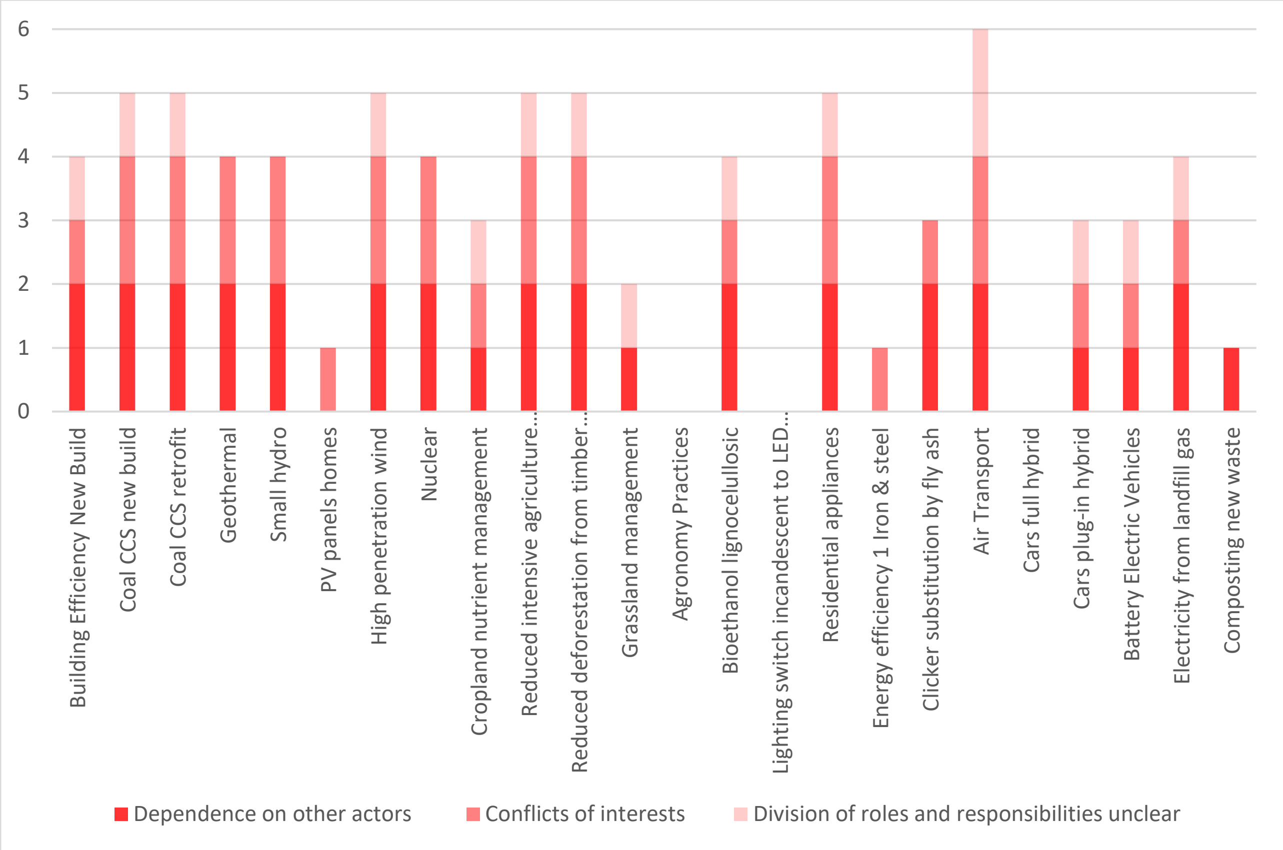
[Vehicles]: Cars full hybrid (HEVs) have been present on the market for the last decade, and buyers can independently purchase them, re-fueling at regular service-stations. Thus, there is no dependency on other actors nor conflicting interests, with a clear division of roles. A score of 0 is thus assigned to the three factors *B1*, *B2* and *B3.*

Instead, [Vehicles]: Cars plug-in hybrid (PHEVs) and Battery electric vehicles (BEVs) need an adequate re-charging infrastructure, which makes their market presence and diffusion dependent on other actors. While car-manufacturers are progressively increasing their investments in EVs, they are still currently interested in selling their non-electric vehicles; thus, a few transition years might be characterized by conflicts, which should be solved by adequate policy-making, currently lacking. Moreover, some people are also opposing the diffusion of charging points for BEVs, worrying about the safety of pedestrians and cyclist and the competition for parking spots. Thus, a score of 1 is assigned to the three factors *B1*, *B2*, and *B3* for both abatement options.

[Vehicles]: Air transport is arguably the abatement option requiring the most negotiation. In fact, while being far-reaching, air traffic is not uniformly distributed worldwide. Many institutions and organizations hold stakes for the management of air transport, as national and international governments, aircraft producers, flight-operating companies, and airport authorities; private users have little bargaining power. Stakeholders have optimized their modus-operandi over the years via long-lasting, dynamic negotiations. Thus, whichever change is implemented (e.g.: fuel-efficient technologies, adoption of alternative fuels, improved operations, policies pricing emissions) creates many conflicts, with roles and responsibilities having to be redefined (e.g.: lack of agreement in ICAO). Thus, a score of 2 is assigned to all three Y-factors *B1*, *B2*, and *B*3.

The production of secondary biofuels such as [Fuels]: Bioethanol lignocellulosic can be initiated by local landowners and refineries, but for it to become a (pre)dominant commodity on the fuels market many stakeholders need to collaborate for production on a large-scale: distributers, car manufactures, producers of other fuels', and arguably governments are fundamental players of a supply chain which needs to achieve a substantial price reduction to compete with regular benzine (score of 2 for the factor *B1*). As there is not yet an appealing business case for secondary biofuels, some negotiation will be needed to achieve sufficient consensus for a large-scale implementation. Nevertheless, the fuel market is large and has a long history; thus, stakeholders have been collaborating for years (e.g.: for the production of primary biofuels), refining their roles and the division of responsibilities. This history should smoothen the needed adjustments to change the business models, currently exploiting large cultivation of biomass. Hence, a score of 1 is assigned to both factors *B2* and *B3.*

Figure 7: Preliminary scores - Multi-actor Complexity



3.1.3 C. Physical Interdependencies

Physical Interdependencies is the third category (named "C") of the Y-factor method, containing three factors: *C1: Physical embeddedness, C2: Disturbs regular operations*, and *C3: Technology uncertainty*.

CCS & Energy

[CCS]: Coal CCS new built, [Energy]: Geothermal, Nuclear and Small hydro are all abatement options substantial environmental modification to the environment, as new power plants are constructed where there were none before; thus, a score of 2 is assigned to these options for the factor *C1*.

The same score is assigned to [CCS]: Coal CCS retrofit, for the implementation of which large pipeline systems and CO_2 transportation systems need to be installed. The installation of on- and offshore wind turbines necessary to achieve a [Energy]: High penetration wind (10% of energy mix as by definition) implies changes to the landscape, often triggering Not-In-My-Backyard (NIMB) phenomena (score of 2 assigned to the factor *C1*). Instead, [Energy]: PV panels homes can be installed on rooftops, thus causing minor environmental changes, mirrored in a score of 1 for the factor *C1*.

Of these five abatement options, the only one majorly disrupting regular operations is Coal CCS retrofit, as activities ongoing in the plant need to be paused to install the needed additional equipment; moreover, once the equipment is installed, new operations procedures (e.g.: routes, deposit) need to be implemented (score of 2 assigned to the factor *C2*).

Oppositely, PV panels can be quickly installed on rooftops, and such quick installation has a very limited geographical scope and does not affect any other service or infrastructure; thus, a score of 0 is assigned to the factor *C2*.

Nuclear, Geothermal, Small hydro, High penetration wind, and Coal CCS new built cause minor disruptions both during their construction and operation phase, as the installation areas need to be cleared (score of 1 for the factor *C2)*. In particular, Nuclear and Coal plants have very long construction times and, while they are normally built in remote areas, people cannot access the site areas.

Large, power-producing geothermal plants disturb operations similarly to nuclear plants, with the additional characteristic of being more location-dependent and thus potentially more invasive; instead, geothermal plants producing heat have smaller sizes and thus cause fewer disruptions.

Small hydropower stations are commonly built on rivers, outside metropolitan areas and, while not evidently disturbing the population, they might obstruct some fishermen and other nearby hydropower stations, which are likely to receive water streams more or less intermittently than ideal. Lastly, a wind turbine can be installed in a few days, and only the installation sites need to be cleared; hence, local operations are only marginally disrupted, with the location of the disruption changing frequently.

Coal CCS new built and Coal CCS retrofit are characterized by large technological uncertainties, because of their few implementations and the necessary, expensive waste-management network, characterize by many governance-uncertainties. Additionally, the effectiveness of CCS technologies is not unanimous. Thus, a score of 2 is assigned to both options for the factor *C3*.

Similarly, Nuclear technology is very debated: there have been accidents in the pasts (Chernobyl, Fukushima), and while security improvements are widely acknowledged, waste management is still unsolved; this is one of the reasons for which nuclear energy is criticized, as it was introduced 100 years ago with the promise of solving the energy supply problem, which is still actual (score of 2 for the factor *C3*).

A lot of experience has been acquired on geothermal and hydro power production, which has helped clearing technological uncertainties; nevertheless, large geothermal plants for power production require deep drilling, which is technically complex and might sometimes lead to small earthquakes. Thus, a score of 1 is assigned to for the factor *C3* of [Energy]: Geothermal, and a score of 0 to [Energy]: Small hydro.

PV panels are not characterized by major technological uncertainties, thanks to their quick and vast diffusion (more complicated is to interconnect them to the power grid, but this is not directly relevant for the PV technology itself); thus, a score of 0 is assigned to the factor *C3*.

Similar argument is valid for onshore wind turbines, while offshore turbines present more complicated technical challenges, considering the lesser experience and environmental challenges such as the interfaces with other marine-installations and the construction of power transportation lines; thus, a score of 1 is assigned to the factor *C3* for the option [Energy]: High penetration wind.

Forestry & Agriculture

The implementation of abatement options such as [Forestry & Agriculture]: Agronomy practices, Cropland nutrient management, and Grassland management does not create or require any physical changes nor disruption of operations: the purpose and output of the cultivation activities do not change, and people who are daily working the land continue in their daily tasks, possibly with modified means. Thus, a score of 0 is assigned to all three options for the factors *C1* and *C2*.

While agronomy practices were developed in South America in the 1970s and their implementation and results are thus well known (score of 0 for factor *C3*), the other two options are more recent, and experience on best-practices and (long-term) consequences is lacking. Thus, a score of 1 is assigned to the factor *C3* for the options [Forestry & Agriculture]: Cropland nutrient management and Grassland management.

Visible physical changes derive from implementing the abatement options [Forestry & Agriculture]: Reduced deforestation from timber harvesting and Reduced intensive agriculture conversion, as the forest which is normally removed instead remains in its place. Additionally, some land protection and monitoring equipment might be needed (e.g.: fences and cameras). Thus, a score of 2 is assigned to both options for the factor *C1*.

Deforestation and conversion to cropland are practices which have been performed for decades; hence, their reduction and regulation cause impactful disruptions to regular operations, with farmers and timber industries having to radically modify their business models (score of 2 for the factor *C2* for both options). The implementation of these two abatement options does not require the utilization of artefacts, and thus the technological uncertainty (factor *C3*) is null.

Household Changes & Buildings

The implementation of the option [Household Changes]: Lighting switch incandescent to LED (residential) only enforces minor environmental changes mostly consisting of slightly modified lights-colors (score of 1 for the factor *C1*); the installation of LEDs is quick and does not disrupt any operation (score of 0 for the factor *C2).* Moreover, they have been available on the market in different forms since the 1970s, and their technology is fully proven (score of 0 for factor *C3*).

A somewhat different argument applies to the implementation of the abatement option [Household Changes]: Residential appliances, the efficiency and smartness of which is guaranteed by built-in components, unnoticeable from the outside but for small displays (score of 0 for factor *C1*). Appliances such as dishwashers and refrigerators require longer installation times than LEDs, especially considering the interconnections with the supporting data-network required for their operations; unambiguous energy and energy-price savings enabled by efficient and smart residential appliances are lacking, mainly due to limited experience. Thus, a score of 1 is assigned to both factors *C2* and *C3*.

The construction of a new building inevitably impacts the surrounding environment, but a newly constructed energy-efficient edifice does not change the landscape more than a non-efficient building; in fact, the differences between an energy-efficient and inefficient building are not visible, as they consist for instance of better insulating construction materials. Thus, to mediate between these two perspectives, a score of 1 is assigned to the factor *C1* of the abatement option [Buildings]: Building Efficiency New Build. Regular operations are only marginally disrupted, as the populations needs to clear the construction sites (score of 1 for the factor *C2*). While different frameworks like Leadership in Energy and Environmental Design (LEED) have been developed, and the nomenclature of “green building” can be found in multiple articles, it is unclear which one is best-fitted for topping the full potential of energy-efficiency improvements in the construction of new buildings. (score of 1 for the factor *C3*).

Industrial Processes

The implementation of [Industrial Processes]: Energy efficiency 1 Iron & steel does not cause changes in the environment, as the product-output and its applications remain the same, with the implemented changes being solely related to the production process (score of 0 for factor *C1*).

Instead, implementing [Industrial Processes]: Clinker substitution by fly ash creates a few physical changes, as a transportation system for fly ash or slag is necessary; to ensure a reliable supply, a new, dedicated furnace is often constructed close to the cement plant (score of 1 for factor *C1*).

The implementation of both abatement options requires some disruptions to regular operations, as they both involve modifications to the production processes, which require machinery and procedural adjustments. While using slag for clinker substitution is a fully proven technology, this is not true for other SCM like fly ash. The reviewed literature suggested the existence of a perceived risk related to the implementation of efficiency practices in the ISI, caused by poor long-term technical performances (e.g.: sulfate attack) of the modified cement. Thus, a score of 1 for both options for factors *C2* and *C3*.

Vehicles & Fuels

[Vehicles]: Cars full hybrid do not require any re-charging infrastructure, and technical change from standard ICE vehicles are internal; thus, they do no enforce any environmental changes (score of 0 for the factor *C1*).

Instead, both [Vehicles]: Cars plug-in hybrid and Battery electric vehicles need a well-diffused charging infrastructure, at least until inductive-charging technologies are introduced. While small in size, re-charging columns reduce parking spots for non-EVs. Thus, a score of 1 is assigned to both options for the factor *C1*.

The implementation of any of these three abatement options does not disturbs any regular operation, as the all three EV-types can be purchased and utilized like standard ICE vehicles, and the installation of charging-stations is quick and space-contained. Thus, a score of 0 is assigned to all three options for the factor *C2*.

HEVs have been available on the market for many years and are refueled just as ICE vehicles, their technology is fully proven (score of 0 for the factor *C3*). PHEVs are more recent, and their need for recharging infrastructure often not sufficiently and uniformly available still leaves unsolved challenges for their large-scale implementation (score of 1 for the factor *C3*). BEVs suffer the same dependence on the charging infrastructure, but they entirely rely on battery-power, thus reducing even further their autonomy-range. Hence, BEVs are still characterized by a large technological uncertainty, as demonstrated by the vast ongoing BEV-themed debate and the high price of most BEVs (e.g.: Tesla’s model 3 starting at around $ 40,000); thus, a score of 2 is assigned to BEVs for the factor *C3*.

Reducing the emissions caused by [Vehicles]: Air transport can be achieved by various means, none of which is yet predominant (score of 2 for the factor *C3*). While some changes might happen to the configuration of the aircrafts' engines for improved fuel-efficiency, such modifications will not be visible; any of the other policy or operational modifications (infrastructure and air-traffic management) does not cause physical changes to the environment, as for instance demonstrated by the inclusion of air traffic in the EU ETS without any noticeable consequences. (score of 0 for the factor *C1*).

Disruptions to regular operations might occur if technological updates on aircrafts would become requirements to comply with new laws, but no ai-transport disruptions should materialize if technical and regulatory updates are timely planned. Some disruptions might occur if air transport providers were to decide not to comply with regulations, interrupting their services and/or changing routes. Thus, to account for such remote, but possible situation (e.g.: ICAO v. EU), a score of 1 is assigned for the factor *C2*.

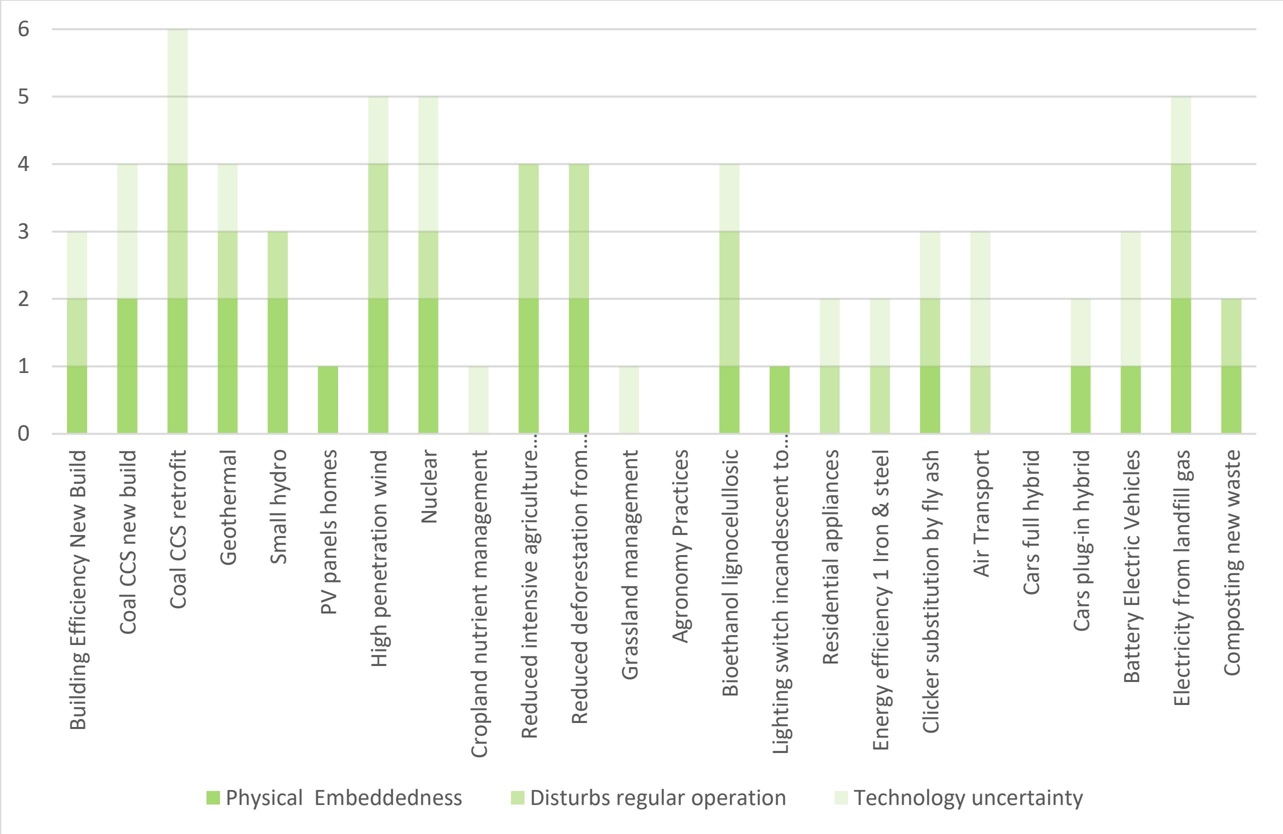
The diffusion of secondary biofuels as [Fuels]: Bioethanol lignocellulosic inevitably causes changes to the environment, for instance in the use of vast lands currently dedicated to the cultivation of biomasses; nevertheless, it is not yet clear the extent of land-purpose transformations, as biomasses might still be used to contribute to the supply of biofuels. Thus, a score of 1 is assigned to the factor *C1*. While the production of secondary biofuels can begin immediately, the conversion of biomass-land to other purposes and the vast diffusion of secondary biofuels takes a long time, disrupting current operation. Thus, a score of 2 is assigned to the factor *C2*. Secondary biofuels are a recent (< 10 years) product, and thus their potential performances are not yet clear, with many authors fearing drawbacks similar to the ones of primary biofuels; thus, a score of 1 is assigned to the factor *C3*.

Waste

Generating [Waste]: Electricity from landfill gas requires substantial physical modifications to the landfill site: power generating turbines need to be installed, supported by an adequate pipeline-system to channel and treat the waste, and by interconnections to the local power-distribution grid to supply the produced electricity. These changes disrupt regular operations, considering the (partial) closure of the landfill for a period of time, and how on-site operations such as activities and routes need to be updated to account for new infrastructure). Thus, a score of 2 is assigned to both factors *C1* and *C2*. While the technology is able to avoid CO_2 emissions, some methane would still be emitted; this remains in the atmosphere for about 20 years, which is less than CO_2, but is considered to be four-times more damaging. Many people argue against the investment in the technology, which is does considered not fully proven (score of 0 for the factor *C3*).

[Waste]: Composting new waste requires the creation of waste-separation and treatment locations, but these can be created directly at the landfill sites. Pipeline installations and transport systems might be needed to manage and employ the resulting compost, but the changes are estimated to be less space-invasive than in the case of generating electricity at landfills. Disruptions to regular waste-collection and recycling operations will occur, especially concerning waste-routing, to allow for its separation and treatment. Nevertheless, operations at landfills and waste-collection can continue in a similar fashion, with only parts of the waste supply chain being modified and affecting workers. Thus, a score of 1 is assigned to the factors *C1* and *C2*. Waste composting is already implemented in different locations and the technology is thus considered fully proven (score of 0 for the factor *C3*).

Figure 8: Preliminary scores - Physical Interdependencies



3.1.4 D. Behavior

Behavior is the fourth and last category (named "D") of the Y-factor method, containing three factors: *D1: Absence of knowledge of actors, D2: Frequency of opportunity*, and *D3: Requires changes in behavior*.

Energy & CCS

Thanks to a long experience (> 100 years), all the stakeholders, including the population, are knowledgeable about geothermal, nuclear, and hydro-power technologies and about their implications, risks and potential. Small hydro power plants are not as popular as the larger ones usually built on mountains, but the technology changes only marginally. Thus, a score of 1 is assigned to the abatement options [Energy]: Geothermal, Nuclear, and Small hydro for the factor *D1*.

Considering the size of the investment, the technological complexity, the long lifetime (> 30 years) and projecting and construction times, power plants can be constructed rarely. Small hydro power plants and geothermal plants for heating are quicker to construct thanks to their reduced sizes, but the other above-mentioned features are comparable; thus, a score of 2 is assigned to all three options for the factor *D2*.

The construction of these power plants does not require behavioral changes, but some might be induced anyways. In fact, differently from nuclear energy, geothermal and hydro power are location-dependent, and might thus be constructed in areas visited by the population, as a river where people fish. Hence, while a nuclear power plants does not induce behavioral changes because they can be built in isolated areas (score of 0 for the factor *D3*), small hydro power plants might require the modification of the course of a river to adjust the water stream. Similarly, large geothermal plants used for power production might transform previously accessible areas into inaccessible; smaller geothermal plants for heat production do not induce behavioral changes. Thus, a score of 1 is assigned to the factor *D3* of the abatement options [Energy]: Small hydro, and Geothermal.

CCS technologies are unknown to most of the population because of their novelty and technological complexity, but have been debated vastly by researchers, as demonstrated by the rich body of literature which discusses them; hence, to account for both these two perspectives, a score of 1 is assigned to the factor *D1* of both [CCS]: Coal CCS new built and Coal CCS retrofit.

The construction of a new coal power plant equipped with CCS technology is characterized by in complexity of construction and independency from natural reservoirs and can thus be compared to the above-described nuclear plants for the factors *D2* and *D3*. Retrofitting an existing coal plant is more expensive and complex than building a new one because of the spatial and technological integrations with precedent installations (score of 2 for the factor *D2*); moreover, substantial behavioral changes are needed on-site to account for modified plant-spacing, material routing, and safety procedures. Thus, a score of 2 is assigned to the factor *D3* of the abatement option [CCS]: Coal CCS retrofit.

Solar PV and wind turbines are the most popular types of renewable energy, well-known to the population; the knowledge is normally superficial, as only a minority of people is aware of their functioning and implications (Kacan, 2015; Karytsas & Theodoropoulou, 2014). Thus, a score of 1 is assigned to both options [Energy]: PV panels homes and High penetration wind for the factor *D1*.

PV panels can be purchased and installed on rooftops frequently, considering their market availability, limited investment and fast installation (score of 0 for the factor *D2*); wind turbines have longer installation times than PVs: onshore, many interfaces with other infrastructure and the population need to be carefully examined, while interaction with infrastructure and ship routes are important offshore. Nevertheless, installation times are much shorter than for power plants, and thus a score of 1 is comparatively assigned to the factor *D2*.

A large diffusion of on- and offshore wind turbines does not require major procedural-changes for TSOs and DSOs up to 20% penetration in the energy mix; these will occur if the wind-penetration percentage increases or if other fluctuating renewables increase their contribution to the power supply. Similarly, installing PV panels at home does not currently require behavioral changes thanks to flat electricity-supply contracts, allowing PV owners to solely witness price-savings in their bills. This is doomed to change in the upcoming future, with the predicted diffusion of smart grids to cope with the control and pricing of renewable energy production and consumption. Judging the current situation, a score of 0 is assigned to both option for the factor *D3*.

Forestry & Agriculture

[Forestry & Agriculture]: Cropland nutrient management and Grassland management are practices which are already, at least partially, implemented in many Western countries but are not well-known in developing countries, where the largest inhabited grasslands and croplands are located (score of 2 for the factor *D1)*.

While these practices can be initiated anytime thanks to the merely-procedural updates they enforce (score of 0 for the factor *D2*), major behavioral changes as required, such as different fertilizer application, land-rotations timing, grain sizes, etc.; in fact, education is the most relevant barrier highlighted by the reviewed literature. Hence, a score of 2 is assigned to both options for the factor *D3*. Once taught, such practices should be easy to perform, and behavioral changes are not constantly but only initially needed.

Instead, [Forestry & Agriculture]: Agronomy practices were initiated in South America in the 1970s, and thus it is assumed most cropland owners are aware of them, also in developing countries. Just as the other land-management practices above, cropland treatments can be modified anytime, implementing different agronomy practices for better long-term land yields (score of 0 for the factors *D1* and *D2*).

Some behavioral changes are needed, as not all cropland is currently treated following the techniques recommended by the South American farmers; being most cropland owners already aware of them and having partially implemented them (e.g.: on a portion of the land), such behavioral changes should be less extreme than for other land management practices (score of 1 for the factor *D3*).

In underdeveloped and developing countries, local populations and at times even governments are not aware of the CO_2-storage role of forests and the consequences of deforestation, to which corruption also contributes. Thus, a score of 2 is assigned to the factor *D1* of [Forestry & Agriculture]: Reduced intensive agriculture conversion. Instead, a score of 1 is assigned to the same factor of [Forestry & Agriculture]: Reduced deforestation from timber harvesting, considering the role of timber companies which are aware but ignore the consequences of deforestation because to safeguard their earnings.

Both options can be initiated at any time, once the intentions are clarified (score of 0 to factor *D2*). Behavioral changes are needed, with local farmers and timber companies having to stop or reduce the removal of trees, which provides income to all the involved parties, possibly changing to more sustainable forestry practices following the Swedish and Canadian model (Elbakidze et al., 2010); a score of 2 is thus assigned to the factor *D3* of both options, also considering the frequent recurrence of the theme of education found in the reviewed literature.

Household Changes & Building

Most people are not sensible to the energy-efficiency issue, mainly because most energy-supply contracts are "flat" and only marginally mirror the price of high energy-consumptions on energy bills. Thus, the majority of the population is not aware of the energy-savings offered by LEDs and by the technological development of efficient and smart appliances fitting with smart grids. Thus, a score of 2 is assigned to the factor *D1* of [Household Changes]: Lighting switch incandescent to LED (residential) and Residential appliances.

Given the modest investment and their market availability, people can frequently purchase LEDs, which can be installed and used immediately without adapting their behaviors (score of 0 for the factors *D2* and *D3*). Residential appliances have a lifetime of 6+ years and thus a score of 1 is assigned to the factor *D2*.

The different energy-efficiency classes of buildings are a rather new theme, which people have experienced mainly in terms of different financial costs and accessible tax-reduction programs. Thus, while most people are somewhat aware of the topic, there is little knowledge on the different energy efficiency frameworks (as LEED and Green buildings) and the technologies they employ.

While buildings are constructed daily in each town, every one of them requires a long planning and permit-collection process. Additionally, purchasing and living in an energy-efficient building does not require any dwellers to adapt behaviors, as changes are mostly structural; construction companies, engineers and architects have to modify their modus-operandi. For these reasons, a score of 1 is assigned to the for all three factors *D1*, *D2*, and *D3* of the abatement option [Building]: Building Efficiency New Build.

Industrial Processes

The Iron & Steel industry has refined its industrial processes over the many years of its existence, and energy-efficient practices are not implemented more for a lack of supporting, long-term policies; the lack of these causes pay-back times of energy-efficient projects to be longer than the industry standards of two-three years; thus, a score of 0 is assigned to the factor *D1* of the abatement option [Industrial Processes]: Energy efficiency 1 Iron & steel.

Considering the needed investment, energy-efficient practices need adequate technical and financial planning and cannot be initiated frequently; nevertheless, their required planning is not comparable to the one needed for constructing a new power plant (score of 1 for the factor *D2*). Behavioral changes are not needed besides marginally adjusting industrial processes and adding filtering and CO_2 recovering components (score of 0 for the factor *D3*).

All actors of the IS industry are aware of SCM materials like slag and fly ash, as they are already used for some applications. These can thus be quickly substituted to clinker, for instance establishing simple supply agreements with coal-burning plants, whose waste can often be used as SCM (score of 0 assigned to the factors *D1* and *D2* of the option [Industrial Processes]: Clinker substitution by fly ash). Clinker-producing processes, most popular for an IS company, have to be slightly adjusted to add SCM, and additional checks might be necessary to ensure the long-term quality of the modified cement. Thus, a score of 1 is assigned to the factor *D3*.

Vehicles & Fuels

Hybrid cars have been present on the market in the last decade, and are thus known to most of the population segments, even if their specifications might not be: [Vehicles]: Cars full hybrid were the first to be introduced and are less expensive, thus the most well-known, but also [Vehicles]: Cars plug-in hybrid have been present on the market for the last 10 years (score of 0 to the factor *D1* of both options). Instead, [Vehicles]: Battery electric vehicles are more recent and technologically complex, with many people recognizing the name but not aware of their implications, as the limited range (score of 1 for the factor *D1*). On average, a person buys a car every 5 years, and thus a score of 1 is assigned to all three options for the factor *D2*.

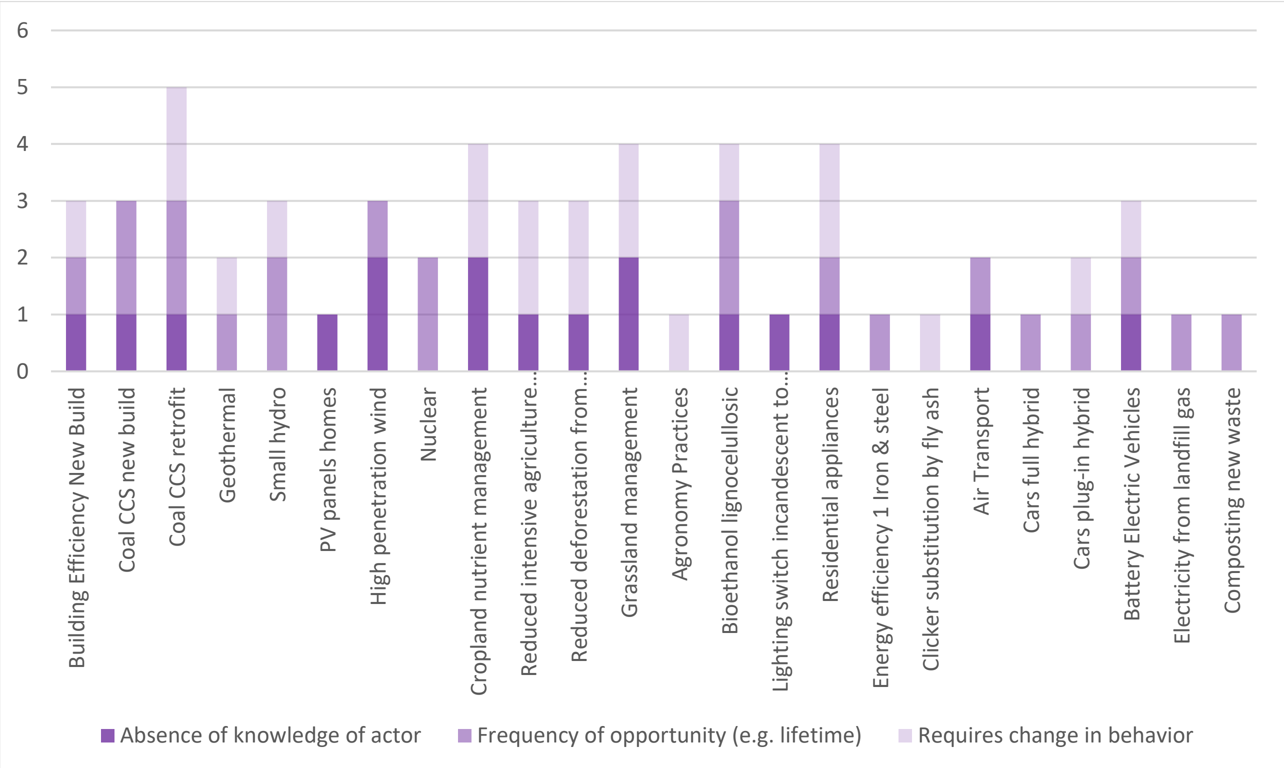
While purchasing a full-hybrid car does not require any behavioral changes because this can be refilled at any existing gas-station (score of 0 for the factor *D3*), plug-in hybrid and electric vehicles have limited range and rely on the installed re-charging infrastructure; thus, PHEVs and BEVs' owners need an accurate time and route planning to allow for the necessary recharging stops. While these behavioral changes are evident and might create travel-anxiety, the charging infrastructure is expanding; hence, a score of 1 is assigned to the factor *D3* of both plug-in hybrid and battery electric vehicles.

While national and international bodies of government, like the EU, are conscious of the importance of GHG emissions caused by [Vehicles]: Air transport, most of the population is not aware the rather techno-political nature of the issue, debating the feasibility on alternative fuels, emission/Km, and alternative policy designs. For any on the possible changes, adequate planning is needed in a dynamic, worldwide context such as the air transportation industry, with technical investments and tight schedules which need to be organized to comply with policy requirements. Hence, a score of 1 is assigned to the factors *D1* and *D2*. No behavioral changes are required from passengers, with air transport providers having to implement some technical upgrades (e.g.: fuel efficiency or alternative fuels) or simply pay more to operate as for the EU ETS, but not having to modify their mission or business model. Thus, a score of 0 is assigned to the factor *D3*.

Waste

Different options to exploit municipal waste such as generating [Waste]: Electricity from landfill gas or Composting new waste have been extensively discussed and have been implemented in certain locations; thus, knowledge of actors does not seem lacking (score of 0 for the factor *D1*). Considering the needed investment and organizational changes for supplying the produced power to the power-distribution grid and for a more accurate waste collection system, a score of 1 is assigned to both options for the factor *D2*. Generating electricity from landfill gas does not affect the population, as municipal waste needs to be separated and pre-treated after collection; only minor procedural changes would have to be implemented at landfills' sites (score of 0 for the factor *D3*). Instead, the population should be directly participating to the separation efforts for enabling a more accurate waste collection system; thus, a score of 1 is assigned to the factor *D3*.

Figure 9: Preliminary scores - Behavior

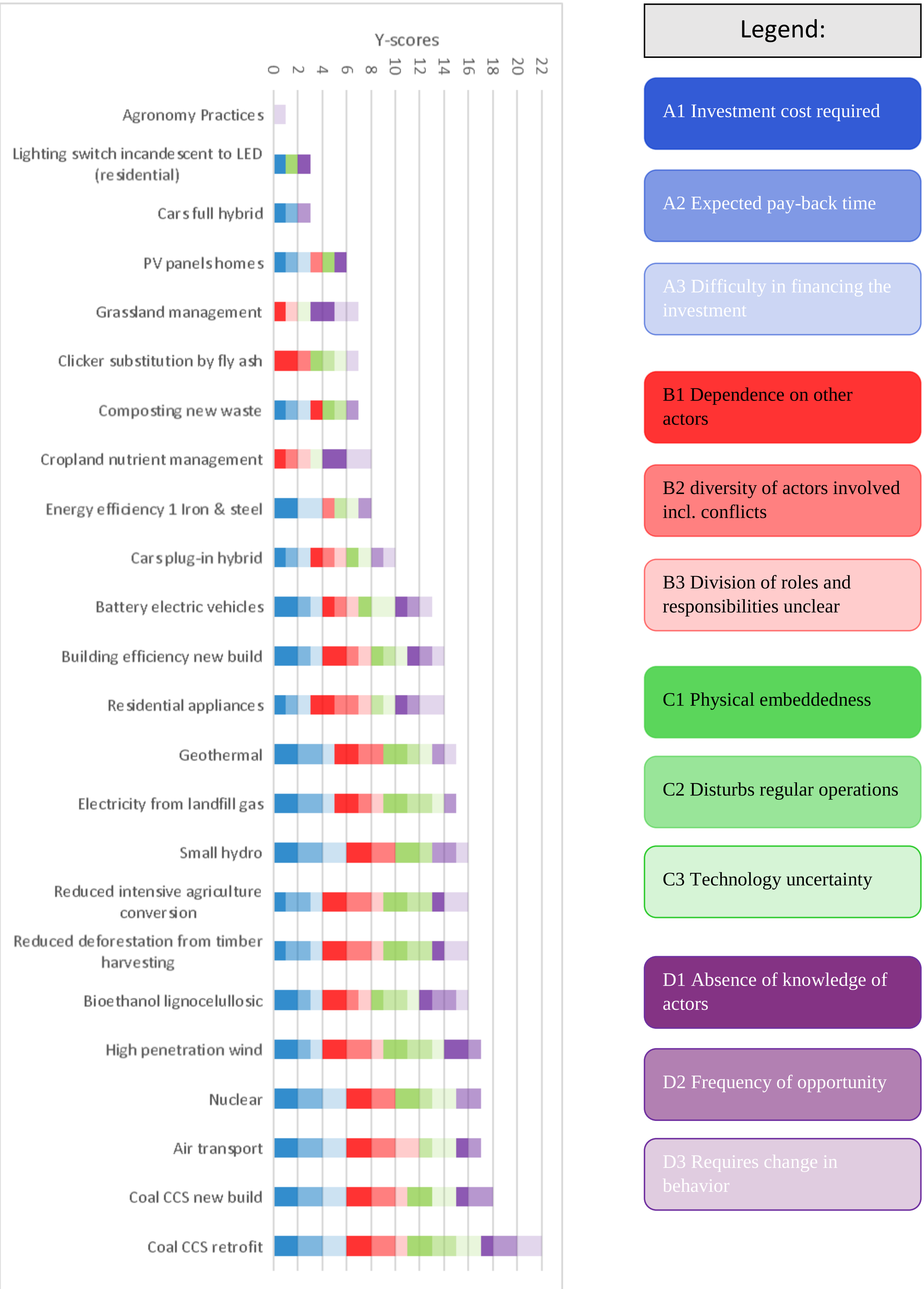


3.2 Preliminary Y-curve

Having assigned preliminary scores to each of the 12 factors of all the considered 24 abatement options, it is now possible to obtain the preliminary Y-curve. As already mentioned multiple times in *Chapter 1*, it is essential to note that the scores do not have an absolute meaning: they belong to factors which are entirely different and thus impossible to compare quantitively, but they can be compared qualitatively to highlight the higher or lower relevance of an implementation barrier for different abatement options, or of different barriers for a specific abatement option. The curve presented below is obtained summing the individual scores for graphical and usage convenience, and for coherency with the previous researches on the Y-factor namely Arensman (2018), Chappin (2016), and Cheung (2018).

Figure 10: Preliminary Y-curve –scores per category

Figure 11: Preliminary Y-curve – scores per factor



Chapter 4: Validated Y-Curve

Validation of the scores and comparison with McKinsey's curve

This chapter reports the outcomes of the interviews with experts performed to validate the preliminary Y-curve presented in *Chapter 3,* and how these can be synthesized to obtain the desired, validated Y-curve. *Section 4.1* and *4.2* present the methodology of the interviews and the interviewed experts, while the synthesis of the collected experts' opinions and its guiding principles are the focus of *section 4*.3. The validated Y-curve is presented in *section 4.4,* combining the validated scores obtained with the performed synthesis. Ultimately, the obtained results and their relevance are discussed *in section 4.5*, reflecting on the validation process and the obtained results, on the differences between the curve from Chappin (2016) and the validated Y-curve, and comparing the latter with McKinsey's MAC curve.

4.1 Interview Methodology

To construct a reliable Y-curve, it is important to reduce the subjectivity of the figures it displays; discussing the preliminary scores with experts knowledgeable in the energy sector is fit-for-purpose, as it reduces the subjectivity of the scores while providing additional remarks able to better justify them. To effectively reduce the subjectivity of each score, opinions of different experts on the same score need to be collected and compared. Because of the time constraints of this investigation, and the time-intensive character of interviews, it is decided to set a minimum of two expert-interviews for each of the analyzed abatement options. People professionally active in different societal sectors, as academia, research institutes, industry and service companies were interviewed, depending on their individual expertise to ensure the affinity with the considered abatement options.

Each expert was asked for a one-hour interview and was appointed a tentative list of abatement options to discuss, fitting with the individual expertise. Before the interview and upon confirmation of the comfort with the appointed options, each expert was provided with the options definitions (*Appendix D*), the table presenting the 12 factors and their scales (*Table 1)*, the preliminary Y-curve presented in *Chapter 3* to better explain the approach and aims of the investigation, and the interview-template sheets. The latter consisted of a sheet for each of the appointed abatement options, highlighting the preliminary scores assigned to each of the 12 factors, and a short justification of these scores at category-level (10-50 words for each trio of factors), to further clarify the scoring approach and to initiate the discussion (see Example in *Appendix E).*

Each interview started with a short (about 10 minutes) introduction of the aim and structure of the Y-factor method, and of the goal of the interview. Then, the expert was asked to select one of the appointed options to initiate the validation process. Only a sub-set of the preliminary appointed options was usually discussed in each interview, depending on time-limits. For each abatement option and for each factor, the assigned preliminary score was mentioned, asking the expert if it could be validated or not. If the score was not validated, the short justification written on the template was employed to ask the expert to provide a confuting argument, ultimately leading to the proposal of an alternative score. Experts often provided supportive arguments also when validating the preliminary score, either remarking the written justification or complementing it with supportive arguments. Experts were not always confident about assigning one of the three possible values; in these cases, an uncertainty score was recorded. Each interview was recorded with the explicit consent of the interviewee; after the interview, the recording was reviewed to obtain an interview-characterization highlighting whether the expert had validated the preliminary scores, the provided arguments, and the uncertainty or proposed scores when relevant. The characterization of each expert interview can be found in *Appendix F*. Once at least two interviews per abatement option had been performed, the interview-characterizations were reviewed, to achieve final, validated scores synthesizing experts' opinions.

4.2 Interviewed experts

12 semi-structured interviews were performed, involving with 11 experts (three interviews performed with Prof. dr. Kornelis Blok and a joint interview with Mr., Dejonghe and Mr. Sprengers at Statkfraft Markets BV). The experts interviewed to validate the preliminary score are reported below in *Table 4*.

Table 4: List of interviewed experts

Expert	Affiliation
Blok, Kornelis Prof. dr.	ECOFYS & Delft University of Technology – The Netherlands
Barthel, Claus dr.	Wuppertal Institut für Klima, Umwelt, Energie gGmbH – Germany
Dejonghe, Koen MA.	Statkraft Markets BV – The Netherlands
Elizondo, Cordero Alejandra dr.	Centro de Investigatiòn y Docencia Economicas – Mexico
Jasper, Jörg Prof. dr.	EnBW – Germany
Morelli, Gargiulo Vittorio MSc.	Bain & Company – The Netherlands
Smith, Pete Prof. dr.	University of Aberdeen – United Kingdom
Sprengers, Peter MSc.	Statkraft Markets BV – The Netherlands
Vaessen, Peter Prof. ir.	DNV GL & Delft University of Technology- The Netherlands
Viebhan, Peter dr.	Wuppertal Institut für Klima, Umwelt, Energie gGmbH – Germany
Verhagen, Jan dr.	Wageningen University & Research – The Netherlands

When possible, the interviews were performed face-to-face; the ones with Dr. Barthel, Dr. Elizondo, Prof. dr. Jasper, Prof. dr. Smith and Dr. Viebhan, were performed via conference-calls as they are based outside The Netherlands, using the programs of Skype (Dr. Elizondo, Prof. dr. Smith) and GoToMeeting (Dr. Barthel, Dr. Viebhan), or via a regular phone call (Prof. dr. Jasper). *Table 5* presents the experts interviewed for each abatement option.

Table 5: Interviewed experts per abatement option

Sector	Abatement Option	Interviewee 1 (I-1)	Interviewee 2 (I-2)	Interviewee 3 (I-3)
Building	Building Efficiency New Build	Barthel	Morelli	
CCS	Coal CCS new build	Viebhan	Jasper	
CCS	Coal CCS retrofit	Viebhan	Jasper	
Energy	Geothermal	Blok	Viebhan	
Energy	Small hydro	Viebhan	Dejonghe & Sprengers	
Energy	PV panels home	Vaessen	Dejonghe	
Energy	High penetration wind	Vaessen	Dejonghe & Sprengers	Jasper
Energy	Nuclear	Blok	Elizondo	
Forestry & Agriculture	Cropland nutrient management	Smith	Verhagen	
Forestry & Agriculture	Reduced intensive agriculture conversion	Blok	Smith	
Forestry & Agriculture	Reduced deforestation from timber harvesting	Blok	Smith	
Forestry & Agriculture	Grassland management	Blok	Smith	

Forestry & Agriculture	Agronomy Practices	Smith	Verhagen	
Fuel	Bioethanol lignocellulosic	Blok	Elizondo	
Household Changes	Lighting switch incandescent to LED (residential)	Barthel	Morelli	
Household Changes	Residential appliances	Barthel	Morelli	
Industrial Processes	Energy efficiency 1 Iron & steel	Blok		
Industrial Processes	Clinker substitution by fly ash	Blok		
Vehicles	Air Transport			
Vehicles	Cars full hybrid	Blok	Vaessen	
Vehicles	Cars plug-in hybrid	Blok	Vaessen	
Vehicles	Battery Electric Vehicles	Blok	Morelli	
Waste	Electricity from landfill gas	Blok		
Waste	Composting new waste	Blok		

4.3 Validation Process & Requirements

This section presents the validation of the preliminary scores which, synthesizing the collected experts' opinions become the validated scores eventually used to compose the Y-curve. Considering the large diversity of the analyzed abatement options and of interviewees' expertise, validation-requirements have to be set to ensure the coherency and transparency of the validation process; the lack of the latter is one of the limitations of McKinsey's MAC curve (*section 1.1.2*), and thus transparency of reporting is an important goal pursued in this investigation. Validation-requirements aid the synthesis of expert's opinions in cases of conflicting or uncertain scores proposed by experts: such scores need to be compared to verify if the different judgments might be caused by diverse interpretations or references. In case of dilemmas, a final, validated score is achieved following these explicitly pre-set validation requirements.

Following the suggestions of some interviewees, the following two scopes are considered to synthesize the experts' opinions and reach final, validated scores:

Scope 1: The 12 factors are barriers potentially hampering the implementation of emission abatement options; thus, the assigned scores should refer to those actors who could proactively implement the respective abatement option, reflecting how the barriers highlighted by the 12 factors might impact their decision-making.

E.g.: A person who buys an EV does not experience the conflicts between the oil-producing corporations, lobbying for benzine-vehicles, and government parties pushing for sustainable transport
(factor *B1: Diversity of actors involved incl. conflicts*).

Scope 2: Most of the considered abatement options propose changes to current practices and/or existing habits. Thus, the scores should reflect the relevance of the changes compared to business-as-usual rather than in any sort of absolute value. While this is immediate for factors such as *D3: Requires changes in behaviors*, it less obvious for other factors.
E.g.: The construction of a new building requires the interaction of multiple actors, and so does the construction of an energy-efficient one, which should thus be considered as having no/minor superior dependency on other actor (factor *B1: Dependence on other actors*).

Having clarified these two scopes, the remaining validation-requirements can be set; these are highlighted with the aid of colors and reference letters, the functions of which are explained in the successive paragraph:

- If all experts validated the preliminary score, this is confirmed as final score; [a]
- If all experts proposed the same score, different from the preliminary one, the proposed score is accepted as final; [b]
- If at least one expert validated the preliminary score, while one or more experts were uncertain between two possible scores, one of which being the preliminary score, the latter is validated for the absence of a clear argument against it; [c]
- If experts were uncertain about different possible scores, similar to each other but different from the preliminary score [d1], (e.g.: p.s. = 0, I-1 proposes 2, I-2 is uncertain between 1 or 2), or different from each other but similar to the preliminary score [d2] (p.s. = 1, I-1 uncertain between 0-1, I-2 uncertain between 1-2) the most "popular" score is validated as final (e.g.: 2 and 1), but reported as "somewhat uncertain" as different from the preliminary score and not proposed by experts without any uncertainty;
- If experts proposed different, not-uncertain scores (either with one validating the preliminary score or not), the arguments presented by the experts are compared:
  - If the argument of one expert is not aligned with either Scope 1 or Scope 2, the argument and the score proposed by the other expert(s) is preferred; [e]
  - If all arguments are aligned with both *Scope 1* and *Scope 2*, the dilemma can be solved in three ways:
    1. Justifying the predominance of one of the arguments and/or scores, and reporting it as "somewhat uncertain" for the sake of transparency; [f]
    2. Selecting one of the proposed scores, and reporting it as "significantly uncertain" for the sake of transparency; [g]
    3. Selecting a medium between the proposed scores and reporting it as "significantly uncertain" for the sake of transparency. [h]

Before presenting the validation process and the reasonings which led to obtaining the final, validated scores, these are presented in the *Table* 6 (below) to provide an overview of the results.
In the table, the assigned preliminary scores are displayed between *(parenthesis)*, and next to each of them the final score is added, in case this differs from the preliminary one. Moreover, each score is highlighted in a color for visual purposes, according to the validation requirements presented above: a yellow or red color represents the differences of opinions amongst experts, and the final score should thus be treated as uncertain, somewhat-uncertain if yellow and significantly-uncertain if red. Green scores signify agreement between experts or minor uncertainties and are thus considered as certain. In *Table 6* only the preliminary and final scores assigned to the abatement options are presented, per sector and alphabetical order, while the final scores are presented summed and ranked in *section 4.4,* after having exposed the validation procedure.

The validation procedure is presented in the next section, repeating the colors and the letters assigned to each validation-requirement are to justify the final scores.

Important to note is that five of the considered abatement options were only discussed with one expert instead of the intended two, due to difficulties in finding interviewees:
[Industrial Processes]: Energy efficiency 1 Iron and steel, Clinker substitution by fly ash,
[Vehicles]: Air transport,
[Waste]: Electricity from landfill gas, Composting new waste.
These options are highlighted by an "*" in the *Table 6*. Thus, for these options the scores validated or suggested by the one interviewee are accepted as final Y-scores and reported as "somewhat uncertain".

DISCALIMER: All the performed and referenced interviews had a personal connotation, and the reported opinions of experts should not be in any form considered as official statements and/or beliefs of the institutions to which the persons interviewed as experts are affiliated.

Table 6: Overview of the validated scores and their uncertainty – with preliminary scorers

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
Building Efficiency New Build	(2)	(1)	(1)	1 (2)	(1)	0 (1)	(1)	0 (1)	0 (1)	(1)	(1)	(0)
Coal CCS new build	(2)	(2)	(2)	(2)	(2)	(1)	(2)	(0)	(2)	(1)	(2)	(0)
Coal CCS retrofit	(2)	(2)	(2)	(2)	(2)	(1)	(2)	(2)	(2)	(1)	(2)	(2)
Geothermal	(2)	(2)	2 (1)	(2)	(2)	1 (0)	1 (0)	(1)	(1)	(0)	(1)	(1)
High penetration wind	(2)	2 (1)	(1)	(2)	(2)	(1)	(2)	1 (2)	(1)	1 (2)	(1)	(0)
Nuclear	(2)	(2)	(2)	(2)	(2)	1 (2)	1 (2)	0 (1)	1 (2)	(0)	(2)	(0)
Small hydro	(2)	(2)	1 (2)	(2)	1 (2)	(0)	(2)	(1)	(0)	(0)	1 (0)	(1)
PV panels homes	(1)	(1)	(1)	(0)	(1)	(0)	(1)	(0)	(0)	(1)	(0)	1 (0)
Agronomy Practices	(0)	1 (0)	(0)	(0)	1 (0)	(0)	(0)	1 (0)	1 (0)	(0)	(0)	(1)
Cropland nutrient management	(0)	(0)	(0)	(1)	(1)	(1)	(0)	(0)	(1)	1 (2)	(0)	1 (2)
Grassland management	(0)	(0)	(0)	(1)	1 (0)	(1)	(0)	(0)	(1)	(1)	(0)	1 (2)
Reduced deforestation from timber harvesting	(1)	(2)	(1)	(2)	(2)	(1)	(2)	(2)	(0)	(1)	(0)	(2)
Reduced intensive agriculture conversion	(1)	(2)	(1)	(2)	(2)	(1)	(2)	(2)	(0)	(1)	(0)	(2)
Bioethanol lignocellulosic	1 (2)	2 (1)	(1)	(1)	(1)	(1)	(1)	1 (2)	2 (1)	(1)	1 (2)	(1)
Lighting switch incandescent to LED (residential)	(1)	(0)	(0)	(0)	(0)	(0)	0 (1)	(0)	(0)	(1)	(0)	(0)
Residential appliances	(1)	(1)	(1)	1 (2)	1 (2)	0 (1)	(0)	(1)	(1)	(1)	(1)	1 (2)
Clinker substitution by fly ash*	(0)	(0)	(0)	(2)	(1)	(0)	(1)	(1)	(0)	(0)	(0)	(1)
Energy efficiency 1 Iron & steel*	(2)	(0)	(2)	(0)	(1)	(0)	(0)	(1)	(1)	(0)	(1)	(0)
Air Transport*	1 (0)	(0)	(0)	(1)	(0)	(0)	(1)	(0)	(1)	(0)	(0)	(1)
Battery Electric Vehicles	1 (2)	(1)	(1)	2 (1)	0 (1)	(1)	(1)	(0)	0 (2)	(1)	(1)	2 (1)
Cars full hybrid	(1)	(1)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)
Cars plug-in hybrid	(1)	(1)	(0)	(1)	(1)	(1)	(1)	(0)	0 (1)	1 (0)	(1)	(1)
Composting new waste*	(1)	(1)	0 (1)	2 (1)	1 (0)	(0)	(1)	1 (0)	(0)	(0)	0 (1)	(1)
Electricity from landfill gas*	(2)	1 (2)	(1)	(2)	(1)	(1)	(1)	(0)	0 (1)	(0)	(1)	(0)

Each score is presented individually in the paragraphs below, abatement option after abatement option, respecting the alphabetical order of the respective economic-sector. For each factor, the preliminary score and the arguments of the interviewed experts are reported; these are synthesized to achieve a validated score, equal or different from the preliminary assigned one, according to the set validation-requirements. Next to the factor name, the preliminary score (p.s.) and the final scores are reported. The [letters] and the colors used to identify the specific validation-requirement applied are also reported, according to their definition in the previous page and in the table above.

4.3.1 Building

Building efficiency new build

A. Cost and Financing

A1 Investment cost required – (p.s. = 2) validated by both interviewees [a]

I-1 remarked how large investments are always required for constructing a building, and that construction-costs for energy-efficient buildings have a mark-up over those of non-efficient buildings, which vary depending on the applied-standards; nevertheless, these mark-up costs are on average higher than the 8% found in the literature. I-2 confirmed the substantial extra-costs for constructing an energy-efficient building over a non-efficient one.

A2 Expected pay-back time – (p.s. = 1) considered validated [e]

I-1 did not validate the preliminary score of 1, mentioning how the investments for the construction of a new building take longer than 12 years to be paid back. Instead, I-2 validated the preliminary score of 1. The difference is caused by the diverse perspectives of the interviewees, as I-1 considered the costs of constructing a building, while I-2 focused on the extra-cost needed for constructing an energy-efficient building. The latter is more aligned with the perspective set by *Scope 2 (section 4.3)*, as the construction of new buildings is common practices while energy-efficient ones are not. Thus, the preliminary score of 1 is considered validated.

A3 Difficulty in financing the investment – (p.s. = 1) considered validated, significantly uncertain [h]

I-1 validated the preliminary score of 1, mentioning how every country has its own programs of incentives supporting investments in energy-efficient buildings. I-2 instead stressed the country-dependency of the score, considering how this can vary from a value of 0 to a value of 2 depending on the local climate and on the available programs of incentives. While acknowledging the reasoning of I-2, very different countries have some program of incentives, which witness how the topic of buildings' energy-efficiency is positively recognized by national governments of different countries. Thus, the preliminary score of 1 is validated, also considering it is the medium of the uncertain-score proposed by I-2; in accordance with validation requirement [h], the score is reported as significantly uncertain, as I-2's comment highlights how the factor could assume all scores. This judgment is further addressed in the *section 4.5.1 – Reflection*.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) changed to 1, significantly uncertain [h]

Both interviewees highlighted how the construction of a building requires the interaction of many parties, but that the interdependence of actors should be only slightly higher than usual for the construction of an energy-efficient one; for instance, there might be the need for more contractors with a more specific expertise. This same reasoning brought I-1 to doubt between a score of 1 or 2, while I-2 was uncertain between a score of 0 or 1. Combining the uncertainty intervals of both interviewees, the preliminary score of 2 is changed to a score of 1, reported as significantly uncertain, as it is a medium between different, uncertain opinions.

B2 Diversity of actors involved incl. conflicts – (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, while I-2 remarked that the many involved actors mainly want to ensure their own financial return, but there are no conflicts on the realization of the building; thus, I-2 was uncertain between a score of 0 or 1. In the absence of a strong argument to change it, the preliminary score of 1 is thus validated.

B3 Division of roles and responsibilities unclear – (p.s. = 1) changed to 0 [e]

I-1 validated the preliminary score of 1, mentioning how frameworks such as "Green buildings" are not very recent, but that there is the need for an expert architect. I-2 instead did not validate the preliminary score, mentioning how the hired architects and engineers should be aware of all the details of the relevant framework to be applied in the project, and thus proposed a score of 0. The argument of I-2 is aligned with *Scope 2 (section 4.1):* most people are commonly not aware of construction techniques and are offered a building designed by skillful architects and engineers, knowledgeable about technical-standards and regulations. Thus, it is decided to change the preliminary score of 1 to a score of 0.

C. Physical Interdependencies

C1 Physical embeddedness – (p.s. = 1) validated by both interviewees [a]

Both interviewees mentioned how the physical differences and implications between a non-efficient and an energy-efficient building are minor.

C2 Disturbs regular operations - (p.s. = 1) changed to 0 [e]

I-1 validated the preliminary score of 1, while I-2 remarked that the disturbances are not different from the ones caused by the construction of a new building, and thus recommended to assign a score of 0 if only the additional disturbances were to be consider. As for the factor B3, the argument of I-2 is more aligned with *Scope 2 (section 4.3)*, and thus the preliminary score of 1 is changed to a score of 0, as proposed by I-2.

C3 Technology uncertainty - (p.s. = 1) changed to 0, somewhat uncertain [d1]

The interviewees did not validate the preliminary score of 1. I-1 remarked how popular frameworks are well known and the technology is fully-proven, but mentioned how new frameworks often appear, which still need to be verified and was thus uncertain between a score of 0 or 1. Instead, I-2 mentioned how civil engineering practices for energy-efficiency have been known for 40 years, and the technology is thus fully-proven, proposing a score of 0. Combining the interviewees' suggestions, the preliminary score of 1 is changed to a score of 0, and is reported as somewhat uncertain, as different from the preliminary score and not being proposed by both experts without any uncertainty.

D. Behavior

D1 Absence of knowledge of actors – (p.s. = 1) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 1, mentioning how only some people are knowledgeable about energy-efficient buildings. I-1 added that people are not responsible for the construction of buildings, but those who are not aware of purpose and costs of energy-efficient buildings might have a negative attitude towards their high final price, refusing the purchase. Instead, I-2 commented that thanks to their daily experiences, all people are instinctively aware of many of the energy-efficient practices and their financial benefits, as for instance the higher thermal isolation enabled by a double glass window compared to a single glass one; what is unknown are the specifics of different frameworks and proposed a score of 0. The two arguments are valid, but it is considered that, while not always, those people aware of potential energy savings enabled by a popular framework are more likely to pay the additional market price. Thus, the preliminary score of 1 is validated as final score and reported as somewhat uncertain.

D2 Frequency of opportunity - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, mentioning how the frequency is rare considering individual buildings, which are nevertheless constructed every day in every city. Thus, a medium score is appropriate. Instead, I-2 was uncertain between a score of 1 or 2. Thus, in the absence of a strong argument for changing it, the preliminary score of 1 is considered validated.

D3 Requires change in behavior - (p.s. = 0) validated by both interviewees [a]

4.3.2 CCS

Coal CCS new built

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) validated by both interviewees [a]

Both interviewees remarked how the investment for a new power plant is always large and CCS technology is almost as expensive as the coal plant itself.

A2 Expected pay-back time - (p.s. = 2) validated by both interviewees [a]

I-1 explained how the lifetime of a coal plant is 40 years, with pay-back estimated at 20 years. Thus, pay-back is larger than 12 years even without the upcoming renewables, reducing operating hours. I-2 remarked how the current carbon price (16 €/tCO_2) should increase to 40-70 €/tCO_2 for CCS technology to have a positive business-case over the entire lifetime of a coal plant.

A3 Difficulty in financing the investment - (p.s. = 2) validated by both interviewees [a]

I-1 cited an increasing number of studies questioning the economic feasibility of CCS technologies, while I-2 mentioned how the lack of stable carbon prices and possible market competition with other coal plants without CCS make investments in CCS unattractive.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated by both interviewees [a]

Both interviewees mostly highlighted the issues related to CO_2 transport and storage: many actors are involved, but standardized procedures for identifying and assigning locations are often lacking (I-2). Besides governments and grid regulators, many environmental agencies are involved.

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) validated by both interviewees [a]

Both interviewees remarked the many conflicts related to the locations of CO_2 storages. I-2 mentioned how in Germany a suitable storage location was found and private owners were forced to sell the land to the government, creating social conflict; thus, offshore storage locations could decrease actors' conflicts.

B3 Division of roles and responsibilities unclear - (p.s. = 1) considered validated [c]

I-1 remarked how the responsibilities at the plant sites are entirely clear, but substantial unclarities characterize the responsibilities for the CO_2 transport and storage: up to the 10th year of storage, the coal plant ownership is responsible, then responsibility shifts to the government, but this is a highly debated topic; I-1 was thus uncertain between a score of 1 or 2. I-2 instead validated the preliminary score of 1, stressing the lack of clarity over the allocation of storage sites: do governments register available locations or shall investors make proposals? Considering the similarity of both arguments and the lack off a clear motivation to change it, the preliminary score of 1 is validated.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 2) validated by both interviewees [a]

Both interviewees highlighted the visible environmental changes brought by the CCS technology to the outlook of new plants, and I-1 highlighted the impact of CO_2 transport and storage infrastructure.

C2 Disturbs regular operations - (p.s. = 0) considered validated [c]

I-1 validated the preliminary score of 0, remarking how there are no previous operations to be disturbed. I-2 mentioned how plant operations might be interrupted if the CCS installation is not terminated once the plant starts operating, thus being uncertain between a score of 0 or 1. In the absence of a clear argument against it, the preliminary score of 0 is validated.

C3 Technology uncertainty - (p.s. = 2) considered validated [c]

I-1 commented how the capture, transport and storage of CO_2 should not be technically a problem, and their implementation must be hampered by policy uncertainty, thus being uncertain between a score of 1 or 2. Instead, I-2 validated the preliminary score of 2, mentioning how CCS technology is mastered but its effectiveness on a large scale is very much unproven. Having both experts recognized the difficulties reflected by the preliminary score and not having proposed a clear argument for changing it, the score of 2 is validated.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) considered validated [c]

I-2 validated the preliminary score of 1, while I-1 had some uncertainty between the scores of 1 and 2 because of the absolute lack of knowledge of most of the population. In the absence of a strong argument for changing it, the preliminary score of 1 is validated.

D2 Frequency of opportunity - (p.s. = 2) considered validated [c]

I-2 validated the preliminary score of 2, stressing how in many Western countries it is even being discussed if to build any new coal plant at all. Instead, I-1 mentioned the many new coal plants projects in India and China, theoretically planned but often not constructed, which made him uncertain between a score of 1 and 2. Thus, in the absence of a clear argument against it, the preliminary score of 2 is validated.

D3 Requires change in behavior - (p.s. = 0) validated by both interviewees [a]

I-1 remarked how every actor is aware of the new processes related to CCS technology from the beginning, and I-2 mentioned possible behavioral changes to be enforced only if the CCS technology is not operational at the start of the plant operations.

Coal CCS Retrofit

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) validated by both interviewees [a]

Both interviewees specified how retrofitting an existing coal plant is even more expensive than constructing a new power plant designed equipping CCS technology, because of spatial constraints which need to be overcome and more problematic equipment operations.

A2 Expected pay-back time - (p.s. = 2) validated by both interviewees [a]

I-1 mentioned a McKinsey's study from 10 years ago which concluded that if a coal plant is older than 12 years there is no business case in retrofitting it with CCS, because the 28 years of remaining lifetime are not sufficient for pay-back; I-2 remarked that the business-case is harsher than for new built plants because of higher costs and shorter lifetime for obtaining a ROI.

A3 Difficulty in financing the investment - (p.s. = 2) validated by both interviewees [a]

I-1 and I-2 repeated what mentioned for the factor *A3* for the abatement option [CCS]: Coal CCS new built.

B. Multi-actor complexity

B1 Dependence on other actors - (p.s. = 2) validated by both interviewees [a]

I-1 and I-2 repeated what mentioned for the factor *B1* for the abatement option [CCS]: Coal CCS new built.

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) validated by both interviewees [a]

I-1 and I-2 repeated what mentioned for the factor *B2* for the abatement option [CCS]: Coal CCS new built.

B3 Division of roles and responsibilities – (p.s. = 1) validated by both interviewees [a]

I-1 and I-2 repeated what mentioned for the factor *B3* for the abatement option [CCS]: Coal CCS new built.

C. Physical interdependencies

C1 Physical embeddedness - (p.s. = 2) validated by both interviewees [a]

Both interviewees remarked how retrofitting an operating coal plant with a CCS system requires a complete reorganization of spaces to allow the insertion of the needed additional large components.

C2 Disturbs regular operations - (p.s. = 2) validated by both interviewees [a]

Both interviewees focused on the long installation times which, according to a McKinsey's study mentioned by I-1, last approximately 1 year.

C3 Technology uncertainty - (p.s. = 2) validated by both interviewees [a]

Both experts provided the same argument reported under the factor *C3* for the abatement option [CCS]: Coal CCS new built, and thus similarly, the preliminary score of 2 is validated.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) validated by both interviewees [a]

Both experts provided the same argument reported under the factor *D3* for the abatement option [CCS]: Coal CCS new built.

D2 Frequency of opportunity - (p.s. = 2) validated by both interviewees [a]

I-1 repeated the same argument reported under the factor *C3* for the abatement option [CCS]: Coal CCS new built, while I-2 validated the preliminary score of 2 highlighting large compatibilities-issues which often hamper the realization of CCS retrofit projects.

D3 Requires change in behavior - (p.s. = 2) validated by both interviewees [a]

Both interviewees mentioned how retrofitting a CCS system requires the design and implementation of totally new operational-processes every stakeholder and worker needs to get used to.

4.3.3 Energy

High penetration wind

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) considered validated [c]

Investment is always needed for installing wind turbines (I-1), estimated to be between 800 and 1,000 €/KW (I-2) and below 1,000 €/KW (I-3) for onshore turbines. Costs for offshore turbines are substantially higher. I-1 and I-3 were uncertain between a score of 1 or 2, while I-2 validated the preliminary score of 2. Thus, in absence of a clear argument against it, the preliminary score of 2 is validated.

A2 Expected pay-back time (p.s. = 1) changed to 2, significantly uncertain [g]

I-2 validated the preliminary score of 1, I-1 was uncertain between a score of 1 or 2, while I-3 mentioned how subsidies for wind farms are usually guaranteed for a 20-year span, and thus proposed a score of 2. Considering the facts provided by I-3 and how market prices for wind energy are expected to decrease thus enlarging pay-back times (I-1), the preliminary score is changed to a score of 2. To transparently report the arbitrariness of this argument, the score is reported as significantly uncertain.

A3 Difficulty in financing the investment - (p.s. = 1) considered validated, somewhat uncertain [d2]

I-1 validated the preliminary score of 1, as a medium between onshore and offshore projects. I-2 mentioned how finding de-risked project is the key-challenge rather than financing and proposed a score of 0 for the factor. Instead, I-3 judged the difficulty to be mainly dependent on the subsidy scheme in place and doubted between a score of 0 or 1. Combining the experts' opinions, financing investments for wind turbines is a challenge, especially for offshore installations, as it is for any investment in energy technology to find a satisfying Power Purchase Agreements (PPA). The preliminary score of 1 is thus validated but reported as somewhat uncertain.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated by all interviewees [a]

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) validated by all interviewees [a]

Main conflicts are not related to the technical functioning of turbines but to their interfaces with the environment (e.g.: local population and animals).

B3 Division of roles and responsibilities - (p.s. = 1) considered validated, somewhat uncertain [d2]

Both I-1 and I-2 mentioned the abundant experience with onshore projects, which has clarified the responsibilities. There is less experience with offshore technology, which is evolving: on one hand roles need to be further clarified, on the other hand the complexity of the technology is being reduced. I-2 specified how offshore installations are still rather close to the shore, and technological innovations cannot be considered as unclarity of responsibilities, thus proposing a score of 0. I-3 also believes that responsibilities are entirely clear in mature energy markets, which are not a worldwide standard, and validated the preliminary score of 1.

Instead, I-1 was uncertain between a score of 0 and 1. In the absence of a decisive agreements amongst the interviewees, the preliminary score of 1 is validated and reported as somewhat uncertain.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 2) validated by all interviewees [a]

The environment is undoubtedly affected, and the question is how many people are impacted by these changes, with regards to the subjective complaints for a "ruined view".

C2 Disturbs regular operations - (p.s. = 2) changed to 1, somewhat uncertain [d1]

Onshore turbines are often located in inaccessible areas (I-1), and the view-changes should not be considered as disruptions (I-3). Nevertheless, some onshore wind parks are close to populated areas which might experience minor access-restrictions (I-2 and I-3), while for the construction of offshore parks some ships routes might be disrupted (I-2), to allow material transport (I-1). I-2 proposed a score of 1, while I-1 and I-3 were uncertain between a score of 0 or 1. Synthesizing experts' remarks, minor disruptions are to be expected; thus, the preliminary score is changed to a score of 1 and is reported as somewhat uncertain, as different from the preliminary score and reported by experts with some uncertainty.

C3 Technology uncertainty - (p.s. = 1) considered validated [c]

All interviewees agreed on how current technology is fully proven, with I-2 mentioning how projects of such magnitude would not be performed if there were doubts on the functioning and environmental effectiveness. Nevertheless, I-1 reported some uncertainty related to the current experience with offshore turbines, shorter than their lifetime, and I-3 highlighted the technological challenge posed by the ongoing size-increase of turbines. Thus, considering how I-1 and I-2 were uncertain between a score of 0 and 1, and that I-3 validated the preliminary score of 1, this is validated in the absence of a strong argument against it.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 2) changed to 1, significantly uncertain [h]

I-1 focused on the superficial knowledge of most people, who know about wind energy but are not aware of its requirements and implications and proposed a score of 2. A similar argument is mentioned by I-2, who see it as less problematic, shifting the attention to the awareness of the environmental impact rather than of technology (proposed score of 1). Instead, I-3 proposed a score of 0, mentioning how the technology is intuitive. Thus, all actors seem to have at least superficial knowledge, and the issue is rather the need to involvement more the population to facilitate the acceptance of the technology. The preliminary score is changed to a score of 1, medium amongst the interviewees' opinions, and is reported as significantly uncertain given the different arguments.

D2 Frequency of opportunity - (p.s. = 1) considered validated [c]

Lifetime for onshore and offshore turbines is 15 and 20 years, respectively (I-1), but the former have a much easier and quicker projecting phase and thus offering more frequent opportunities for construction (I-1 and I-3). I-2 remarked the relevance of scalability for determining the frequency of opportunity. The score of 1 was validated (I-2) or in the uncertainty range of all interviewees and considering the high demand and the consequent many installations, the preliminary score of 1 is considered validated.

D3 Behavioral changes - (p.s. = 0) validated, somewhat uncertain [f]

I-1 and I-2 validated the preliminary score of 0. Instead, I-3 mentioned how many places might become inaccessible due to heavy presence of turbines; moreover, a heavy reliance on volatile wind power might force the implementation of smart grid, causing behavioral changes, and thus proposed a score of 1. Implementing the abatement option causes changes mostly related to fluctuating energy prices but has fewer effects on privates' energy bills than PVs, which are willingly installed on rooftops and directing impacting the energy consumption of individual households. Thus, the preliminary score of 0 is validated, also considering the majority of opinions in its favor, and it is reported as somewhat uncertain.

Geothermal

Definition issues: Both interviewees distinguished between deep-drilling, large scale geothermal plants for power generation, and smaller, shallow-drilling geothermal-heat plants. The former ones were generally used as reference, unless differently specified

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) validated by both interviewees [a]

Exploration activities are the main cost-driver for deep drilling, power-generating plants (I-2), but also geothermal heating production is not expected to become cheaper than (e.g.:) gas due to high construction and operational costs (I-1).

A2 Expected pay-back time - (p.s. = 2) validated by both interviewees [a]

Lifecycle assessments, even with subsidies for renewable energy, estimate a 20-year span as pay-back (I-2).

A3 Difficulty in financing the investment – (p.s. = 1) changed to 2, somewhat uncertain [f]

Referring to geothermal-heat plants, I-1 validated the preliminary score of 1, and highlighted the high uncertainty of the investment, caused by the unknown well-productivity which might cause no ROI. Considering also the many accidents and damages to households caused by deep geothermal-drilling leading to opposition of the population and the consequent aversity of investors (highlighted by I-2 and also frequently discussed by the literature) the preliminary score of 1 is changed to 2, as proposed by I-2, and is reported as somewhat uncertain.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated by both interviewees [a]

Both interviewees stressed the many hustles with municipalities, often preventing private-investments in any geothermal project (I-1).

B2 Diversity of actors involved - (p.s. = 2) considered validated, somewhat uncertain [f]

I-2 validated the preliminary score of 2, referring to the previously mentioned accidents and damages, and the consequent conflicts with the population. Considering geothermal-heat plants, I-1 confirmed actors' diversity and the presence of conflicts, but would not classify them as strong, proposing a score of 1. As for the previous factor *A3*, and considering the many social conflicts reported in the reviewed literature in countries rich of suitable locations as Italy, the preliminary score of 2 is considered validated, and is reported as somewhat uncertain to account for the different experts' opinions.

B3 Division of roles and responsibilities unclear – (p.s. = 0) changed to 1 [b]

The two interviewees did not validate the preliminary score of 0, disagreeing with the extensive experience preliminarily highlighted proved for instance by the few (only two or three) exploration sites in Germany (I-2), and remarking the hustles caused to investors by municipalities' lack of understanding of own responsibilities (I-1). The preliminary score is switched to the score of 1, as proposed by both interviewees.

C. Physical interdependencies

C1 Physical embeddedness – (p.s. = 0) changed to 1 [b]

The two interviewees did not validate the preliminary score of 2, remarking how environmental changes are mostly related to connecting the geothermal installations with the surrounding heat and power network (I-1). Besides a few pipes, most of the needed installations are underground, and thus do not cause large physical changes. Thus, the preliminary score is switched to the score of 1, as proposed by both interviewees.

C2 Disturbs regular operations - (p.s. = 1) considered validated, somewhat uncertain [f]

Considering geothermal-heat plants, I-1 commented that very limited disruptions to regular operations are needed, proposing a score of 0. While confirming I-1's argument for geothermal-heat plants, I-2 also focused on power-producing geothermal plants, which require longer, and more changeling construction works, thus validating the preliminary score of 1. Following the same argument as for the above factors *B2* and *B3*, the preliminary score of 1 is considered validated, and reported as somewhat uncertain.

C3 Technology uncertainty - (p.s. = 1) considered validated, somoewhat uncertain [f]

I-1 validated the preliminary score of 1, while I-2 highlighted how the induced earthquakes and damages to households often prevent the realization of the installations, thus proposing a score of 2. While relevant, these problems are considered not directly related to the technology, which is entirely mastered, but rather to its environmental impact, which cannot be eliminated without unexpected scientific breakthroughs. The preliminary score of 1 is considered validated and reported as somewhat uncertain.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) considered validated [c]

Both interviewees consider relevant actors to having a high knowledge about geothermal power for heating, but I-2 remarked a lower knowledge on large, deep-drilling plants, which are less frequently constructed. I-1 validated the preliminary score of 0, while I-2 was uncertain between a score of 0 and 1. Lacking a strong argument against it, the preliminary score of 0 is considered validated.

D2 Frequency of opportunity - (p.s. = 1) considered validated [c]

I-2 highlighted the longer projecting time and more limited locations for power-generation geothermal plants, while a single project for geothermal-heat can be initiated more frequently, as also confirmed by I-1. I-1 validated the preliminary score of 1, while I-2 was uncertain between a score of 1 and 2. Considering the lack of a strong argument against it, the preliminary score of 1 is considered validated.

D3 Requires change in behavior - (p.s. = 1) considered validated [c]

I-1 mentioned how behavioral changes are dependent on the size of the project, as large geothermal power plants can be spatially-invasive, especially in terms of access restrictions to certain locations (I-2). I-2 validated the preliminary score of 1, while I-1 was uncertain between a score of 0 and 1. Considering the lack of a strong argument against it, the preliminary score of 1 is considered validated.

Nuclear

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) validated by both interviewees [a]

Both interviewees referred to the high capital cost of the technology.

A2 Expected pay-back time - (p.s. = 2) validated by both interviewees [a]

I-1 added how most examples of profitable nuclear-plant projects are in China.

A3 Difficulty in financing the investment - (p.s. = 2) considered validated, somewhat uncertain [f]

I-1 remarked how it is possible to find positive business cases for nuclear projects, as in the UK where Feed-In-Tariffs specific for nuclear energy exist, and thus proposed a score of 1. Instead, I-2 mentioned how besides the difficulties related to the magnitude of the investment and nuclear being a debated technology, governments often maintain at least a partial control over nuclear investments (e.g.: in Mexico), as they regard a national-security domain; I-2 thus validated the preliminary score of 2. While there might be specific incentive programs supporting nuclear energy, the controversies characterize the technology worldwide; nuclear power is also a national security topic, as the recent situation in North Korea has shown. Thus, it is decided to validate the preliminary score of 2, and to report it as somewhat uncertain.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) considered validated, somewhat uncertain [f]

I-1 commented how the supply chain for nuclear energy has proven to work and a new nuclear plant can be initiated without having to solve many interdependencies, and thus proposed a score of 1. Instead, I-2 highlighted how, after the nuclear accidents, civil society has to be involved in multiple forms before a project is approved, thus validating the score of 2: the many parties wanting to obstacle nuclear projects have often a platform to do it. The comment of I-1 is evidently correct considering the many running nuclear projects, but a functioning supply chain does not necessarily signify the lack of interdependencies. Thus, it is decided to validate the preliminary score of 2, and to report it as somewhat uncertain.

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) validated by both interviewees [a]

I-1 remarked how local populations often feel threatened by nuclear plants, and large NGOs are always against them. I-2 highlighted how the animosity towards nuclear power does not seem to diminish, even if technology keeps improving.

B3 Division of roles and responsibilities unclear – (p.s. = 0) changed to 1 [b]

I-1 remarked how the issue of long-term responsibilities over nuclear-waste disposal remains unclear; I-2 mentioned the periodical performance of nuclear projects, also dependent on diverse political views, with responsibilities having to be clarified at the start of a new favorable period. Thus, the preliminary score of 0 is changed to 1, as proposed by both interviewees.

C. Physical Interdependencies

C1 Physical embeddedness – (p.s. = 2) changed to 1, somewhat uncertain [d1]

Both interviewees remarked how technological developments allow for a compact construction, close to which waste material can also be stored (I-2). I-1 proposed a score of 1, while I-2 was uncertain between a score of 1 or 2. Thus, noting the main arguments being related to the compact size of the plant, the preliminary score is changed to a score of 1, reported as somewhat uncertain as different from the preliminary score and not being proposed by both experts without any uncertainty.

C2 Disturbs regular operations - (p.s. = 1) changed to 0, somewhat uncertain [f]

I-1 mentioned how relevant themes such as the long time needed for the preparation of the land and the construction of the plant are not problematic, thus proposing a score of 0. I-2 highlighted how plants are normally constructed in scarcely populated areas, and thus the long construction-time does not impact many people (uncertain between a score of 0 or 1). Synthesizing their comments, experts did not consider the construction of plants problematic; the preliminary score is changed to a score of 0 and reported as somewhat uncertain as different from the preliminary score and not being proposed by both experts without any uncertainty.

C3 Technology uncertainty - (p.s. = 2) changed to 1, somewhat uncertain

I-1 commented that the uncertainties are related to waste disposal, which besides all arguments, can be effectively stored underground, and proposed a score of 1. I-2 mentioned the extensive research which has been performed worldwide on nuclear energy and was uncertain between a score of 0 or 1. To combine experts' proposal, the preliminary score is changed to 1, and reported as somewhat uncertain as different from the preliminary score and not being proposed by both experts without any uncertainty.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) considered validated [c]

I-1 validated the preliminary score of 1, while I-2 was uncertain between a score of 0 or 1, mentioning how some of the actors who have the authority for expressing an opinion on the feasibility of nuclear projects (e.g.: some governmental agencies) are not highly knowledgeable on the topic. A score of 0 synthesizes the opinions of both experts.

D2 Frequency of opportunity (p.s. = 2) considered validated, somewhat uncertain [f]

I-2 validated the preliminary score of 2, mentioning the long construction period, while I-2 proposed a score of 1, remarking how nuclear energy is often present in national long-term energy strategies. Besides the consideration in energy strategy, nuclear plants require long planning, given the high investment and the long construction time, which increase the difficulty of implementing strategies which include it. The preliminary score is considered validated and is reported as somewhat uncertain for the sake of transparency.

D3 Requires change in behavior - (p.s. = 0) validated by both interviewees [a]

PV panels homes

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) considered validated [c]

I-2 validated the preliminary score of 1, while I-1 remarked the many companies offering leases for PV panels or even installing them for free, with the goal of sharing part of the revenues, and thus being uncertain between a score of 0 or 1. In the absence of a strong argument against it, the preliminary score of 1 is validated.

A2 Expected pay-back time - (p.s. = 1) considered validated [c]

Both interviewees mentioned 7 years as average pay-back time, but I-1 reported fluctuating costs: prices decrease with the increasing amount of installations, but this is offset by the progressive reduction of subsidies. This commonly leads to pay-back times of 12 years and made I-1 uncertain between a score of 1 or 2. In the absence of a strong argument against it, the preliminary score of 1 is validated.

A3 Difficulty in financing the investment - (p.s. = 1) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 1, stressing how only reasonably-wealthy people can afford the investment. I-2 instead mentioned the many cheap loans and financing-plans including the costs of PVs in the household lease, and thus proposed a score of 0. This reasoning is valid only for the most developed countries; employing a worldwide scope, the difficulty in financing the investment is relevant in many nations, either because the overall investment-amount is problematic or due to the lack of ad-hoc policies and leasing possibilities. Thus, the preliminary score of 1 is validated, and reported as somewhat uncertain.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 0) validated by both interviewees [a]

I-2 highlighted the little number of permits needed.

B2 Diversity of actors involved - (p.s. = 1) considered validated, somewhat uncertain [d1]

Both interviewees were uncertain between a score of 0 and 1, with I-1 remarking how most conflicts arise with neighbors who might not like how PVs change the rooftops' outlook. Given the uncertainty of the interviewees and the lack of a clear conflicting argument, the preliminary score of 1 is validated, and reported as somewhat uncertain.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated by both interviewees [a]

Both interviewees validated the preliminary score of 0.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) considered validated [c]

I-2 validated the preliminary score of 1, stating how PVs are visible on both flat and tilted roofs, which at times have to be strengthened to support them. Instead, I-1 remarked how only the rooftop's view is affected, while its functionality is not, and thus being uncertain between a score of 0 or 1 In the absence of a strong argument against it, the preliminary score of 1 is validated.

C2 Disturbs regular operations - (p.s. = 0) validated by both interviewees [a]

I-1 remarked that only rooftop cleaning and maintenance activities might be slightly disrupted but does not consider it a relevant disturbance of operations.

C3 Technology uncertainty - (p.s. = 0) considered validated [c]

I-2 validated the preliminary score of 0, while I-1 made an interesting distinction: the technology of PVs is entirely proven, but there are still large unsolved issues on the consequence many PVs' installations have on the balancing on the power grid. Thus, I-1 was uncertain between a score of 0 and of 1. The perspective of *Scope 1 (section 4.3)* suggests considering how people installing PVs do not currently experience the technology uncertainty of the supporting (smart) grid system but just the PVs functioning. Thus, the preliminary score of 0 is validated, also for the lack of a strong argument against it.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) validated by both interviewees [a]

I-2 considers people to be aware of the existence of PVs but to often ignore their implications.

D2 Frequency of opportunity - (p.s. = 0) validated by both interviewees [a]

I-1 highlighted the correlation between the number of installations and the subsidy availability.

D3 Requires changes in behavior – (p.s. = 0) changed to 1, significantly uncertain [h]

The interviewees did not validate the preliminary score of 0. I-1 distinguished between a) the present moment, in which the low diffusion of renewables does not require smart grid systems and the behavioral changes enforced by them, and b) the future when this happen, thus being uncertain between a score of 0 and 1. Instead, I-2 proposed a score of 2, focusing on the behavioral changes required by upcoming smart grid systems. Acknowledging the experts' arguments, combining the present perspective with a future characterized by many PV panels installations and smart grids, a score of 1 is assigned, as a medium to the interviewees' arguments: major changes will be related to fluctuating energy prices, as highlighted by the literature, with people induced but not required to change their energy consumption behaviors to reduce costs. To transparently report this arbitrary scoring, the score is reported as significantly uncertain.

Small hydro

Definition issues: I-1 employed a hydro power plant on the Rhine as reference. I-2 mentioned how The Clean Development Mechanism (CDM, Kyoto Protocol) defines "small hydro power plants" as having a capacity below 20 MW. In the UK, small hydro power plants are defined as having less than 15 MW.

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) considered validated, somewhat uncertain [f]

Both interviewees agreed that the investment is substantial, and dependent on the size and location of each project. I-1 validated the preliminary score of 1, while I-2 mentioned how the majority of the cost normally incurred for traditional, large hydro power plants is caused by mountaineering activities, absent for smaller plants, and thus proposed a score of 1. This is a clear but relative argument; moreover, although not due to mountaineering, costs for connecting the plant with the surrounding environment should also be considered, as highlighted by the literature and by I-1. Thus, the preliminary score of 2 is validated, and reported as somewhat uncertain.

A2 Expected pay-back time - (p.s. = 2) considered validated, somewhat uncertain [f]

I-2 expects the pay-back time to be comparable to the one for investments in wind turbines, and thus did not validate the preliminary score of 2, proposing a score of 1. Instead, I-1 validated the preliminary score, mentioning how lifecycle assessment consider a pay-back time of 20 years, also including subsidies for renewable energy production. Thus, for the more factual nature of the remarks of I-1, and for their similarity with figures found in the literature, the preliminary score of 2 is considered validated and reported as somewhat uncertain.

A3 Difficulty in financing the investment - (p.s. = 2) is changed to 1, somewhat uncertain [f]

I-2 did not validate the score, mentioning how financing the investment is not a problem once the Power Purchase Agreements (PPA) is clear, thus proposing a score of 0. I-1 also did not validate the score, highlighting how, although the investment is substantial, there are often ad-hoc subsidies for supporting the installation of small hydropower system, especially in a retrofit fashion, and proposing a score of 1. The argument of I-2 relates more to signing satisfactory PPA, which are always a challenge regardless of the technology. Thus, the preliminary score is changed to a score of 1 and reported as somewhat uncertain.

B. Multi-actor complexity

B1 Dependence on other actors - (p.s. = 2) validated by both interviewees [a]

B2 Diversity of actors involved incl. conflicts – (p.s. = 2) changed to 1 [b]

Both interviewees did not validate the preliminary score of 2. I-2 highlighted the irrelevance of issues for the relocation and remuneration of local communities, typical of traditional hydropower projects. Both interviewees mentioned the most relevant conflicts to be with environment-protection organizations (local flora and fauna), and both proposed a score of 1, which is accepted as final, validated score.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated by both interviewees [a]

I-2 mentioned how the long experience has helped clarifying the role of all stakeholders involved.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 2) considered validated [c]

I-1 validated the preliminary score of 2, while I-2 remarked how the physical changes depend on the project type, with run-of-river projects being less invasive than dam-projects, and thus being uncertain between a score of 1 or 2. In the absence of a clear argument against it, the preliminary score of 2 is validated.

C2 Disturbs regular operation - (p.s. = 1) validated by both interviewees [a]

I-2 mentioned how possible disruptions might occur for boats, not able to travel upstream anymore.

C3 Technology uncertainty - (p.s. = 0) validated by both interviewees [a]

I-1 remarked how the technology is proven across projects of very different scale.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated by both interviewees [a]

Both interviewees validated the preliminary score of 0, because of the long experience with hydropower technology (I-1), which most people know better than other renewable energies, as wind power (I-2).

D2 Frequency of opportunity - (p.s. = 0) is changed to 1, somewhat uncertain [f]

I-1 validated the preliminary score of 0, while I-2 proposed a score of 1, stressing how hydropower projects cannot be initiated at any time, but quite a high number of small hydropower installations are present, often hidden and not much discussed. Thus, reflecting on the projecting time of small hydropower plants, shorter than for other power plants, but still existent, the preliminary score of 0 is change to the score of 1, and reported as moderately uncertain.

D3 Requires change in behavior - (p.s. = 1) validated by both interviewees [a]

Both interviewees mentioned potential access-restrictions for fisherman, depending on the location.

4.3.4 Forestry & Agriculture

Agronomy practices

A. Cost and Financing

A1 Investment cost required - (p.s. = 0) validated by all interviewees [a]

I-1 mentioned how some seeds with longer roots are slightly more expensive than commonly used ones.

A2 Expected pay-back time - (p.s. = 0) changed to 1, significantly uncertain [h]

I-m validated the preliminary score of 0 commenting how there is no real investment incurred.

Instead, I-2 mentioned how such agronomy practices often lead to lower productivity in the long-term (after 10 years), which cause a "negative pay-back", and thus being uncertain between a score of 1 or 2. Given the large diversity of the experts' opinions, the preliminary score of 0 is changed to 1, better able to mediate amongst experts' opinions, and the score is reported as significantly uncertain.

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

Differently from I-2, I-1 expects better land yields, making the practices very attractive considering its almost-null costs.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 0) validated by all interviewees [a]

I-1 highlighted the dependence of farmers on the availability of advanced agricultural products on the market, such as seeds with deeper roots, and mentioned that once the market for such products exists, the technology is quickly developed, and thus validated the score of 0, described as "Low" rather than as "No".

B2 Diversity of actors involved incl. conflicts - (p.s. = 0) changed to 1, somewhat uncertain [f]

I-1 validated the preliminary score of 0, mentioning Genetically Modified (GM) products to be the only exception, as they are badly welcome on the EU market and on a few other markets around the world. Instead, I-2 commented that there might be some conflicts with local laws as a result of certain practices (e.g.: if too much unwanted-weed is produced as a consequence of low-till practices, chemical spray is needed, and this is legally-problematic), thus proposing a score of 1. Considering how both interviewees mentioned specific, different conflictual matters, the preliminary score of 0 is changed to 1 and is reported as somewhat uncertain.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated by all interviewees [a]

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) validated by all interviewees [a]

I-1 mentioned how agronomy practices only implement procedural changes and have no visible impact besides improved land yield.

C2 Disturbs regular operations - (p.s. = 0) changed to 1, significantly uncertain [g]

I-1 validated the preliminary score of 0, while I-2 mentioned how these agronomy practices lead to lower outputs-per-hectare, thus needing more land to maintain the same output (similar to organic agriculture). This disrupts the regular production, and thus I-2 proposed a score of 1. In the absence of a supporting argument for the score of 0, the preliminary score is changed to 1, reported as significantly uncertain.

C3 Technology uncertainty - (p.s. = 0) changed to 1, significantly uncertain [h]

I-1 validated the preliminary score of 0, mentioning how more biological-R&D can further improve products' performance, but the performance of available practices is fully proven. Instead, I-2 was critical with such practices, mentioning how the outcome is very location specific, and such practices might even have an undesirable impact on land yield, thus proposing a score of 2. To combine interviewees' arguments, the preliminary score of 0 is changed to the medium score of 1, which is reported as significantly uncertain.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated by all interviewees [a]

I-1 mentioned how all farmers around the world are aware of practices like adjusting crops' rotation to improve the land yield.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 1) validated by all interviewees [a]

I-1 remarked how some behavioral changes are needed, not directly related to the performance of new activities, but to a more regular performance of already-known activities, as crops' rotation. I-2 highlighted how some behavioral changes are needed for all new agricultural practices and are severely influenced by the common practices of the local community.

Cropland nutrient management

A. Cost and Financing

A1 Investment cost required – (p.s. = 0) considered validated, somewhat uncertain [d1]

Both interviewees were uncertain between a score of 0 or 1. I-1mentioned how slow-release fertilizers and nitrification inhibitors can cause slightly higher expenses than for common fertilizers. I-2 instead remarked how the investment-size depends on the crop and the cropland location. For instance, shifting from a dry fertilization to a fertigation system is a relatively high investment, especially for the small farmers, which is nevertheless much lower compared to the investment for other abatement option. In absence of a strong argument against it, the preliminary score of 0 is considered validated, but is reported as somewhat uncertain.

A2 Expected pay-back time - (p.s. = 0) validated by all interviewees [a]

I-1 commented how the proposed nutrients have neutral or positive impacts on the land yield, thus extra costs are quickly paid back, while I-2 highlighted how the investments is expected to have a return in terms of increased or more stable land yield, and benefits are visible in 1 year, especially in low-fertility areas.

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

I-2 mentioned how for decades there have often been subsidies from governments for the purchase and application of fertilizers, which take the burden of the costs.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 1) considered validated, significantly uncertain [h]

I-1 did not validate the preliminary score of 1, mentioning how farmers have direct oversight over the land they manage, either because they own it (most of cases) or because they live on it. Thus, they can adopt nutrient management practices without anyone stopping them, and thus proposed a score of 0. Instead, I-2 remarked how farmers are highly dependent on the fertilizers' suppliers: in Europe supply of fertilizer is reliable, but it is not so obvious in developing countries, where farmers are often dependent on price-taker and have no negotiating position, and was thus uncertain between a score of 1 or 2. To account for the very diverse opinions of the interviewees, the preliminary score of 1 is validated as a medium, as reported as significantly uncertain.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how some public complaints might arise from the use of certain fertilizers, as these might leach on dairy products. In New Zealand for instance, traces of nitrogen were found in milk. Similarly, I-2 highlighted the presence of conflicts related to the application of fertilizers with neighbors, who complain about the smell, the nitrate leaching, ground water pollution, etc.

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated, significantly uncertain [g]

I-1 validated the preliminary score of 1, remarking how some procedural clarifications are likely needed to introduce such relatively new practices. Instead, I-2 believes roles are clear, and proposed a score of 0. To solve the dilemma, the preliminary score of 1 is considered validated but reported as significantly uncertain.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) validated by all interviewees [a]

I-1 commented how the amount of used land remains the same and so does its purpose and output-type, thus there is no physical constraints. I-2 remarked how some irrigation system and tractors might be added to the landscape, but these do not seem to be contemplated by the definition of the abatement option.

C2 Disturbs regular operation - (p.s. = 0) validated by all interviewees [a]

I-1 remarked how operations are no disrupted because of the neutral or positive impacts of these practices on land yield, and new fertilizers can be applied without any preparation. I-2 commented how, thanks to higher yields, agricultural land can expand, and it is sometimes the case that roads need to be enlarged, thus causing some minor disruptions in the long term. Such disturbances are not expected in a short-term time period.

C3 Technology uncertainty - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how some slow-release fertilizers and nitrogen inhibitors have been used for enough time to be fully proven, while newer ones still require testing. Moreover, some more R&D is needed to eliminate small undesired leaches. I-2 commented how agricultural technology cannot ever be fully proven for its dependence on the location for factors like nitrate leaching and weather impact.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 2) changed to 1, significantly uncertain [h]

I-1 stressed the context dependency of this factor: in developed countries farmers are well aware of the negative impacts of nitrogenous fertilizers and of alternatives to reduce them, while in developing countries there is lack or no knowledge on the issue; thus, the score could variate between 0 and 2. I-2 did also not validate the preliminary score, mentioning how all farmers are aware of the beneficial effects of nutrient application, even in developing countries, thus proposing a score of 1. The preliminary score of 2 is thus changed to a score of 1, which is reported as significantly uncertain to highlight the context dependency suggested by I-1, as his score could assume all the three possible values.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 2) changed to 1 [b]

I-1 mentioned how some behavioral changes are needed as different fertilizers require different application-timing, and additional nitrogen inhibitors need to be applied. I-2 commented how agriculture is quite conservative: a farmer has only a maximum of 30 or 40 growing seasons in a lifetime (even less in developing countries), so experiments are not much welcomed. The reliable perspective of higher land yields can largely facilitate difficult behavioral changes.

Grassland management

A. Cost and Financing

A1 Investment cost required - (p.s. = 0) validated by all interviewees [a]

I-1 mentioned that the implementation of this abatement option mostly relies on the actions of pool-farmers in developing countries. Thus, there might be the need for extra land-tools, the price of which is modest. I-2 instead commented that the core concept is to manage differently the grassland, better coordinating actives already being performed (e.g.: fires to burn woody roots are already initiated by local farmers).

A2 Expected pay-back time - (p.s. = 0) validated by all interviewees [a]

Both interviewees mentioned the better land yields which can be quickly obtained.

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

I-1 remarked how the better yields make the modest, necessary expense attractive, while I-2 stressed how the is no real investment needed.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how the dependency can often be caused by the need of an irrigation system. I-2 instead remarked how much of the grassland is exploited by multiple users, as farmers belonging to the same consortium. Thus, changing management practices requires the collaboration with a few stakeholders.

B2 Diversity of actors involved incl. conflicts - (p.s. = 0) changed to 1, somewhat uncertain [f]

I-1 validated the preliminary score of 0, referring to the irrigation system mentioned under factor *B1*. I-2 instead highlighted how conflicts are likely to arise over crucial zones as shed areas and areas of common grazing, thus proposing a score of 1. Considering that much grassland is exploited by multiple users, the score proposed by I-2 is accepted as additional to what considered by I-1, and the preliminary score of 0 is changed to the score of 1, reported as somewhat uncertain.

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how roles are context specific, and thus need to be discussed.

C. Physical Interdependencies

C1 Physical embeddedness – (p.s. = 0) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 0, mentioning how there are no evident physical changes, with lands looking greener thanks to higher land productivity. Instead, I-2 remarked that practices such as fire management might affect the surrounding environment beyond intentions and proposed a score of 1. Given the possibilist character of I-2's argument and judging the spoiling of grassland with fire a highly unwanted event, the preliminary score of 0 is validated, and the reported as somewhat uncertain.

C2 Disturbs regular operations - (p.s. = 0) validated by all interviewees [a]

C3 Technology uncertainty - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, mentioning how management practices are climate-dependent, and are thus not proven in all situations. I-2 was uncertain between a score of 0 or a score of 1. In the absence of an argument to modify it, the preliminary score of 1 is considered validated.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) considered validated, significantly uncertain [h]

I-1 validated the preliminary score of 1, while I-2 stressed its context dependency, suggesting that the score can vary between a value of 0 and a value of 2. The preliminary score is reported as significantly uncertain.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 2) changed to 1, somewhat uncertain [f]

I-1 validated the preliminary score of 2, mentioning how land-management practices are passed down from one generation to the next, and it is thus difficult to modify such traditional habits. I-2 instead highlighted the minor behavioral changes needed, as people are always spontaneously taking care of the land they exploit and need, proposing a score of 1. The comment of I-1 is referring more to the difficulty of the changes, which are few according to I-2. Considering the clearly higher land-yields mentioned by both interviewees, it is expected that traditional practices could be abandoned for higher financial returns, probably the only acceptable motivation. The preliminary score of 2 is changed to the 1, reported as somewhat uncertain.

Reduced intensive agriculture conversion

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) validated, somewhat uncertain [d1]

Both interviewees were uncertain about the score: I-1 doubted between a score of 0 or 1, mentioning how the investment is modest and in the form of annual payments to protect areas from being run-over (monitoring costs). With a similar argument, and defining the investment as an opportunity cost, I-2 was doubting between a score of 1 or 2, considering the investment substantial. The two uncertainty intervals meet at the score of 1, which is also the preliminary assigned score, thus validated and reported as somewhat uncertain.

A2 Expected pay-back time - (p.s. = 2) validated by all interviewees [a]

Both interviewees mentioned how there is no ROI, as the money is invested in the wellbeing of the planet and does not have a financial return (I-2).

A3 Difficulty in financing the investment - (p.s. = 1) validated by all interviewees [a]

Both interviewees provided the same argument: the funds are provided by national governments and international organizations from developed countries. It is never easy to gather funds, but deforestation is a sensible topic, to which is easy to destine money as it is positively accepted by the public.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated by all interviewees [a]

Both interviewees highlighted the high number of institutions involved for the money distribution, as local and national governments, besides local populations.

B2 Diversity of actors involved incl. conflicts (p.s. = 2) validated by all interviewees [a]

I-1 remarked the higher difficulty of preventing an event to happen rather than implementing a new practice. I-2 stressed how local populations are impacted by the abatement option, rather than the organizations providing the funding: conflicts arise as the population needs to abandon a reliable source of income, possibly not trusting the governments responsible for the payment.

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how it is often clear what every actor should do, but national governments need to draft supporting regulations, which is problematic. I-2 instead mentioned how unclarities arise due to the many needed interactions amongst stakeholders.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 2) validated by all interviewees [a]

Both interviewees mentioned the drastic change in land usage and the consequent modification of its outlook as, instead of being converted to cropland, the forest is conserved. I-1 added there might be the need of fences and surveillance cameras for supervision.

C2 Disturbs regular operations - (p.s. = 2) validated by all interviewees [a]

Both interviewees commented that the conversion of forest to cropland is a practice which has been performed by many generations and has been providing the income to local communities; thus, preventing such practice causes disruptions.

C3 Technology uncertainty - (p.s. = 0) validated by all interviewees [a]

I-2 mentioned how there are no doubts on the carbon capture role of forests.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) considered validated, significantly uncertain [g]

I-1 did not validate the preliminary score of 1, mentioning how small land owners and local communities are not aware of the consequences of deforestation and thus proposing a score of 2. Instead, I-2 validated the preliminary score of 1, confirming how local populations have little knowledge about the CO_2 capture role of forests, but mentioning how programs for forest protection such as RED have been successfully implemented in the last decades and most people have heard about or have gotten paid by them. This argument is considered valid and exceeding the scope of the comments of I-1 and helps solving the dilemma: the preliminary score of 1 is validated but reported as significantly uncertain.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 2) validated by all interviewees [a]

I-1 used the same argument mentioned for the factor *C2*, and somewhat similarly I-2 commented that local populations have been living from farming for generations and stopping land conversion to agriculture not only disrupts operations but requires severe behavioral changes, as finding a new occupation.

Reduced deforestation from timber harvesting

A. Cost and Financing

A1 Investment cost required -(p.s. = 1) validated by all interviewees [a]

Both interviewees mentioned the need to compensate timber corporations for their lost revenues. I-2 specified that an initial investment is needed, which then transforms in annual payments.

A2 Expected pay-back time - (p.s. = 2) validated by all interviewees [a]

Both interviewees specified how there is not a financial return.

A3 Difficulty in financing the investment - (p.s. = 1) validated by all interviewees [a]

Each interviewee proposed the same argument presented under the factor *A3* for the abatement option [Forestry & Agriculture]: Reduced intensive agriculture conversion.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated by all interviewees [a]

Both interviewees highlighted the involvement of many national and local governments, and international organizations for the provision of funds, besides timber corporations.

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) validated by all interviewees [a]

I-1 remarked the conflicts always arising when trying to prevent an event from happening, while I-2 highlighted the large conflicts with timber corporations which loose, at least partially, a source of income or a profitable business model.

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated by all interviewees [a]

I-1 commented that what-to-do is clear, but local governments often lack the ability to organize regulations and funding. I-2 instead mentioned how roles and responsibilities are to be discussed, regardless the project specifics, because of the many parties involved.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 2) validated by all interviewees [a]

Both interviewees remarked the resulting different land-outlook, as the forest remains in place. I-1 added how fences and cameras might be needed for supervision.

C2 Disturbs regular operations - (p.s. = 2) validated by all interviewees [a]

Both interviewees highlighted how deforestation has been common practice for decades, and a reliable source of income for timber corporations and local communities.

C3 Technology uncertainty - (p.s. = 0) validated by all interviewees [a]

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) considered validated, significantly uncertain [h]

I-1 validated the preliminary score of 1, commenting how small land owners are not aware of the consequences of deforestation, but large timber corporations, the main perpetuators of deforestation, are. I-2 instead followed the same reasoning but chose to leave the score uncertain between a score of 0 and a score of 2, depending of the consideration of timber corporations or the local population, respectively. Thus, combining experts' arguments and the literature, the preliminary score of 1 is validated: financial payment seems to be a factor better able to prevent deforestation than knowledge of actors, and it is thus decided not to assign a high relevance to the factor D1. The score is reported as significantly uncertain as I-2's comment highlights the dependency of the factor, which could assume all scores; this argument is addressed in the following *Reflection* paragraph.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 2) validated by all interviewees [a]

I-1 remarked how timber companies need to abandon their proved "cut and leave it" business model, embracing sustainable forestry, for instance following the Swedish and Canadian models. I-2 commented how timber has been produced for the mass market for decades, and that a less-intensive timber production not only forces timber corporations to adapt their business models but might require a modification of timber demand on the market.

4.3.5 Fuels

Bioethanol lignocellulosic

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) changed to 1, significantly uncertain [g]

I-2 validated the preliminary score, while I-1 mentioned how second-generation biofuels can also be produced on a small scale, and thus it is not needed to change the whole supply chain, thus proposing a score of 1. In the absence of an opposite argument, the preliminary score is arbitrary changed to 1 and reported as significantly uncertain for the sake of transparency.

A2 Expected pay-back time - (p.s. = 1) changed to 2, somewhat uncertain [f]

While I-2 validated the preliminary score of 1, I-2 provided some specific figures: the production cost of diesel is below 0.6 $/L, and both primary and secondary ethanol are expected to cost more than diesel if oil prices remain in the common 60-70$/barrel price range. Thus, mentioning how no investment pay-back is to be expected, I-1 proposed a score of 2. Considering the more quantitative character of I-1's argument compared to I-2's subjective estimate, the preliminary score is changed to 2 and is reported as somewhat uncertain, as the two experts did not agree but a dominant argument was found.

A3 Difficulty in financing the investment - (p.s. = 1) considered validated, significantly uncertain [h]

I-1 remarked the uncertainties characterizing the biofuels market, especially in Europe, where negative experiences with primary biofuels are influencing; thus, I-1 proposed a score of 2. Instead, I-2 believes second-generation biofuels to be considered promisingly able to improve the sustainability of the crucial transport sector and was thus undecided between a score of 0 or 1. Combining experts' arguments, the preliminary score of 1 is validated, and reported as significantly uncertain.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) considered validated [c]

Both interviewees mentioned how the whole fuels value chain is involved for implementing this abatement option on a large scale, but a single producer can start dropping biofuel on the market although; the dropped amount needs to be carefully monitored to avoid damaging vehicles' performances, and thus coordination amongst actors is required. Both experts were uncertain between a score of 1 or 2; in the absence of a strong score against it, the preliminary score of 2 is validated.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) considered validated [c]

I-2 mentioned how second-generation biofuels are still competing for land usage with other agricultural products, although much less than primary-biofuels, thus being uncertain between a score of 0 or 1. I-2 highlighted the rather diffused acceptance towards second-generation biofuels for their higher sustainability compared to primary biofuels, with some tensions arising between the environmental and the transport sectors; I-2 thus validated the score of 1, not considering Mexico, for its specifically negative policy against bioethanol. Thus, in absence of a strong argument against it, the preliminary score of 1 is validated.

B3 Division of roles and responsibilities- (p.s. = 1) validated, somewhat uncertain [f]

I-1 mentioned how responsibilities are clear, as they do not need to be adapted, if the percentage of biofuels in regular diesel remains in the current, feasible range of 10-20%, thus proposing a score of 0. Instead, I-2 validated the preliminary score of 1, remarking how second-generation biofuels are not being extensively discussed, which causes responsibilities to be much less clear than for innovations in other sectors (e.g.: EVs in the transport sector). The 10-20 % range is currently feasible but will probably increase if a large diffusion of biofuels happens; hence, the preliminary score of 1 is considered validated, and reported as somewhat uncertainty to account for the diversity of experts' opinions.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) validated by all interviewees [a]

I-2 remarked that the production of second-generation biofuels requires new technologies, and some planning for implementing some physical changes (e.g.: plantation of algae); these should nevertheless be minor, thanks to the high efficiency of the materials.

C2 Disturbs regular operations - (p.s. = 2) changed to 1, significantly uncertain [g]

I-2 validated the preliminary score of 2, highlighting how the production of second-generation bioethanol requires new production processes, thus disrupting the ones of primary-biofuels. Instead, I-1commented how vehicles' drivers witness no disruption of operations, which instead can be experienced by biofuels producers, thus proposing a score of 1. The key challenge is to identify which of the arguments is more aligned with *Scope 1 (section 4.1)*: are the producers or the vehicles' drivers who can chose to purchase it the actors most responsible for the implementation of bioethanol? In the absence of a clear answer to this interrogative, drivers are considered responsible, for similarity with the analysis of EVs (*section 4.3.8)*. Hence, the preliminary score of 2 is changed to a score of 1, reported as significantly uncertain.

C3 Technology uncertainty - (p.s. = 1) changed to 2, somewhat uncertain [d1]

I-2 mentioned how the technology is not proven on a large scale, thus being uncertain between a score of 1 or 2. I-2 instead remarked that most bioethanol production technologies are still being researched and are not yet ready for market introduction, proposing a score of 2. The preliminary score is changed to a score of 2, reported as somewhat uncertain.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) validated by all interviewees [a]

D2 Frequency of opportunity – (p.s. = 2) changed to 1 [b]

The preliminary score of 2 is changed to 1, as proposed by both interviewees. I-1 mentioned how it is possible to start dropping second-generation biofuels in the produced benzine in progressively higher percentages, without having to wait for the release of new cars running on bioethanol.

D3 Requires change in behavior - (p.s. = 1) validated by all interviewees [a]

4.3.6 Household Changes

Lighting switch incandescent to LED (residential)

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) validated by all interviewees [a]

I-1 mentioned how the current cost of an LED is approximately 10 €.

A2 Expected pay-back time - (p.s. = 0) validated by all interviewees [a]

I-1 commented that LEDs currently pay-back their extra costs in less than a year.

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

Both interviewees mentioned how the cost of LEDs are accessible to most people.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 0) validated by all interviewees [a]

I-1 remarked how the offer of LEDs on the market is abundant.

B2 Diversity of actors involved incl. conflicts - (p.s. = 0) validated by all interviewees [a]

Both interviewees mentioned how a buyer does not have to necessary interact with any other actor for purchasing and installing an LED.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated by all interviewees [a]

C. Physical Interdependencies

C1 Physical embeddedness – (p.s. = 1) changed to 0 [c]

I-1 remarked that when first introduced on the market, LEDs emitted a bluer light than incandescent bulbs, but now all desirable colors are available, and they do not have any start-up times. Thus, I-1 proposed a score of 0. I-2 mentioned the same argument and was uncertain between a score of 0 or 1. Combining the comments of the two interviewees, the preliminary score of 1 is changed to a score of 0.

C2 Disturbs regular operations - (p.s. = 0) validated by all interviewees [a]

Both interviewees mentioned how installation times are very short.

C3 Technology uncertainty - (p.s. = 0) validated by all interviewees [a]

D. Behavior

D1 Absence of knowledge of actors – (p.s. = 1) considered validated, somewhat uncertain [f]

I-2 did not validate the preliminary score of 1, mentioning how LED technology has become rather mainstream by now, with people being aware of its lower consumptions, thus proposing a score of 0. Instead, I-1 validated the preliminary score of 1, mentioning how people are used to Watts, and not to Lumen (600 Lm = 40 W) and that the desired brightness and colors need to be known for the purchase. While LEDs have indeed been on the market for a few years and are thus rather popular, their technical specifications mentioned by I-1 are considered to be unknown to most, and can become an obstacle to the purchase, as such information are needed for the selection. Moreover, LEDs are much less known than the most popular incandescent bulbs, which should be the reference as commanded by *Scope 2* (*section 4.3)*. Thus, it is decided to validate the preliminary score of 1 and report it as somewhat uncertain.

D2 Frequency of opportunity - (p.s. = 0) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 0) considered validated, somewhat uncertain [f]

I-2 validated the preliminary score of 0. Instead, I-1 highlighted the multiple factors which need to be considered when selecting and purchasing the adequate LED and was thus uncertain between a score of 1 or 2. While the different information needed for the purchase is an existing obstacle, it is of short duration and does not affect the usage of the LED by the buyer. Thus, the preliminary score of 0 is considered validated, but is reported as somewhat uncertain to highlight the different interviewees' opinions.

Residential Appliances

Definition issues: There are two main themes for Residential appliances: efficiency and smartness. Both interviewees specified how energy-efficient appliances are already vastly available on the market, but smart appliances are currently only very high-end ones. Smartness will be the key point in the very near future, enabling further energy-efficiency. Thus, the discussion focused on smart, energy-efficient appliances.

A. Cost and Financing

A1 Investment cost required – (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, mentioning how the energy-efficient appliances are expensive (e.g.: a refrigerator of energy class A++ can be 50% more expensive than one of class A+) but already constitute the majority of current residential appliances, and that the smart component might only increase the costs of 5%. Thus overall, there is a little investment needed. I-2 was instead uncertain between a score of 1 or 2, remarking how depending on the appliance, structural modification to the household (e.g.: walls and electricity network) might be needed. Thus, in the absence of a strong argument to change it, the preliminary score of 1 is validated.

A2 Expected pay-back time - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, nevertheless commenting that different field tests (especially in the UK) show very diverging results, some recording savings and others which do not. I-2 mentioned how the pay-back time very much depends on the consider appliances, but it is surely below 12 years, and was thus uncertain between a score of 0 or 1. Thus, combining experts' arguments, and in the absence of a strong argument to change it, the preliminary score of 1 is validated.

A3 Difficulty in financing the investment - (p.s. = 1) considered validated [c]

I-1 reported how the extra cost of smart residential appliances is very limited compared to the currently installed one, already energy-efficient, and was thus doubting between a score of 0 or 1. Instead, I-2 validated the preliminary score of 1, mentioning the importance of subsidy plans, which vary country-per-country. Thus, in the absence of a strong argument to change it, the preliminary score of 1 is validated.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) changed to 1 [b]

The interviewees highlighted the high-level of automation of the appliances. Stakeholder interdependencies are a topic relevant for the supporting data-network, but are not experienced by households' dwellers, the ones buying and thus implementing the appliances, which is the perspective specified by *Scope 1* (*section 4.3*). Both interviewees proposed a score of 1, to which the preliminary score is thus changed.

B2 Diversity of actors involved incl. conflicts – (p.s. = 2) changed to 1, somewhat uncertain [f]

I-1 highlighted the data-privacy issues related to smart, energy-efficient residential appliances, and how their relevance is depended on personal values and the trust in the parties responsible for the data-management;

thus, I-1 was uncertain between a score of 1 and 2. Instead, I-2 mentioned how people installing the appliances in their households do not interface with the supporting data-network system, which is managed by e.g.: aggregators and vendors, thus proposing a score of 0. While the perspective suggested by I-2 is aligned with the one presented in *Scope 1* (*section 4.1*), and people who install autonomous residential appliances are not interfacing with the supporting background network, they are aware of the need for data, which creates conflicts depending on the personal values, as mentioned by I-1 and highlighted in the literature review. The preliminary score of 2 is changed to the score of 1, reported as somewhat uncertain.

B3 Division of roles and responsibilities unclear - (p.s. = 1) changed to 0 [e]

I-1 validated the preliminary score of 1, mentioning how stakeholders, although very experienced, have to adapt to a new concept of residential appliances' usage, and thus a few new responsibilities need to be re-defined. I-2 instead repeated the suggestion to only focus on the buyers' perspective, who can simply purchase and install appliances which automatically reduce their energy consumptions, thus proposing a score of 0. Considering how the reasoning of I-2 is better aligned with the perspective of *Scope 1 (section 4.3)*, the preliminary score of 1 is changed to the score of 0.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) considered validated [c]

I-1 validated the preliminary score of 0, while I-2 highlighted how the score is dependent on the type of appliance considered, as some of these, like an autonomous heating system, might require substantial physical changes to the walls and electricity network, and thus doubting between a score of 0 of 1. Thus, in the absence of a strong argument to change it, the preliminary score of 0 is validated.

C2 Disturbs regular operations - (p.s. = 1) considered validated, somewhat uncertain [f]

I-1 did not validate the preliminary score of 1, mentioning how the connection of new appliances to the network should not cause disruptions and proposing a score of 0. Instead, I-2 validated the preliminary score, mentioning how the connection with the network is not immediate, especially for appliances such as autonomous heating which have longer installation times due to supporting works (e.g.: wall and electricity network adaptation). Systemic appliances such as an autonomous heating were not considered in I-1's reasoning but have longer installation times than self-standing appliances such as a dishwasher (I-2). Undeniably, the installation of a residential appliances takes longer than the installation of a LED, to which a score of 0 was assigned for the factor *C2*. Thus, it is decided to consider validated the preliminary score of 1, which is reported as moderately uncertain.

C3 Technology uncertainty - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1. I-2 was uncertain between a score of 0 and 1, mentioning how thanks to huge technological improvements the functioning of efficient and smart appliances is now fully proven; technological uncertainties are related to macro-systems, like smart-grid, which might be necessary for the functioning of appliances. Thus, in absence of a strong argument to change it, the preliminary score of 1 is considered validated.

D. Behavior

D1 Absence of knowledge of actor - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, while I-2 was uncertain between a score of 0 referring to those working in the smart appliances' industry and a score of 1 referring to the population responsible for the purchase of the appliances. Thus, in the absence of a strong argument against it, the preliminary score of 1 is considered validated.

D2 Frequency of opportunity - (p.s. = 1) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 2) changed to 1, significantly uncertain [h]

I-1 validated the preliminary score of 2, mentioning how smart appliances will require severe behavioral changes related to the different operation-periods of appliances. I-2 instead raised a philosophical issue, highlighting how the score depends on the definition of behavioral changes: having the washing machine running at 8 am or 8 pm should not be philosophically considered a severe behavioral change, as well as an automatic heating does not require behavioral changes. Moreover, I-2 specified that if behavioral changes were to be excessively large, people would not implement them and such appliances would have not been developed; thus, I-2 was uncertain between a score of 0 and 1. Considering the strong argument against the preliminary score of 2 by I-2, and the predictive more than factual character of the remarks of I-1, the preliminary score of changed to 1, a medium which matches the perspectives of the two interviewees; to transparently report this arbitrary argument, the score is reported as significantly uncertain.

4.3.7 Industrial Processes

Clinker substitution by fly ash*

A. Cost and Financing

A1 Investment cost required - (p.s. = 0) validated, somewhat uncertain

I-1 was uncertain between a score of 0 or 1, mentioning how it depends on the project size. Thus, in the absence of a strong argument against it, the preliminary score of 0 is considered validated.

A2 Expected pay-back time - (p.s. = 0) validated, somewhat uncertain

A3 Difficulty in financing the investment - (p.s. = 0) validated, somewhat uncertain

I-1mentioned how considering the little investment and short payback times, investments should be easy to finance.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated, somewhat uncertain

I-1 highlighted the dependence on parties able to supply fly ash and/or other CSMs as slag, with which there is the need to establish long term contracts.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) validated, somewhat uncertain

I-1 remarked the country-dependency of the score, as in some countries cement with additives might be considered as not qualitative (e.g.: in India, ads celebrating the purity of "real Portland cement, without waste products") and create conflicts.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated, somewhat uncertain

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) validated, somewhat uncertain

I-1 highlighted the changes caused by the needed new transportation system for CSMs, which is at times avoided by building cement-producing companies directly next to steel plants (e.g.: blast furnace of steel companies has slag as by-product).

C2 Disturbs regular operations - (p.s. = 1) validated, somewhat uncertain

C3 Technology uncertainty - (p.s. = 1) changed to 0, somewhat uncertain

I-1 did not validate the preliminary score of 1, mentioning how the technology for substituting clinker with slag is clear and the most popular, but there is uncertainty about procedures with other substitutes as fly ash.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated, somewhat uncertain

D2 Frequency of opportunity - (p.s. = 0) validated, somewhat uncertain

D3 Requires change in behavior - (p.s. = 1) validated, somewhat uncertain

I-1 stressed how the usage of products in the cement-mix is completely different, and thus requires some procedural changes.

Energy efficiency 1 Iron & steel*

A. Cost and Financing

A1 Investment cost required – (p.s. = 2) validated, somewhat uncertain

I-1 mentioned how individual projects have large investments, which should be classified as medium in terms of €/tCO_2 avoided.

A2 Expected pay-back time - (p.s. = 0) validated, somewhat uncertain

I-1 remarked how all projects must have short investment pay-back times to be successful, because of the difficulty of financing investments in the IS industry.

A3 Difficulty in financing the investment - (p.s. = 2) validated, somewhat uncertain

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 0) validated, somewhat uncertain

B2 Diversity of actors involved incl. conflicts – (p.s. = 1) validated, somewhat uncertain

I-1 mentioned how Iron & Steel (IS) companies are large and international, and are working via complex decision-making processes, thus it is common to have internal conflicts.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated, somewhat uncertain

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) validated, somewhat uncertain

C2 Disturbs regular operations – (p.s. = 1) validated, somewhat uncertain

I-1 reported how processes need to be paused to implement technical and procedural changes in IS plants, as these are operating 24/hours per day.

C3 Technology uncertainty - (p.s. = 1) validated, somewhat uncertain

I-1 remarked how the technology might be fully proven but there is often a perceived risk associated to energy-efficient procedures.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated, somewhat uncertain

D2 Frequency of opportunity - (p.s. = 1) validated, somewhat uncertain

I-1 highlighted how every 3 to 4 years IS plants must be closed and revisited, which allows for substantial process modifications.

D3 Requires changes in behavior - (p.s. = 0) validated, somewhat uncertain

4.3.8 Vehicles

Air transport*

Definition issues: The interviewee remarked how the definition of the abatement option "Air transport" contains different abatement options, namely "Operational efficiency (OE)" (cheap) and "Alternative fuels (AF)" (expensive), which were thus discusses separately; this led to assigning two scores to each factor, depending on the considered definition (see *Appendix F)*. As under-estimations are considered more problematic than over-estimations, the highest of the two scores was considered as final value.

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) changed to 1, somewhat uncertain

I-1 was uncertain between a score of 0 or 1 considering OE, while for AF no investment is required (score of 0), but price of alternative fuel (production cost and market price) are higher than for conventional fuels and should be considered. Preferring over to under -estimation, the preliminary score of 2 is changed to 1.

A2 Expected pay-back time - (p.s. = 2) changed to 0, somewhat uncertain

A3 Difficulty in financing the investment - (p.s. = 2) changed to 0, somewhat uncertain

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) changed to 1, somewhat uncertain

OE: There is the need for cooperation with air traffic control, airports, etc.

AF: There is the need to rely on fuel suppliers.

B2 Diversity of actors involved incl. conflicts - (p.s. = 2) changed to 0, somewhat uncertain

B3 Division of roles and responsibilities unclear - (p.s. = 2) changed to 0, somewhat uncertain

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) changed to 1, somewhat uncertain

AF: Some physical changes are necessary for creating an alternative fuels infrastructure.

C2 Disturbs regular operations - (p.s. = 1) changed to 0, somewhat uncertain

OE: System operations must be changed, thus disrupting previous ones.

C3 Technology uncertainty - (p.s. = 2) changed to 1, somewhat uncertain

OE: Uncertainty regarding the ability of ensuring safety with new operational models.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) changed to 0, somewhat uncertain

D2 Frequency of opportunity - (p.s. = 1) changed to 0, somewhat uncertain

D3 Requires change in behavior - (p.s. = 0) changed to 1, somewhat uncertain

Behavioral changes are automatically enforced when implementing a new OE-models.

Battery electric vehicles

A. Cost and Financing

A1 Investment cost required - (p.s. = 2) changed to 1, somewhat uncertain [f]

I-1 validated the preliminary score of 2, mentioning how BEVs are currently very expensive but are expected to become sensibly cheaper in the next 5-10 years, with the score consequently moving towards the value of 1. I-2 instead answered with the example of the Nissan LEAF, the first BEV having competitive market price (about 25,000 $) and just released in 2018, thus proposing a score of 1. Considering the example mentioned by I-2, and the considerations of I-1 regarding a very near future, it is decided to change the preliminary score of 2 to the score of 1, reported as somewhat uncertain.

A2 Expected pay-back time - (p.s. = 1) considered validated, somewhat uncertain [f]

I-2 highlighted how savings from reduced fuel costs are not sufficient to substantially decrease pay-back times because of the large investment and proposed a score of 2. Instead, I-2 mentioned how the pay-back time depends on the oil price and vehicle usage, but should nevertheless not exceed 7-8 years, thus being uncertain between a score of 0 and 1.Considering the price of the newly released Nissan LEAF, much lower than previously available BEVs, and the expected release of more models with a competitive price, it is decided to validate the preliminary score of 1, to combine experts' opinions. To transparently report this arbitrary synthesis, the score is reported as somewhat uncertain.

A3 Difficulty in financing the investment - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, mentioning how many people are not able to afford the extra-cost of BEVs, which is instead not a problem for richer people, and thus 1 is an average score. I-2 highlighted how there are often incentives encouraging the purchase of EVs (as for the HEV Toyota Prius a few years back), which are country-specific, and was thus uncertain between a score of 0 or 1. In the absence of a strong argument against it, the preliminary score of 1 is considered validated.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 1) changed to 2 [b]

The two interviewees did not validate the preliminary score of 1. I-1 highlighted the relevance of the supporting recharging infrastructure, causing large dependence of BEVs' owners on the parties providing the infrastructure, not just nationally but also across border for holidays. A similar argument was mentioned by I-2, who metaphorically compared the situation to the chicken-egg dilemma: should BEVs or the charging infrastructure be implemented first? Both interviewees proposed a score of 2, accepted as final score.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) changed to 0 [b]

I-1 highlighted the popularity of BEVs and proposed a score of 0. Similarly, I-2 mentioned how background conflicts involving industrial lobbies exist, but these do not involve the population, on which the score should be focusing (*Scope 1, section 4.1*). The score of 0 proposed by both interviewees is validated.

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated by all interviewees [a]

Both interviewees highlighted how there are uncertainties related to the management and usage of the charging infrastructure.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, mentioning the environmental changes caused by charging stations and by some of the parking spots becoming reserved to BEVs, to which also I-2 referred, doubting between a score of 1 or 2. In the absence of a strong argument against it, the preliminary score of 1 is validated.

C2 Disturbs regular operations - (p.s. = 0) validated by all interviewees [a]

C3 Technology uncertainty - (p.s. = 2) changed to 0 [b]

The two interviewees did not validate the preliminary score of 2, both mentioning how range limitation should not be considered a technological uncertainty, as it is known beforehand and it is rather an implication of the technology. Both interviewees proposed a score of 0, which is accepted as final score.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 1) validated by all interviewees [a]

I-1 described the score of 1 as "Little" rather than "Low", adding how, for instance, garage-workers are trained to deal with the technology of a BEV, but still lack specific knowledge (e.g.: battery of BEVs on sales left discharged).

D2 Frequency of opportunity - (p.s. = 1) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 1) changed to 2, somewhat uncertain [f]

I-1 validated the preliminary score or 1, mentioning how range anxiety is more of an issue for BEVs than for ICE vehicles. Instead, I-2 proposed a score of 2, stressing the relevance of range anxiety for BEVs. Range anxiety and the consequently required planning are very relevant challenges for BEVs, as highlighted by the literature and especially comparing them to PHEVs: the latter can be used for short travels without electric power, while BEVs cannot function without electric-power, making range anxiety clearly a more relevant issue than for PHEVs. Thus, the preliminary score of 1 is changed to the score of 2, reported as somewhat uncertain.

Cars full hybrid

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, while I-2 mentioned how HEVs are only slightly more expensive than normal ICE vehicles and was thus doubting between a score of 0 or 1. Thus, in absence of a strong argument to change it, the preliminary score of 1 is validated.

A2 Expected pay-back time - (p.s. = 1) validated by all interviewees [a]

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

I-1 commented that the overall extra cost for purchasing an HEV are modest compared to the costs of a normal ICE vehicle; I-2 instead mentioned how frequently are HEVs being leased, just like ICEs, and how thus financing is not an issue.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 0) validated by all interviewees [a]

I-1 mentioned how HEVs can be easily purchased at any dealer shop. I-2 highlighted how the interdependencies with other actors are null, as HEVs do not need a special recharging infrastructure for functioning, as it happens for BEVs.

B2 Diversity of actors involved incl. conflicts - (p.s. = 0) validated by all interviewees [a]

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated by all interviewees [a]

I-2 mentioned how roles and responsibilities are clear thanks to the similarities of HEVs to ICEs, as the former are not reliant on an electric engine.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 0) validated by all interviewees [a]

C2 Disturbs regular operations - (p.s. = 0) validated by all interviewees [a]

C3 Technology uncertainty - (p.s. = 0) validated by all interviewees [a]

I-1 remarked how the technology is fully proven after 20 year of experience.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 0, while I-2 argued how people are not much aware of HEVs and their functioning and that they also are not interested in knowing, thus proposing a score of 2. Such score is conflicting with the opinion of I-1, who mentioned how HEVs have been on the market for 20 years, and the figures found in the literature, reporting for instance a 12% yearly increase of HEVs on the Dutch market (Cbs, 2018). For these reasons, the preliminary score of 0 is validated, but it is reported as somewhat uncertain for the sake of transparency.

D2 Frequency of opportunity [- (p.s. = 1) validated by all interviewees [a]

Both interviewees mentioned how the frequency of opportunity is to be related to the frequency of purchasing an ICE vehicle, as the two technologies are alternative. I-1 mentioned how on average, a person purchases a car every 5-10 years.

D3 Requires change in behavior - (p.s. = 0) validated by all interviewees [a]

Cars plug-in hybrid

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) considered validated [c]

I-1 validated the preliminary score of 1, while I-2 judged the additional investment for a PHEV vehicle to be only marginally higher than the one for an ICE vehicle or an HEV and was thus uncertain between a score of 0 or 1. In the absence of a strong argument against it, the preliminary score of 1 is validated.

A2 Expected pay-back time - (p.s. = 1) validated by all interviewees [a]

A3 Difficulty in financing the investment - (p.s. = 0) validated by all interviewees [a]

I-1 remarked the modest extra cost compared to an HEV, and I-2 highlighting the ease in finding leasing programs supporting the purchase of PHEV.

B. Multi-actor complexity

B1 Dependence on other actors - (p.s. = 1) validated by all interviewees [a]

Both interviewees highlighted the dependence of PHEVs' owners on the electric charging infrastructure. I-1 expects the infrastructure to become more reliable in the future, but it is still being built.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) validated by all interviewees [a]

I-2 mentioned the many interfaces between the electric core of the vehicles and all other systems typical of an ICE vehicle, which require the compatibility of different technical components and stakeholders having to agree on common standards.

B3 Division of roles and responsibilities - (p.s. = 1) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 1 and mentioned how the main unclarities relate to which party is responsible for the development of the charging infrastructure, but that it is nevertheless possible to continue driving PHEVs also with a limited availability of recharging points. Instead, I-2 mentioned the many new technical interfaces of components with the electric core of the vehicles, causing unclarities and doubts which need to be coherently solved, and thus proposed a score of 2. While accurate, I-2's argument is referring to issues of technical compatibility, relevant in the design phase but not directly related to the roles of the different stakeholders in the implementation of PHEVs. Thus, the preliminary score of 1 is considered validated, and is reported as somewhat uncertain.

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) validated by all interviewees [a]

I-2 highlighted the changes brought by the needed charging infrastructure.

C2 Disturbs regular operations - (p.s. = 0) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 0. Instead, I-2 remarked how charging times create disruptions to the regular daily planning, thus proposing a score of 1. While valid, this argument is not aligned with the scope of the factor, which is defined as referring to disruptions caused by the implementation of the abatement options, in this case referring to the installation of charging stations; the argument rather refers to behavioral changes in the daily operations of people, who are impacted by charging times. Thus, the preliminary score of 0 is validated, and reported as somewhat uncertain.

C3 Technology uncertainty - (p.s. = 1) changed to 0 [c]

I-1 validated the preliminary score 1, mentioning how further technological developments are still needed to increase the effectiveness of PHEV technology. Instead, I-2 judged the technology to be fully proven and proposed a score of 0. The arguments used to assign the preliminary score and by I-1 are mostly referring to the limited availability of charging infrastructure, leading to the questioning of the societal feasibility of the PHEV technology. Instead, I-2 refers more directly to the functioning of the PHEV technology, as I-1 also did during a different interview BEVs. Thus, it is decided to consider the different scores to be caused by a difference in approach, and the preliminary score of 1 is changed to the score of 0. This is not reported as uncertain given how I-1 assigned a score of 0 to the factor *C3* for the abatement option [Vehicle]: Battery electric vehicles.

D. Behavior

D1 Absence of knowledge of actors – (p.s. = 0) changed to 1, significantly uncertain [h]

I-1 validated the preliminary score of 0, while I-2 remarked how only those people with sufficient money are aware of PHEVs and thus able to purchase them, and was uncertain between a score of 1 or 2. PHEVs have been present on the market for about 10 years as reported by the literature, but the financial barrier can lead some social classes to contrast the plug-in hybrid technology, as mentioned by I-2. Thus, it is decided to change the preliminary score of 0 to the score of 1, a medium able to combine interviewees' opinions, and to report the score as significantly uncertain.

D2 Frequency of opportunity - (p.s. = 1) validated by all interviewees [a]

D3 Requires change in behavior - (p.s. = 1) considered validated, somewhat uncertain [f]

I-1 validated the preliminary score of 1, while I-2 mentioned the problem of range anxiety and its implications, proposing a score of 2. While range anxiety is one of the most discussed problems for all electric vehicles, PHEVs can function for short ranges without electricity, thus reducing the relevance of range anxiety and the behavioral changes it requires. The preliminary score of 1 is validated and reported as somewhat uncertain.

4.3.9 Waste

Composting new waste*

A. Cost and Financing

A1 Investment cost required - (p.s. = 1) validated, somewhat uncertain

A2 Expected pay-back time - (p.s. = 1) validated, somewhat uncertain

A3 Difficulty in financing investment - (p.s. = 1) changed to 0, somewhat uncertain

I-1 characterized the composting procedures as relatively common and, also considering the limited investment required, proposed a score of 0.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 1) changed to 2, somewhat uncertain

I-1 highlighted the need for municipalities to have an adequate recycling system in place, and to sell the produced compost. Moreover, a qualitative collection of waste relies on the actions of the population, and thus proposed a score of 2.

B2 Diversity of actors involved incl. conflicts - (p.s. = 0) changed to 1, somewhat uncertain

I-1 remarked how some conflicts are likely to arise given the many actors involved, proposing a score of 1.

B3 Division of roles and responsibilities unclear - (p.s. = 0) validated, somewhat uncertain

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) validated, somewhat uncertain

C2 Disturbs regular operations - (p.s. = 0) changed to 1, somewhat uncertain

I-1 remarked the importance of changing the waste-separation process performed by individuals which is challenging change but nevertheless not drastic, thus proposing a score of 1.

C3 Technology uncertainty - (p.s. = 0) validated, somewhat uncertain

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated, somewhat uncertain

D2 Frequency of opportunity - (p.s. = 1) changed to 0, somewhat uncertain

I-1 highlighted how policy-decisions for recycling and waste composting can be taken anytime, thus proposing a score of 0.

D3 Requires change in behavior - (p.s. = 1) validated, somewhat uncertain

Electricity from landfill gas*

Definition issues: The interviewee highlighted how this technology is not so popular anymore, as it is normally preferred to collect and upgrade the collected landfill gas to use it as regular gas.

A. Cost and Financing

A1 Investment cost required- (p.s. = 2) validated, somewhat uncertain

I-1 mentioned how the generators are not expensive, but the pipes needed to recover the gas are.

A2 Expected pay-back time – (p.s. = 2) changed to 1, somewhat uncertain

Differently from what expected by the interviewee, the cost displayed by McKinsey's MAC is negative. Thus, instead of assigning a score of 2, the interviewee suggested a score of 1.

A3 Difficulty in financing the investment - (p.s. = 1) validated, somewhat uncertain

I-1 remarked how it is always easier to finance a 600 MW wind farm than a small-scale landfill project, as the former is more impactful.

B. Multi-actor Complexity

B1 Dependence on other actors - (p.s. = 2) validated, somewhat uncertain

I-1 remarked how the operator of the power plant at the landfill site and the owner of the landfill site do not necessarily coincide.

B2 Diversity of actors involved incl. conflicts - (p.s. = 1) validated, somewhat uncertain

B3 Division of roles and responsibilities unclear - (p.s. = 1) validated, somewhat uncertain

C. Physical Interdependencies

C1 Physical embeddedness - (p.s. = 1) validated, somewhat uncertain

C2 Disturbs regular operations - (p.s. = 0) validated by the only interviewee

I-1 reported how, depending on the dimension of the landfill, part of it might be emptied to install the needed infrastructure, but no regular process needs to be discontinued.

C3 Technology uncertainty - (p.s. = 1) changed to 0, somewhat uncertain

I-1 specified how the burned landfill gas still contains a bit of CO_2 and Methane, but it is less than 1% of the original amount. Moreover, landfill gas is biogenic (produced by organic organisms), and thus its emissions "do not count". Thus, I-1 proposed a score of 0.

D. Behavior

D1 Absence of knowledge of actors - (p.s. = 0) validated, somewhat uncertain

D2 Frequency of opportunity - (p.s. = 1) validated, somewhat uncertain

I-1 mentioned how the needed infrastructure can be retrofitted on existing landfills, but it needs to be installed swiftly once landfill begins operations to maximally exploit the produced gas, as gas production decays over time.

D3 Requires change in behavior - (p.s. = 0) validated, somewhat uncertain

4.4 Validated Y-curve

The previous section presented the scores' validation process, synthesizing the opinions of multiple experts on each of the preliminary assigned scores and transforming them into validated scores. In this section, the validated scores are displayed together: first graphically, divided in the four categories *Cost and Financing*, *Multi-actor Complexity*, *Physical Interdependencies*, and *Behavior*; then in a table which shows their uncertainty, sums them as in in the research of Chappin (2016) to obtain the final Y-value of each abatement options and ranks them; and finally the ranked Y-values are graphically compared, forming the validated Y-curve.

Figure 12: Validated scores - A - Cost and Financing

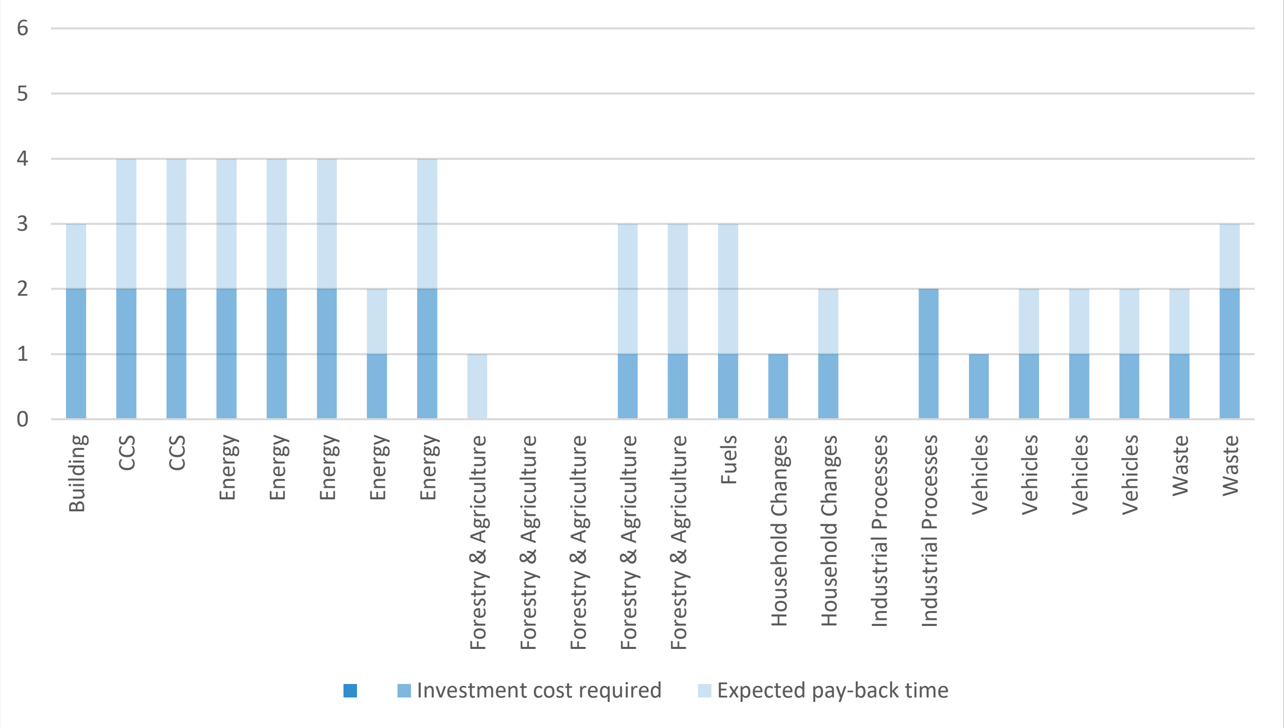


Figure 13: Validated scores - B - Multi-actor Complexity

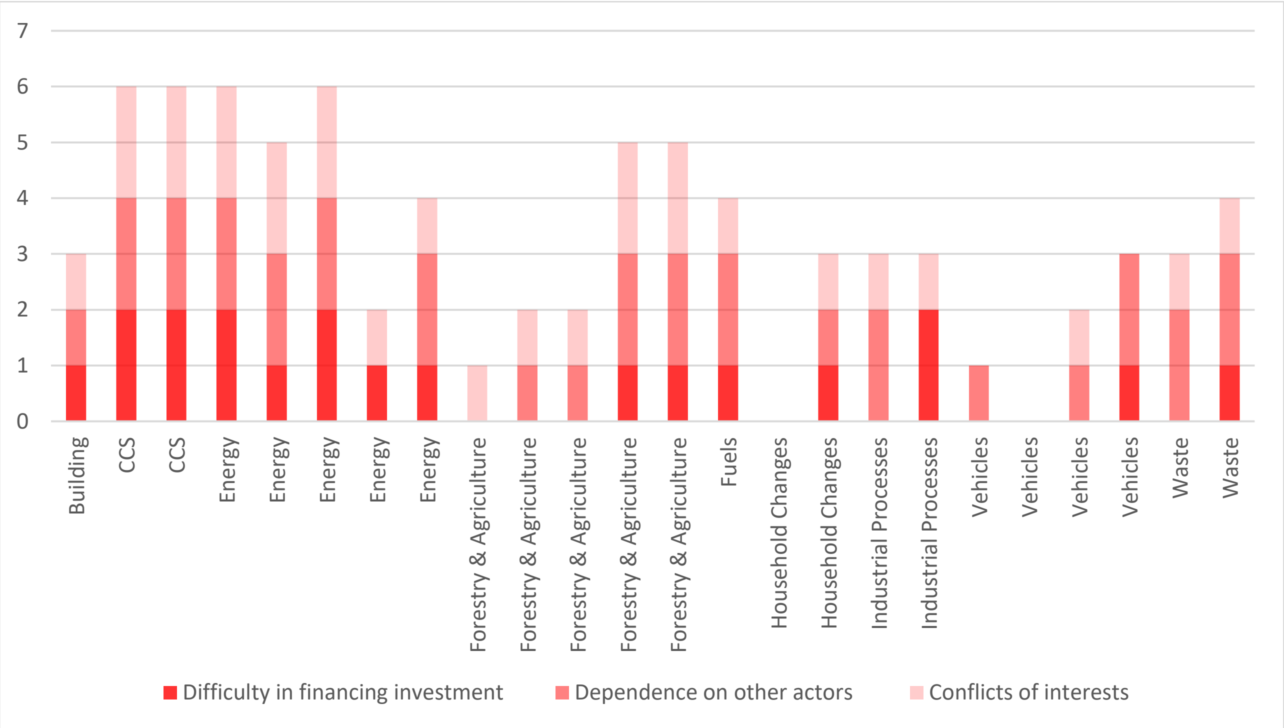


Figure 14: Validated scores - C - Physical Interdependencies

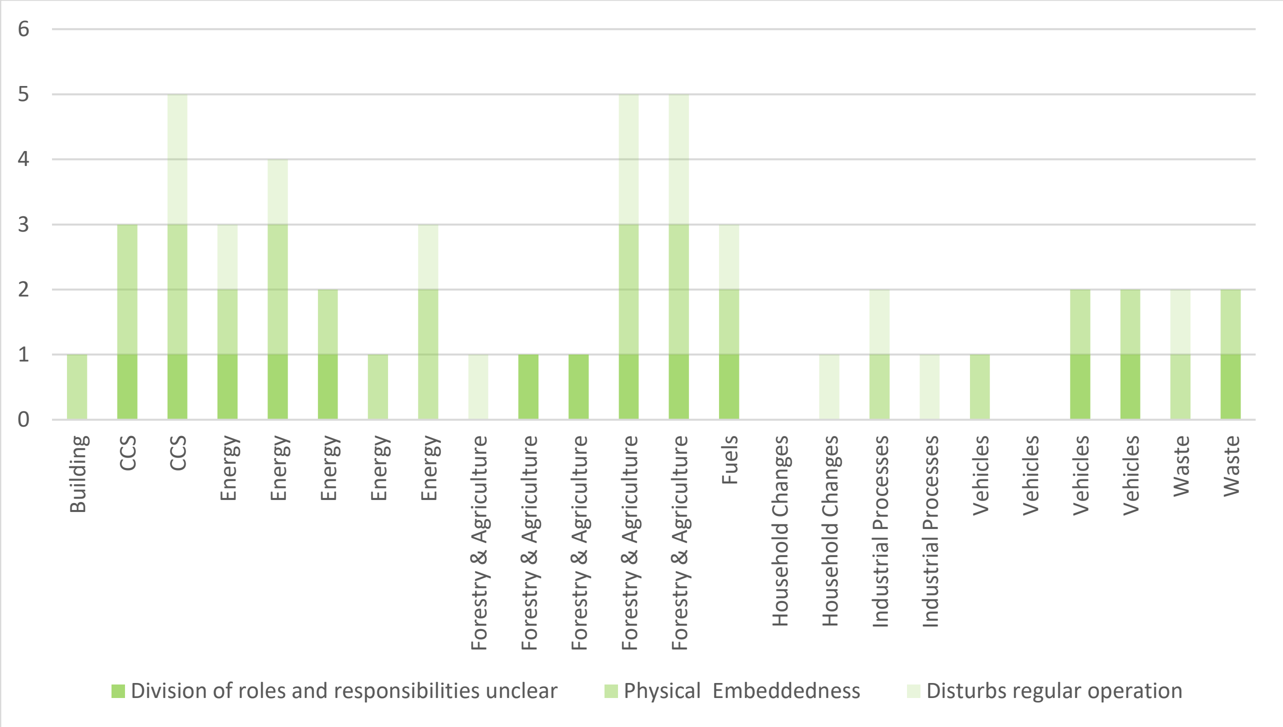
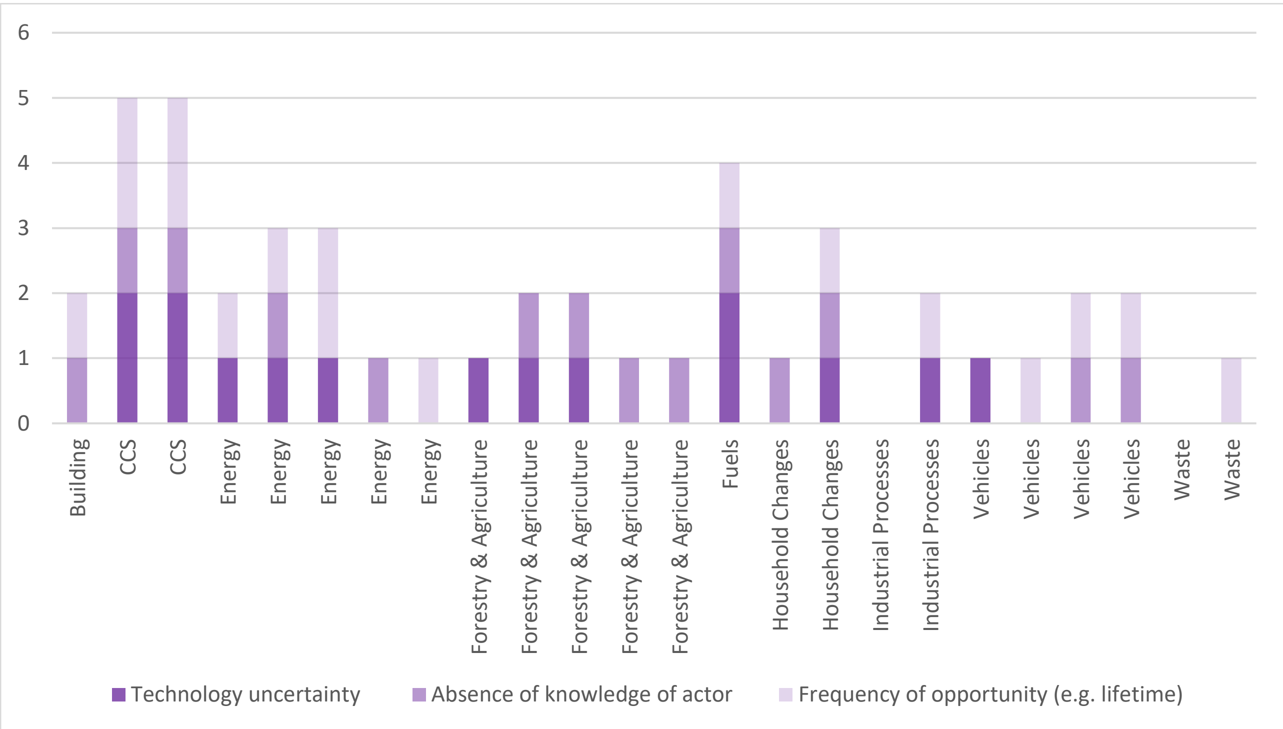


Figure 15: Validated scores - D - Behavior



Similarly to *Table 6*, the validated scores and their uncertainties are presented in *Table 7*, without including the preliminary score for an improved visualization. The validated scores are summed per-abatement-option to obtain the Y-value of each; these are ranked in increasing order to obtain a ranking of the abatement options, used to list them in the table.

All abatement options have a maximum Y-value of 24, as they are characterized over 12 factors each having a score of 2 as maximum value.

Table 7: Overview of validated scores and their uncertainties

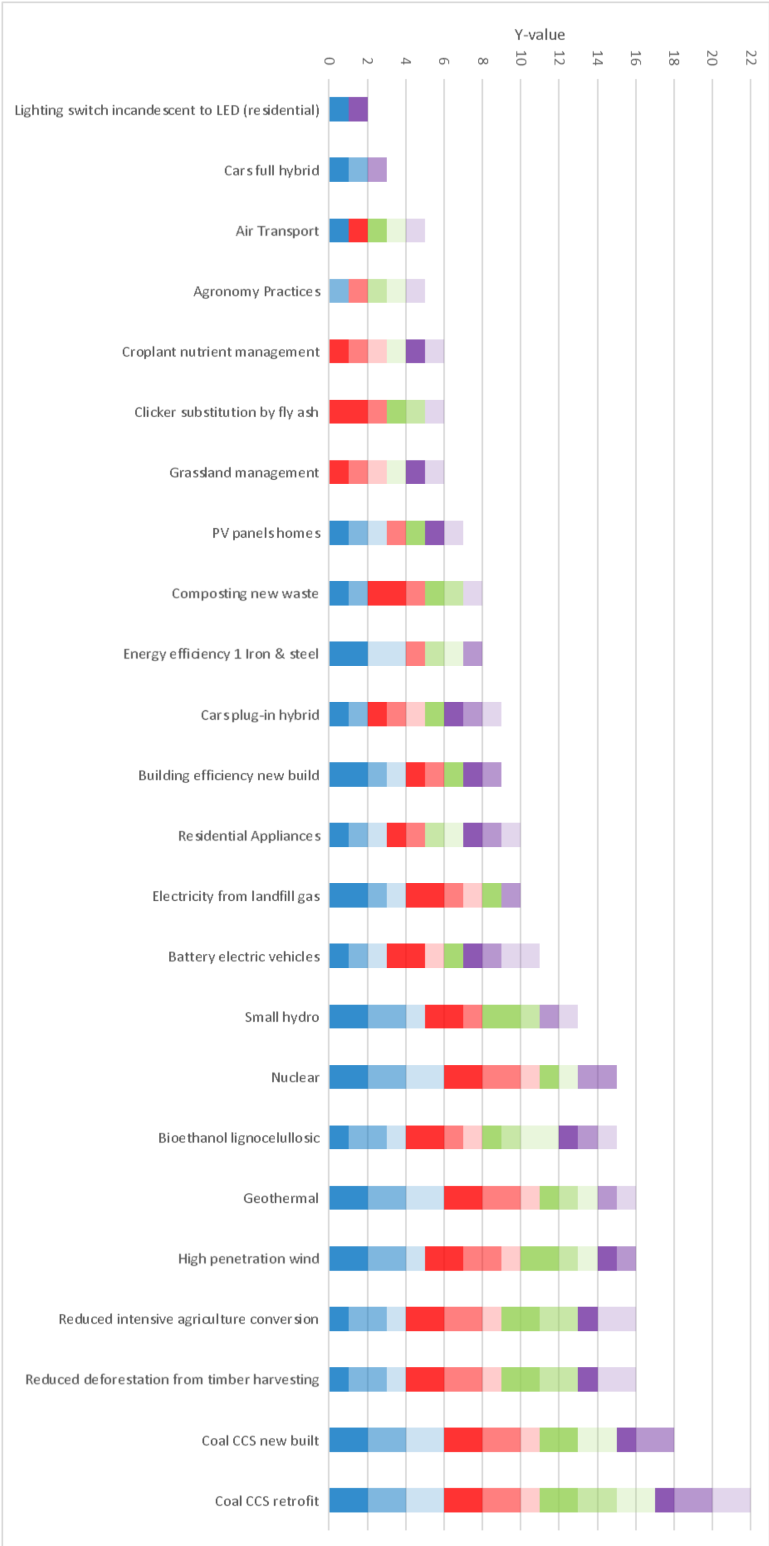
Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	sum
Lighting switch incandescent to LED (residential)	1	0	0	0	0	0	0	0	0	1	0	0	2
Cars full hybrid	1	1	0	0	0	0	0	0	0	0	1	0	3
Air Transport*	1	0	0	1	0	0	1	0	1	0	0	1	5
Agronomy Practices	0	1	0	0	1	0	0	1	1	0	0	1	5
Cropland nutrient management	0	0	0	1	1	1	0	0	1	1	0	1	6
Clinker substitution by fly ash*	0	0	0	2	1	0	1	1	0	0	0	1	6
Grassland management	0	0	0	1	1	1	0	0	1	1	0	1	6
PV panels homes	1	1	1	0	1	0	1	0	0	1	0	1	7
Composting new waste*	1	1	0	2	1	0	1	1	0	0	0	1	8
Energy efficiency 1 Iron & steel*	2	0	2	0	1	0	0	1	1	0	1	0	8
Cars plug-in hybrid	1	1	0	1	1	1	1	0	0	1	1	1	9
Building Efficiency New Build	2	1	1	1	1	0	1	0	0	1	1	0	9
Residential appliances	1	1	1	1	1	0	0	1	1	1	1	1	10
Electricity from landfill gas*	2	1	1	2	1	1	1	0	0	0	1	0	10
Battery Electric Vehicles	1	1	1	2	0	1	1	0	0	1	1	2	11
Small hydro	2	2	1	2	1	0	2	1	0	0	1	1	13
Nuclear	2	2	2	2	2	1	1	0	1	0	2	0	
Bioethanol lignocellulosic	1	2	1	1	1	1	1	1	2	1	1	1	15
Geothermal	2	2	2	2	2	1	1	1	1	0	1	1	16
High penetration wind	2	2	1	2	2	1	2	1	1	1	1	0	16
Reduced intensive agriculture conversion	1	2	1	2	2	1	2	2	0	1	0	2	16
Reduced deforestation from timber harvesting	1	2	1	2	2	1	2	2	0	1	0	2	16
Coal CCS new build	2	2	2	2	2	1	2	0	2	1	2	0	18
Coal CCS retrofit	2	2	2	2	2	1	2	2	2	1	2	2	22

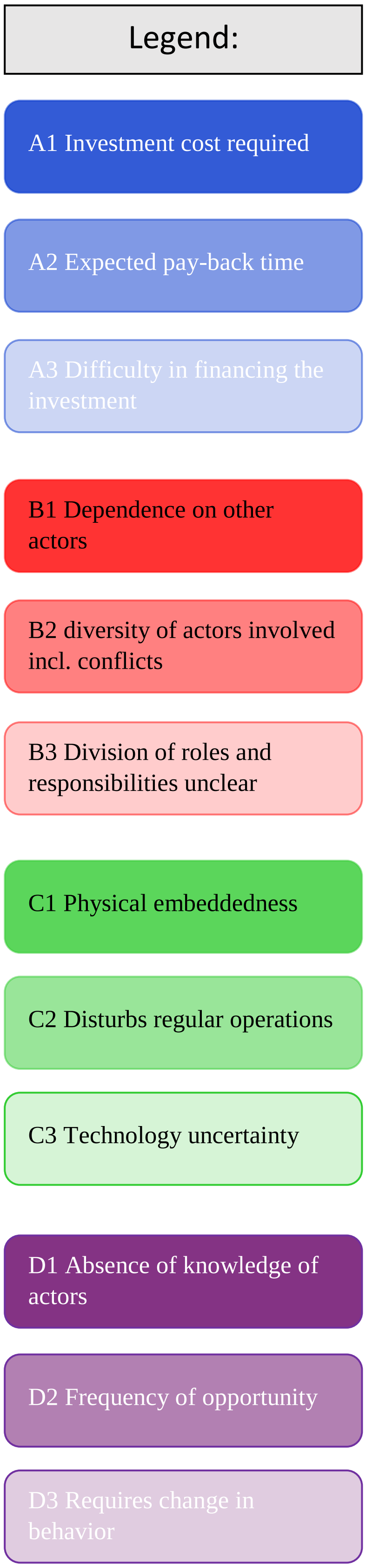
The validated scores presented can be classified as follows: the table displays 288 scores (24 abatement options * 12 factors), of which 60 rely on the opinion of 1 expert and 228 on the opinion of at least 2 experts. Of these 228, 168 (74%) are classified as certain (color green) in *Table 7*. 41 (18%) of the scores relying on at least 2 experts' opinions are classified as somewhat uncertain (color yellow), and 19 (8%) as significantly uncertain (color red).

Figure 16: The Y-curve – scores per category

The category scores displayed in the above *Figure 16* result from the combination of the individual scores belonging to each category, displayed in the figure below.

Figure 17: The Y-curve – scores per factor





As already explained in *Chapter 1*, these scores are summed for purposes of graphical display and for facilitating a visual comparison of the abatement options and of the Y-curve with McKinsey's MAC curve, but do not aim for a quantitative comparison. Rather, they highlight the combined difficulty of implementation characterizing each abatement option.

4.5 Reflection on the Y-curve and its validation process

The Y-curve presented in *section 4.4* is a multi-criteria emission abatement curve, combining in one graph some of the most characterizing variables of different scientific and societal domains: Finance, Stakeholders Management, Technology, and Behavioral Science. It is the first one of its genres: the curve presented by Chappin (2016) is more comprehensive than the Y-curve but less reliable, considering the subjective scores it displays; the investigations on the Y-factor method performed by Arensman (2018) and Cheung (2018) did not aim to obtain a Y-curve. Thus, the Y-curve presented in the previous section is the most extensive application of the Y-factor method so far performed and presents the most qualitative results currently achievable in the available time and information.

Different considerations shall be made on the obtained Y-curve, to which this section is dedicated: firstly, the the obtained scores and the score-validation procedure are focalized, especially to reflect on the impact the latter has had on the final results and to verify if the 12 factors are relevant. Then, the validated Y-curve can be compared to the subjective curve presented by Chappin (2016), to reflect on the differences of experts' opinions and on the new insights they provide. Finally, it is extremely interesting to compare the validated Y-curve with McKinsey's MAC curve, to discuss differences in the ranking of the investigated options, and to propose some possible combined usage of the two method.

4.5.1 Results and validation procedure

The first reflections worth highlighting relate to the obtained validated scores:
Basing on the scores-overview provided in *Table 7*, the validated Y-curve is significantly robust, considering how most of its characterizing scores could be validated easily combining consonant experts' opinions. In fact, considering the similarity of the opinions of the interviewed experts, the selection of different interviewees might only marginally affect the displayed ranking of the abatement options.

Besides the robustness of the curve, it is interesting to highlight how some abatement options are characterized by more uncertain scores than others, and similarly are some of the 12 factors composing the Y-factor method.

Most abatement options have some of their characterizing 12 scores reported as somewhat uncertain; some options have more than others, highlighting their contentious nature. Specifically, the abatement options: [Energy]: <u>High penetration wind</u> and <u>Nuclear</u>, and [Fuels]: <u>Bioethanol lignocellulosic</u> have 6 of their 12 scores which are moderately or highly uncertain.

Other abatement options characterized by fewer, but nonetheless noticeable uncertainties (4/12 scores) are: [Building]: <u>Building efficiency new built</u>, [Energy]: <u>Geothermal</u> and <u>Small hydro</u>, [Forestry & Agriculture]: <u>Cropland nutrient management</u> and <u>Agronomy practices</u>, and [Vehicles]: <u>Cars plug-in hybrid</u>. All other abatement options, excluding the five for which only one expert interview was conducted, are characterized by three or less uncertain scores.
Two possible justifications of such uncertainty can be different interpretations of the abatement options' definitions and different personal opinions of the consulted experts. Such uncertainty suggests the need to investigate the abatement options further, to verify if the collected uncertain-scores are only depended on the interviewed experts or if the abatement options themselves are generally debated. Profound differences of opinions do not support the implementation, as conflicts among stakeholders are likely to arise; hence, they should be specifically discussed to try finding compromise or disregarded as socially-unfeasible.

Considering the scores characterizing the 19 abatement options discussed by two or more experts, the factors over which the interviewees had most conflicting opinions are *D1: Absence of knowledge of actors* (uncertain for 9 of the 19 abatement options) and three other factors *ex-equo* (uncertain for 7/19 abatement options): *A3: Difficulty in financing the investment*, *C2: Disturbs regular operations*, and *D3: Requires change in behavior*. These four factors should be considered even more carefully than the others:

As highlighted in the validation process in *section 4.*3, the uncertainty characterizing the factors *D1* and *D3* was most often caused by the different contexts (geographical scope mainly) to which the score could refer to. This uncertainty was sometimes solved by considering an average between the high knowledge of some actors (e.g.: developers and researchers) and the little knowledge of the population, not responsible for the implementation of the abatement option but recognized as a directly-involved stakeholder. Some other time, as recommended by *Smith*, the score was reported as uncertain between the value of 0 and 2, thus along the whole scoring scale. To achieve a score-synthesis, such scores were assigned a middle value by the researcher (e.g. = 1) and are reported as significantly uncertain.

The uncertainty characterizing the factor *D3* has an additional root, which is the philosophical understanding of behavioral change. For instance, as remarked by *Morelli*, is a dishwasher starting at 8am rather than at 8pm to be considered a behavioral change? While the perception of behavioral change might change depending with the cultures and traditions of a population, this has also a subjective character. While changes are normally evident, it is more interesting to discuss their consequences and thus consider the change as an implementation barrier only it creates more functional, problematic impediments than benefits. This is an interesting theme for further sociological discussion.

All other factors are considered uncertain for 5 or less of the 19 abatement options scored by at least 2 experts.

Interviewed Experts and Methodology

The methodological decision to ask experts to validate preliminary scores rather than allowing them to assign scores directly was taken pursuing two principles: time-efficiency and clarity. Providing the interviewees with a preliminary score and a brief explanation (see *section 4.1*) helped explaining the importance of achieving a final score and prevented experts' storytelling, precious but not functional to the research need of considering numerous abatement options. With the implemented interview methodology, interviewees tended to provide immediately an argument supporting or contrasting the preliminary score, which was well-aligned with the definition of the considered factor; this shortened the time spent on validating each individual score, which varied from a few seconds to a few minutes (maximum 5-7 minutes).
It is evidently unknown how much time and clarification would have been needed if interviewees had been asked to assign the scores themselves, but the implemented interview methodology was effective and functional to the time constraints of the investigation.

A legitimate doubt is whether a different interview methodology or a different selection of interviewees would have led to different validated scores. While having diverse expertise and pursuing very different careers, the interviewed experts are all professionally active in the energy sector; thus, the sample of interviewees is considered reliable. Nevertheless, the results of a qualitative investigation are always dependent on the subjective opinions considered, and this Y-curve is not an exception.

It is impossible to know what results would have been collected with a different interview-methodology (e.g.: without providing preliminary score), but the researcher is confident that most of the scores presented as validated would have not been different, considering the robustness of the curve mentioned at the start of this section. In particular:

- The scores highlighted in green in *Table 7* (74% of the scores validated by at least two experts) are expected to be the final scores resulting from any score-validation process, as the interviewed experts either agreed with the preliminary score or all suggested the exact same, alternative score. Thus, experts showed to have strong arguments in favor of the final scores, and it would be surprising if two or more experts would change such strong opinions following a different score-validation procedure.
- The scores highlighted in red (8%) are significantly uncertainty and consequently have a high chance of changing over the entire scale-length with a different score-validation process, both in terms of the interview procedure and of the synthesis-strategy guiding *section 4.3* for combining experts' opinions.
- The scores relying on at least two experts' opinions highlighted in yellow (18%) are somewhat uncertain, and there is a chance they would change following a different score validation procedure. This chance is nevertheless minor than for the score highlighted in red, and the final scores are not expected to vary over the entire scale-length but for a maximum of one value.
- Instead, the scores reliant on just one expert's opinion have a very subjective character.

Relevance of the two Scopes se in *section 4.3*

The two scopes introduced in *section 4.3* enabled solving some of the conflicts between experts' opinions encountered during the score-validation process. Their impact is discussed below.

Scope 1:
Multiple interviewees wondered about the actor-perspective to which the scores should be referring too, which was intentionally not specified upfront. When no questions were raised about it, no further specification was provided, to strive towards the most generalizable scores possible. When the interviewees raised doubts, they were asked to provide a suggestion; referring to those actors having the decision-making power of implementing the abatement options (e.g.: the person who purchase an LED, a residential appliance, the owner of a coal plant, etc.) was the perspective suggested different times as the most relevant one. Thus, it was decided to use Scope 1 for synthesizing experts' opinions and solve possible dilemmas. For instance, *Scope 1* helped solving the dilemma related to the score of the factor *C3: Technology uncertainty* for the abatement option [Energy]: PV panels homes: people installing PVs do not experience the technology uncertainty of a supporting smart grid system but just the PVs' functioning; this led to the validation of the preliminary score of 0. Hence, *Scope 1* is considered relevant and helpful.

Scope 2:
Even more often that for Scope 1, *Scope 2* was suggested by the interviewees as a necessary clarification to achieve a final score, especially for the factors *A1: Investment cost required*, *B1: Dependence on other actors*, and *B2: Diversity of the actors involved incl. conflicts*. Thus, after this was suggested the first time, it was decided to clarify the importance of comparing the implementation of the abatement option to the existing status-quo every time an interviewee expressed uncertainty about a score. A clear example is constituted by the score for the factor *A2: Expected pay-back time* for the abatement option [Building]: Building efficiency new build: the construction of a new building requires a substantial investment, paid-back over many years; the construction of an energy efficient-building requires additional costs, prolonging the pay-back time. Hence, the pay-back time for an energy-efficient building should be compared to the pay-back of regular, non-efficient buildings, which constitute the business-as-usual scenario. *Scope 2* also provided effective support to the score-validation process and is thus considered relevant and helpful.

Interviews timing & methodological comments

The timing of the interviews varied substantially. While all interviews lasted about an hour, the number of abatement options discussed in each interview fluctuated between a minimum of 2 abatement options to a maximum of 7. One of the reasons of such variance was the different duration of the introduction to the approach and aims of the Y-factor method, with some of the interviewees being more interested in discussing the structure and motivation of the Y-factor method, and curious to hear about its development. Another reason was the duration of the discussion for validating the individual scores, which varied across abatement options and factors.
Besides enabling the validation of the scores, the interviews with experts provided some clarifications on the definition and characterization of the discussed abatement options, and some interesting methodological comments. All these are reported the individual interview-characterizations in *Appendix F*, but some are highlighted below:

a) *Blok* highlighted possible interdependencies between the factors *A1*, *A2*, *A3*, specifying how if a score of 0 is assigned to the factor *A1*, it is likely for *A2* and *A3* to also assumed a value of 0; an example of this is the abatement option [Industrial Processes]: Clicker substitution by fly ash.
b) *Blok* criticized the definition of the abatement option [Vehicle]: Air Transport, which entails multiple abatement options; he distinguished Operational Efficiency (OE) from Alternative Fuels.
c) Discussing the abatement option [Energy]: High penetration wind, *Dejonghe & Sprengers* suggested to modify the name of the factor *D1: Absence of knowledge of actors* in "Absence of information sharing" or "Communication with actors", and to add the word "scalable" to the definition of the factor *D2: Frequency of opportunity.*

Suggestions for the introduction of three additional factors were also collected in the interviews:

1. *Smith* suggested to add a factor capturing *Governance* to the Y-factor method, for instance using a government-corruption index. This would help capturing the difficulty of implementing supporting policies;
2. *Smith* suggested to add a factor capturing *Regulation* to the Y-factor method. Many of the abatement options belonging to the [Forestry & Agriculture] sector, such as Agronomy practices are not implemented mainly due to the lack of non-financial incentives, as favorable regulation.
3. *Morelli* suggested to add a factor capturing the *Emotional decision-making* characterizing people's actions. This would help explaining buyers not being willing to purchase a 10€ LED because of the immediate additional costs compared to a normal incandescent bulb, or the difficulty of paying more to purchase a building classified by a higher energy-efficiency class.

While different, all these factors refer to the ability of supporting the practical implementation of the abatement option and could thus be considered belonging to a new category, *E: Contextual support*. The three factors could be named *E1: Political Governance*, *E2: Regulatory Support*, and *E3: Emotional Impact*.

4.5.2 Relevance of the Y-factor method

Besides validating the scores, interviewing experts had also the goal to underpin the relevance of the 12 factors proposed by the Y-factor method; in fact, the combination on these two operations constitutes the scientific contribution of this master thesis, as explained in *section 1.1*.6. The relevance of the 12 factors can be verified following the procedure proposed by Hekkert and Negro (2009): to validate the relevance of the seven system functions proposed by Hekkert et al. (2007), they propose to "First, based on the different event databases we can count how many events are allocated to each system function and calculate the share of each system function per case study and in total. Second, based on the earlier described cases, we argue what the relative importance is of the different system functions" (p. 590).

Comparing these seven functions to the 12 factors considered in this investigation, their relevance can be verified following the same procedure. The procedure can be applied to the validated scores presented in *Table 7* (*section 4.4*) following two numerical strategies, presented in *Table 8* and *9* with the aid of colors:

A) Relevance per Abatement Option:

The share-contribution of each individual score to the overall Y-value of each abatement option can be easily calculated. Averaging the share-contributions of each factor over all the abatement options provides the average contribution of each factor to all Y-values, thus highlighting their relevance.

Table 8: Relevance of the 12 factors – per option

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
Building Efficiency New Build	22.2	11.1	11.1	11.1	11.1	0.0	11.1	0.0	0.0	11.1	11.1	0.0
Coal CCS new build	11.1	11.1	11.1	11.1	11.1	5.6	11.1	0.0	11.1	5.6	11.1	0.0
Coal CCS retrofit	9.1	9.1	9.1	9.1	9.1	4.5	9.1	9.1	9.1	4.5	9.1	9.1
Geothermal	12.5	12.5	12.5	12.5	12.5	6.3	6.3	6.3	6.3	0.0	6.3	6.3
High penetration wind	12.5	12.5	6.3	12.5	12.5	6.3	12.5	6.3	6.3	6.3	6.3	0.0
Nuclear	13.3	13.3	13.3	13.3	13.3	6.7	6.7	0.0	6.7	0.0	13.3	0.0
PV panels homes	14.3	14.3	14.3	0.0	14.3	0.0	14.3	0.0	0.0	14.3	0.0	14.3
Small hydro	15.4	15.4	7.7	15.4	7.7	0.0	15.4	7.7	0.0	0.0	7.7	7.7
Agronomy Practices	0.0	20.0	0.0	0.0	20.0	0.0	0.0	20.0	20.0	0.0	0.0	20.0
Cropland nutrient management	0.0	0.0	0.0	16.7	16.7	16.7	0.0	0.0	16.7	16.7	0.0	16.7
Grassland management	0.0	0.0	0.0	16.7	16.7	16.7	0.0	0.0	16.7	16.7	0.0	16.7
Reduced deforestation from timber harvesting	6.3	12.5	6.3	12.5	12.5	6.3	12.5	12.5	0.0	6.3	0.0	12.5
Reduced intensive agriculture conversion	6.3	12.5	6.3	12.5	12.5	6.3	12.5	12.5	0.0	6.3	0.0	12.5
Bioethanol lignocellulosic	6.7	13.3	6.7	13.3	6.7	6.7	6.7	6.7	13.3	6.7	6.7	6.7
Lighting switch incandescent to LED (residential)	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0
Residential appliances	10.0	10.0	10.0	10.0	10.0	0.0	0.0	10.0	10.0	10.0	10.0	10.0
Clinker substitution by fly ash	0.0	0.0	0.0	33.3	16.7	0.0	16.7	16.7	0.0	0.0	0.0	16.7
Energy efficiency 1 Iron & steel	25.0	0.0	25.0	0.0	12.5	0.0	0.0	12.5	12.5	0.0	12.5	0.0
Air Transport	20.0	0.0	0.0	20.0	0.0	0.0	20.0	0.0	20.0	0.0	0.0	20.0
Cars full hybrid	33.3	33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	0.0

Cars plug-in hybrid	11.1	11.1	0.0	11.1	11.1	11.1	11.1	0.0	0.0	11.1	11.1	11.1
Battery Electric Vehicles	9.1	9.1	9.1	18.2	0.0	9.1	9.1	0.0	0.0	9.1	9.1	18.2
Composting new waste	12.5	12.5	0.0	25.0	12.5	0.0	12.5	12.5	0.0	0.0	0.0	12.5
Electricity from landfill gas	20.0	10.0	10.0	20.0	10.0	10.0	10.0	0.0	0.0	0.0	10.0	0.0
AVERAGE CONTRIBUTION - per factor (%)	**13.4**	**10.2**	**6.6**	**12.3**	**10.4**	**4.7**	**8.2**	**5.5**	**6.2**	**7.3**	**6.6**	**8.8**
AVERAGE CONTRIBUTION – per category (%)	**30.1**			**27.3**			**19.9**			**22.6**		

While the relevance of each factor seems evident, the obtained figures could be biased because of the employed calculation method. In fact, for an abatement option characterized by a low overall Y-value (e.g.: Lighting switch incandescent to LED, Y-value = 2), a factor having a score of 1 (e.g.: *A1: Investment cost required*) contributes to the overall Y-value for 50% and would thus be assigned a relevance of 50%. While this is valid to establish the relevance of each factor, it might be considered having an excessively relative character, capturing the factor's relevance for a specific abatement option rather than its generic relevance.

Thus, a second numerical method can be used to verify these figures.

B) Relevance per Factor

In this case, the scores assigned to a specific factor for all the 24 abatement options can be summed, and the overall sum can be divided by, thus obtaining the score assigned on average to each factor.
The *Average score – per factor* figures display the share-contribution of each factor to the total overall Y-values over the considered abatement options; these can be grouped also by category. Thus, the last two lines in *Table 9* have then the same meaning of the last two lines of *Table 8*.

Table 9: Relevance of the 12 factors – per factor

Factors	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	Total
Average score - per factor	1.2	1.1	0.8	1.3	1.1	0.5	1.0	0.6	0.6	0.6	0.7	0.8	10.5/24
Average score - per category	3.2			3.0			2.2			2.1			10.5/24
AVERAGE CONTRIBUTION -per factor (%)	**11.5**	**10.7**	**7.9**	**12.7**	**10.7**	**5.2**	**9.1**	**6.0**	**6.0**	**5.6**	**6.7**	**7.9**	100 %
AVERAGE CONTRIBUTION – per category (%)	**30.2**			**28.6**			**21.0**			**20.2**			100 %

Comparing the same variables in the two tables (matching over the same color), shows how the relevance figures are not identical, but very similar. The factor-relevance figures obtained in *Table 8* and *9* can be averaged to a final relevance-figure per factor, displayed in *Table 10*.

Table 10: Relevance of the 12 factors

Factors	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
AVERAGE CONTRIBUTION - per factor (%)	**12.4**	**10.4**	**7.3**	**12.5**	**10.6**	**4.9**	**8.7**	**5.7**	**6.1**	**6.4**	**6.7**	**8.4**
AVERAGE CONRIBUTION – per category (%)	**30.1**			**27.9**			**20.5**			**21.4**		

The following can be concluded: Each of the 12 factors is verified to be relevant. In fact, all the "functions used in the empirical analyses can be related to actual events that took place" (Hekkert & Negro, 2009, p. 590), which translates to each factor having been considered able to capture existing implementation barriers by the interviewed experts. This conclusion was sought by this research (*section 1.1.6*), as previous researches could only underpin in the existing literature the relevance of the four categories composing the Y-factor method. Following a very different approach, this result adds to the theoretical reliability of the Y-factor method, showing the relevance of the 12 individual factors and connecting them to the methodology proposed by Hekkert and Negro (2009).

The factors belonging to the *Cost and Financing* category account for a slightly larger share than the other three individual categories, but only approximately 30% of the barriers hampering the implementation of the considered emission abatement options are related to financial factors. Even assuming the barriers captured by the factors in the *Cost and Financing* category are captured by the Abatement Costs displayed in MAC curves such as McKinsey's, the remaining 70% of the barriers is dominant and cannot be captured with conventional MAC curves.
Further conclusions should not be drawn from the displayed figures, as remarked by Hekkert and Negro (2009): "This does not mean that the system functions with the most events are the most important ones. To some system functions many events may be allocated where the total influence may be lower than a small number of events for other system functions" (p. 590).

4.5.3 Differences with the curve of Chappin (2016)

Having reflected on the individual scores and their validation process, it is now interesting to reflect on the validated Y-curve. A first interesting reflection is the comparison with the curve presented by Chappin (2016), to verify the impact of considering different experts' opinions.
In Chppain's research the Y-factor method is applied to score the 50 abatement options ranked by McKinsey's MAC curve with the highest abatement potential. As explained in *section 2.1*, this investigation only considers 23 of those 50 options, and additionally considers the abatement option [Vehicles]: Battery electric vehicles. Thus, to enable the comparison between the two curves, the 23 options considered in this investigation are extrapolated from the curve presented by Chappin (2016), relatively ranked (*Figure 18)* and compared to the Y-curve. While the displayed legend is valid for both curves, the curve from Chappin (2016) has an additional factor ("*B2: Number of actors*", see *section 1.1.4* for explanations), highlighted in the color yellow. Because of this difference, besides the overall Y-values it is relevant to compare the relative ranking of the abatement options, as considering only the overall Y-values might be structurally misleading.

Multiple differences between the overall Y-values and ranking order of the considered abatement options in the two curves can be noticed, both from the curves themselves and from the relative-ranking figures presented in *Table 11* below.

Figure 18: Curve from (Chappin, 2016) only displaying the considered abatement options

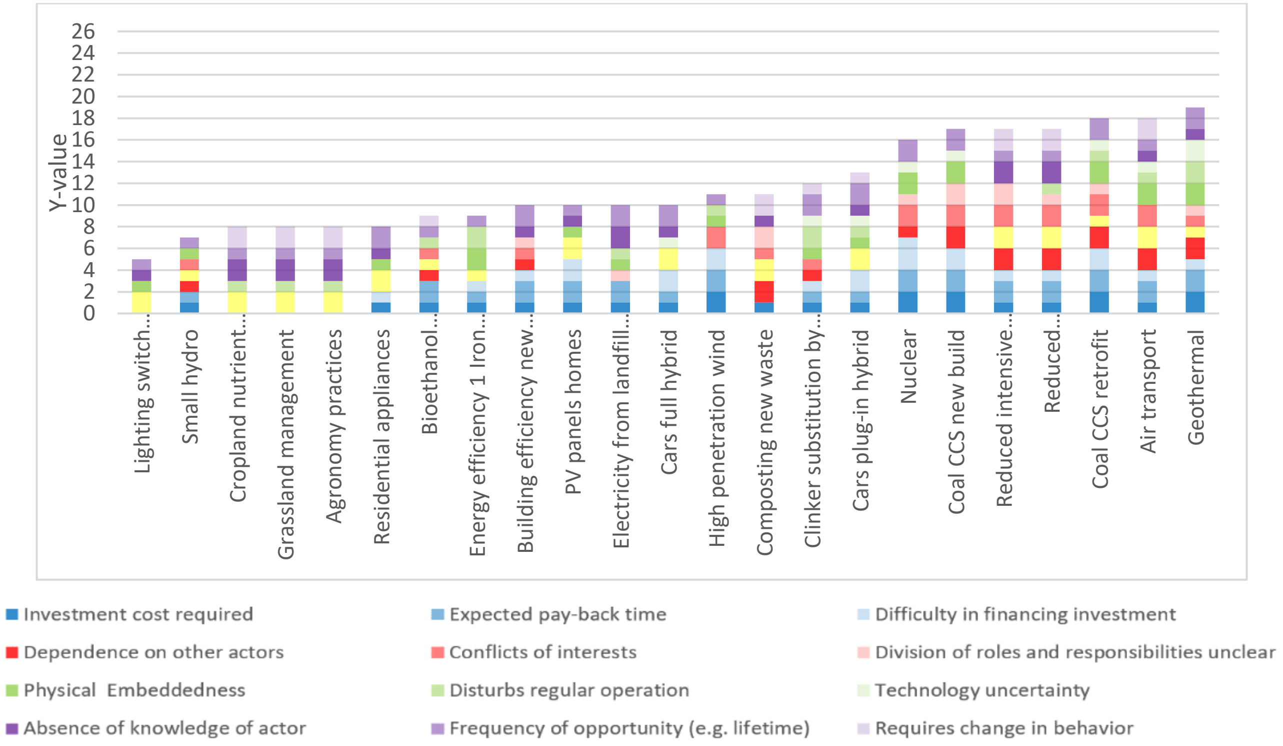


Figure 19: Validated Y-curve

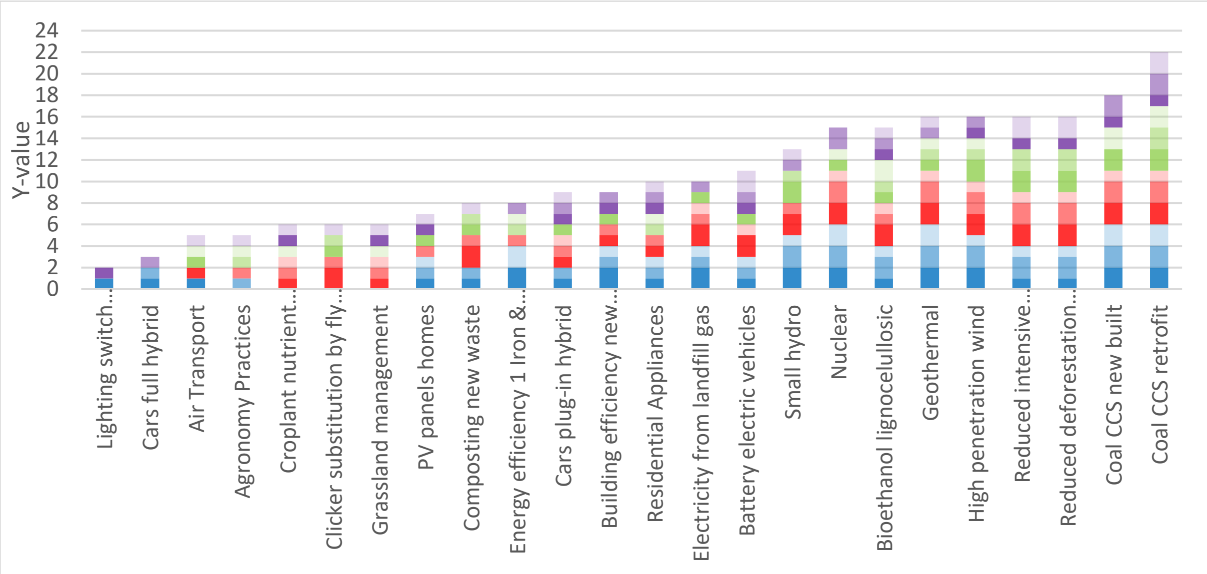


Table 11: Ranking comparison validated Y-curve and (Chappin, 2016)

Sector	Abatement Option	Y-value (Chappin, 2016) [out of 26]	Y-value in Y-curve [out of 24]	Relative ranking (Chappin, 2016) → Ranking Y-curve
Building	Building Efficiency New Build	10	9	9 → 11
CCS	Coal CCS new build	17	18	18 → 23
CCS	Coal CCS retrofit	18	22	21 → 24
Energy	Geothermal	19	16	23 → 19
Energy	High penetration wind	11	16	13 → 19
Energy	Nuclear	16	15	17 →17
Energy	PV panels homes	10	7	9 →8
Energy	Small hydro	7	13	2 → 16
Forestry & Agriculture	Agronomy Practices	8	5	3 → 3
Forestry & Agriculture	Cropland nutrient management	8	6	3 → 5
Forestry & Agriculture	Grassland management	8	6	3 → 5
Forestry & Agriculture	Reduced deforestation from intensive agriculture conversion	17	16	18 → 19
Forestry & Agriculture	Reduced deforestation from timber harvesting	17	16	18 → 19
Fuels	Bioethanol lignocellulosic	9	15	7 → 17
Household Changes	Lighting switch incandescent to LED (residential)	5	2	1 →1
Household Changes	Residential appliances	8	10	3 → 13
Industrial Processes	Clinker substitution by fly ash	12	6	15 → 5
Industrial Processes	Energy efficiency 1 Iron & steel	9	8	7 → 9
Vehicles	Air Transport	18	5	21 → 3
Vehicles	Cars full hybrid	10	3	9 → 2
Vehicles	Cars plug-in hybrid	13	9	16 → 11
Vehicles	Battery Electric Vehicles	/	11	
Waste	Composting new waste	11	8	13 → 9
Waste	Electricity from landfill gas	10	10	9 → 13

The most evident differences, namely those consisting of a score ≥ 5, are highlighted in the table and individually addressed by the following comments.

- The most evident difference is in the score assigned to the abatement option [Vehicle]: Air Transport. This is the 21st/23 ranked abatement option in the curve from Chappin (2016), having one of the highest Y-values (18). Instead, [Vehicle]: Air Transport has a lower Y-value (5) in the validated Y-curve, and it is thus only the 3rd/24 ranked abatement option. Two comments can frame this disparity:
  1. [Vehicle]: Air transport is one of the five abatement options which were validated by only one interviewee, and thus its final scores are all somewhat uncertain. This consideration is nevertheless methodological, and not inherent to the displayed results.
  2. A vast amount of literature is dedicated to the discussion of sustainable air transport, many international and diplomatic problems are reported (e.g.: conflicts EU-ICAO over Directive 2008/101/EC), and different strategies to reduce the sector-emissions are jointly considered. Instead, the interviewed expert highlighted a definitional issue for the abatement option, containing multiple means to achieve emission reduction, and in particular OE and Alternative Fuels (AF), thus ranking them separately as separate abatement options. Each of the two solutions was assigned low, similar scores (see *Appendix F* for individual scores). While the scores might be subjective, they suggest the abatement option is often debated in too general terms and broaches a higher complexity than discussed. This would explain the similar high-scores assigned to the abatement option [Vehicle]: Air Transport in the preliminary Y-curve (*Chapter 3*) and in the relative Y-curve from Chappin (2016), basing on the same McKinsey's definition and existing literature.

- A substantial ranking difference also characterizes the abatement option [Vehicles]: Cars full hybrid, assigned a score of 10 (ranking = 9th/23) by Chappin (2016) and only of 3 (ranking = 2nd/24) in the validated Y-curve. A comment made by both the interviewed experts can explain the low value in the final Y-curve: the definition of the abatement option incorporates a vast range of vehicle technologies, from start-and-stop systems to electric and ICE motors in parallel; the interviewed experts remarked how the majority of vehicles nowadays on the road could then be classified as HEVs with this definition. This issue is confirmed also considering the figures from Cbs (2015), which for instance states how HEVs account for 2% of the total distance covered by all Dutch passenger cars. Such low number does not fit with the comments of the interviewed experts but is explained by the definition provided in a linked web-page: "The term hybrid covers any car that uses a combination of a battery-driven electric motor and a conventional internal combustion engine to move itself along. In this article, cars with only electric propulsion are also included in the category hybrid cars." Thus, McKinsey's definition is much broader and more comprehensive, and arguably strangely so.

- [Energy]: Small hydro is also assigned a Y-value higher than the one in Chappin's curve (2016), 13 compared to 7, but even more impressive is the overall ranking of the abatement option, the 2nd/23 against the 16th/24 in the validated Y-curve. Checking the individual scores, an evident disparity in the category *A. Cost and Financing* immediately emerges. Two clarifications are worth mentioning:
  1. The scores *A1, A2, and A3* are reported as somewhat uncertain, reflecting differences of opinions among the interviewed experts.
  2. There are different size-boundaries when referring to "small hydro" power plants, but these have normally a maximum varying from 15 MW (in the UK) and 20 MW as defined by The Clean development Mechanism (CDM) of the Kyoto Protocol. Because of the size, these installations are not realized in locations similar to the traditional, larger hydropower plants, often constructed on or close to a mountain. But while not incurring in mountaineering costs, which are a large portion of the construction costs, investment is present for adapting the surrounding environment and/or connecting to it, as recognized by both interviewees; moreover, lifecycle assessments mentioned by one of the two interviewees estimate investments to be paid-back in 20 years.

Thus, the take-away message is not to underestimate investment costs and their pay-back time for smaller-than-usual hydro power plants.

- [Fuels]: Bioethanol lignocellulosic is assigned a Y-value of 15 in the validated Y-curve, while it is ranked only with a Y-value of 9 in the curve of Chappin (2016). As for [Energy]: Small hydro, the difference in relative ranking is evident, as [Fuels]: Bioethanol lignocellulosic holds the 7th/23 position in the ranking of Chappin (2016), while it is only ranked as the 17th/24 option in the validated Y-curve. The major differences relate to the category *C. Physical Interdependencies*: both experts agreed on the many uncertainties concerning the technical feasibility and effectiveness of bioethanol, which are instead not considered as relevant in Chappin (2016). Moreover, while bioethanol can be progressively added to the regular benzine, its large-scale production causes interruptions to the business models of producers and substitutes primary biofuels, with large portion of biomass land having to change its utilization and outlook. Thus, the introduction of second-generation biofuels seems to be rather disruptive.

- Instead, [Industrial Processes]: Clinker substitution by fly ash is assigned a lower score in the validated Y-curve than in the curve of Chappin (2016), 6 against 12, and consequently the option has a very different ranking in the two curves, 5th/24 against 15th/23. Two comments are worth mentioning:
  1. The abatement option was discussed only with one interviewee; thus, all its scores are reported as moderately uncertain.
  2. The option is assigned a score of 3 in the curve from Chappin (2016) for the category *A. Cost and Financing*, while the same category has a score of 0 in the validated Y-curve. The interviewed expert (*Blok*) mentioned multiple times how clinker is often a mere waste product, thus very cheap to purchase and with consequent short pay-back time.

  Being CSM like fly ash or slag, which the interviewee reported being more popular than fly ash, purchased as waste from third-parties instead of being produced in-house as cement, the *Multi-actor Complexity* increases, and becomes the most dominant of the four categories.

- The difference in the scoring of the abatement option [Energy]: High penetration wind, Y-value of 11 (ranking = 13th/23) in the curve of Chappin (2016) and of 16 (ranking = 19th/24) in the validated Y-curve, is caused by the higher relevance of the factors in the categories *B. Multi-actor Complexity* and *C. Physical Interdependencies* in the validated Y-curve. All interviewees highlighted the needed for many stakeholders to cooperate to install any turbine different from a backyard turbine, and their interdependencies are to increase exponentially to achieve at least a 10% penetration in the energy mix as by the definition of the abatement option. Moreover, the existence of conflicts with the local population and especially with environmental agencies for flora and fauna protection is undisputed, and different programs are being developed location-specific to reduce such conflicts, for instance by providing local population with a share of the turbine's profits. *Physical Interdependencies* are also high, with the question not being if the environment is affected but rather how many people are impacted and bothered by such physical changes. New technological uncertainties arise as the technology develops and aims to new horizons: the interconnection of floating offshore turbines to the shore is highly challenging, and the increasing size of the turbines poses new unknowns to both on- and offshore engineering. Hence, wind turbines not only face substantial financial challenges, but their environmental impact and stakeholders' interdependencies should be carefully debated.

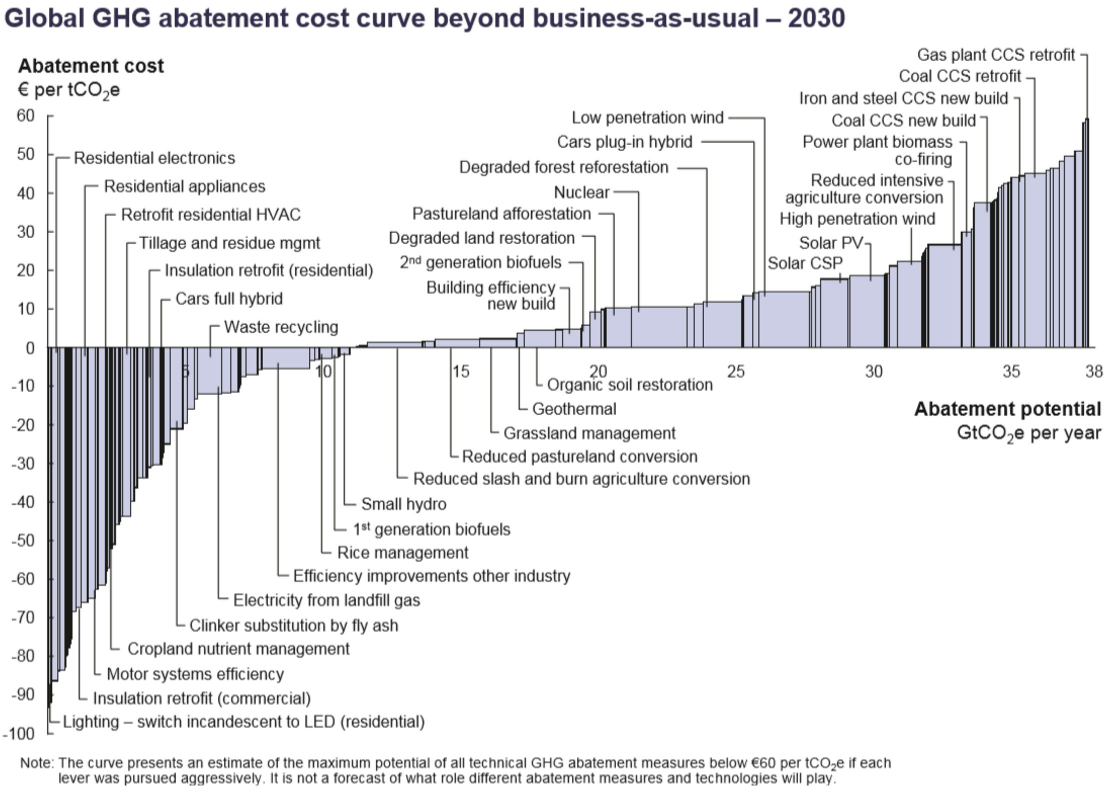
Having commented six very different Y-values, it is worth highlighting two additional points:

1. The abatement option [Forestry & Agriculture]: Reduce intensive agriculture conversion is characterized by a score of 0 in the category *C. Physical Interdependencies* in the curve of Chappin (2016), while the interviews with experts highlighted how, although the wording "reduced" used in McKinsey's definition is "interpretable", traditional daily-activities of local population are heavily disrupted, and non-chopped trees constitute a substantial physical change to the environment.
2. The abatement option [Waste]: Composting new waste is characterized by the high score of 7 for the category *B. Multi-actor Complexity* in the curve of Chappin (2016), while it is assigned a Y-value of 3 in the Y-curve. While this is partially justified by the additional considered factor, unclarity in the division of roles and responsibilities highlighted by the curve of Chappin (2016) does not seem to be an issue.

4.5.4 Differences with McKinsey curve: new insights from the Y-curve

The most interesting comparison is the one between the validated Y-curve and McKinsey's MAC curve, the limitations of which were among the inspirations for the development of the Y-factor method.

Figure 20: McKinsey's MAC curve



Source: https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to-a-low-carbon-economy

A direct graphical comparison between the two curves cannot provide much information, because of the higher number of abatement options in McKinsey's MAC curve (218) and the different themes of the curve axis, Abatement Cost (€/tCO_2e) on the Y-axis and Abatement Potential (MtCO_2e-in-2030) on the X-axis.

Thus, the most meaningful comparison focuses on the relative ranking assigned by McKinsey's MAC curve to the options included in this investigation paralleled to their ranking in the validated Y-curve. In fact, McKinsey's MAC highlights the Abatement Costs as the main discriminating factor, thus suggesting how to a higher implementation cost corresponds a higher difficulty of implementation; instead, the Y-curve explicitly considers 12 factors as influencers of implementation of an abatement option. It is thus relevant to compare the "difficulty of implementation" assigned by these two curves to the 24 abatement options, to verify if and which new insights the Y-factor method is able to provide to the emission abatement debate.

The abatement potential and implementation cost assigned in McKinsey's MAC curve are reported in *Table 12* (below), as they were provided by McKinsey & Company to the investigation of Chappin (2016).
While [Vehicles]: Battery Electric Vehicles is not one of the 50 top-abatement potential options in McKinsey's MAC curve and is thus not highlighted in *Figure 20*, it is possible to retrieve its implementation cost from McKinsey's report (Nauclér & Enkvist, 2009) which, in *Exhibit 8.6.4* on page 100, reports it to be about 90 €/tonCO_2e, the highest Abatement Cost among the considered abatement options. The abatement potential is not unequivocally reported, as it is related to different scenarios characterized by a mix of transport technologies; as it is also not relevant for the comparison in object, it is not reported.

Following the ranking criterion set by McKinsey's MAC curve, it is then possible to rank the Abatement Cost figures in increasing order and compare their relative ranking to the respective ranking proposed by the validated Y-curve. To compare the options' rankings in the two curves, comparison criteria need to be set.

Considering the curves rank 24 abatement options, a ranking-difference of more than a third of the curve (8-spots) is considered to be “substantially different”. Ranking differences up to 8 spots are divided in 2 classes-of-similarities. Thus, the following three comparison criteria are set:

- An abatement option has a “most similar ranking” if this differs of less than 4 (≤ 4) positions in the two curves (color green);
- An abatement option has a “somewhat different ranking” if this differs between 4 and 8 (> 4 & ≤ 8) positions in the two curves (color yellow);
- An abatement option has a “most different ranking” if this differs of more than 8 (> 8) positions in the two curves (color red);

This comparison is the object of *Table 12* below; the abatement options are listed according to the ranking in McKinsey’s MAC curve, and thus according to their increasing Abatement Cost.

Table 12: Figures from McKinsey's MAC curve and ranking comparison with the Y-curve

Sector	Abatement Option	Abatement Potential [$MtCO_2e$ in 2030]	Abatement Cost [€/tCO_2e]	Y-value [out of 24]	Ranking MAC → Ranking Y-curve
Household Changes	Lighting switch incandescent to LEDs, residential	221	-253.1	2	1 → 1
Household Changes	Residential appliances	255	-195.8	10	2 → 13
Fuels	Bioethanol lignocellulosic	248	-138.8	15	3 → 17
Vehicles	Cars full hybrid	359	-72.9	3	4 → 2
Forestry & Agriculture	Cropland nutrient management	132	-68.8	6	5 → 5
Building	Building efficiency new built	624	-40.2	9	6 → 11
Industrial Processes	Clinker substitution by fly ash	189	-32	6	7 → 5
Waste	Electricity from landfill gas	351	-23.4	10	8 → 13
Vehicles	Air Transport	256	-20.5	5	9 → 3
Energy	Small hydro	329	-8.9	13	10 → 16
Energy	Geothermal	269	-3.9	16	11 → 19
Forestry & Agriculture	Grassland management	1,343	3.4	7	12 → 7
Forestry & Agriculture	Reduced deforestation from timber harvesting	262	6.9	16	13 → 19
Industrial Processes	Energy efficiency 1 Iron & Steel	246	8.2	8	14 → 9
Waste	Composting new waste	221	9.9	8	15 → 9
Energy	Nuclear	1,840	10.4	15	16 → 17
Forestry & Agriculture	Agronomy Practices	255	15.8	5	17 → 3
Vehicles	Cars plug-in hybrid	282	18.1	9	18 → 11
Energy	PV panels homes	1,216	27.9	7	19 → 7
Energy	High penetration wind	1,043	32.4	16	20 → 19
Forestry & Agriculture	Reduced deforestation from intensive agriculture conversion	1,208	39.9	16	21 → 19
CCS	Coal CCS retrofit	572	62.2	22	22 → 24
CCS	Coal CCS new built	1,620	64.6	18	23 → 23
Vehicles	Battery electric vehicles	/	90	11	24 → 15

Before analyzing the differences between the characterization of each abatement option in the two curves, some more general comparative remarks are presented below.

General insights from comparison

- 9 abatement options are assigned a "most similar" ranking in the two curves, 5 others have a "most different" one; the remaining 10 abatement options have a "somewhat different" ranking.
- Coal CCS technologies are recognized as the most challenging options to implement by both curves, and LED and HEVs among the easiest.
- The options PV panels homes and Battery electric vehicles are characterized by a substantially higher ranking in McKinsey's MAC curve than in the Y-curve. For these options, the outdated cost-figures available in 2009 (year of publication of McKinsey's MAC curve) are most evident, and large technological developments have occurred since then.
- Bioethanol lignocellulosic and Residential appliances are also amongst the most differently ranked abatement options; both have a category-score ≥ 2 for each category in the Y-curve, which highlights the relevance of non-financial barriers, not considered by McKinsey's cost curve.
- Agronomy practices are characterized in McKinsey's MAC curve by an Abatement Cost bigger than for the other options related to land-management practices (Cropland nutrient management and Grassland management), but such higher costs were not highlighted by experts in the interviews and are thus not reflected in the Y-curve.

To further compare the options' rankings proposed by McKinsey's MAC curve and the Y-curve, the latter can be decomposed in two sub-curves: the first only consists of "financial barriers", the three factors composing the category *A. Cost and Financing* and relatable to the financial analysis of a MAC curve; the other sub-curve contains the remaining nine, "non-financial barriers". This dissection exposes the similarities and differences between the financial barriers captured by the Y-curve and the financial figures proposed by McKinsey's MAC curve. The ranking of the two sub-Y-curves is presented in *Table 13* and compared with the ranking in McKinsey's MAC; the similarities and differences are highlighted with the aid of colors, referring to the previously established criteria (previous page, above *Table 12*).

Table 13: Ranking comparison McKinsey's MAC curve v. Y-curve - Financial and Non-Financial factors

Abatement Option	Ranking MAC → Ranking Y-curve	Financial Y-value [out of 6]	Ranking Financial Y-curve	Non-Financial Y-value [out of 18]	Ranking Non-Financial Y-curve
Lighting switch incandescent to LEDs, residential	1 → 1	1	4	1	1
Residential appliances	2 → 13	3	10	7	13
Bioethanol lignocellulosic	3 → 17	4	13	11	19
Cars full hybrid	4 → 2	2	7	1	1
Cropland nutrient management	5 → 5	0	1	6	8
Building efficiency new built	6 → 11	4	13	5	7
Clinker substitution by fly ash	7 → 5	0	1	6	8
Electricity from landfill gas	8 → 13	4	13	6	8
Air Transport	9 → 3	1	4	4	3
Small hydro	10 → 16	5	19	8	15
Geothermal	11 → 19	6	21	10	18
Grassland management	12 → 7	0	1	6	8
Reduced deforestation from timber harvesting	13 → 19	4	13	12	21
Energy efficiency 1 Iron & Steel	14 → 9	4	13	4	3
Composting new waste	15 → 9	2	7	6	8
Nuclear	16 → 17	6	21	9	17
Agronomy Practices	17 → 3	1	4	4	3
Cars plug-in hybrid	18 → 11	2	7	7	13
PV panels homes	19 → 7	3	10	4	3
High penetration wind	20 → 19	5	19	11	19
Reduced deforestation from intensive agriculture conversion	21 → 19	4	13	12	21
Coal CCS retrofit	22 → 24	6	21	16	22
Coal CCS new built	23 → 23	6	21	12	21
Battery electric vehicles	24 → 15	3	10	8	15

The results are surprising, as there are more abatement options with a ranking "most similar" to the one in McKinsey's MAC curve in the "Non-Financial" Y-curve than in the "Financial" one.

The ranking difference between McKinsey's MAC curve and the Y-curve substantially reduces (changing class-of-similarity) considering only "Financial Y-curve" for four abatement options, namely Reduced deforestation from timber harvesting and Energy efficiency 1 Iron & Steel and Battery electric vehicles and Residential appliances. In fact, for these abatement options the ranking in the "Financial Y-curve" is much more similar to the one in McKinsey's MAC curve than the latter is to the one in the Y-curve and in the "Non-Financial Y-curve".

Nevertheless, the ranking in the "Non-Financial Y-curve" is more similar to the one in McKinsey's curve than the ranking of the "Financial Y-curve" for some other abatement options which change class-of-similarity, as Building efficiency new built, Electricity from landfill gas, Grassland management and Nuclear.

This highlights how the figures in McKinsey's MAC curve are only partially capturing the financial implementation barriers highlighted by the Y-curve. Besides the fact that the Y-curve considers three factors rather than one variable(Abatement Cost) as McKinsey's curve, three other reasons can explain the ranking differences: the figures in this latest McKinsey's curve are largely outdated, and thus costs are considered by experts to have reduced; the variable Abatement Cost has a scale much more sensitive than the factors of the Y-factor method: the three financial factors can assume 7 different values (from 0 to 6) and thus abatement options are more likely to be assume the same score than in a MAC curve; lastly, the financial-factors of the Y-factor method do not capture cost-savings, which are instead included in the McKinsey's financial figures. Hence, while few conclusions on the similarities between the financial factors and the financial analysis of McKinsey's MAC curve can be drawn from splitting the Y-curve, the two sub-Y-curves confirm how much the ranking of abatement options changes when considering also non-financial factors.

Nevertheless, the scores presented by the validated Y-curve can explain why all the 11 abatement options ranked with a negative Abatement Cost in McKinsey's global cost curve and considered in this investigation are not yet implemented on a large scale (the limited diffusion of these abatement options can be verified in the existing literature summarized in *section 2.2* and in the summaries of experts' interviews in *Appendix F*). In fact, as it is displayed in *Table 14*, non-financial implementation barriers (factors belonging three non-financial categories: *Multi-actor Complexity, Physical Interdependencies,* and *Behavior*) account for 50% or more of the total barriers relevant for 10 of these 11 options, highlighted by their summed-scores. The missing option, Cars full hybrid, is characterized by a low overall Y-value (3), of which a third consists of non-financial barriers; considering its definition in McKinsey's report considers any vehicle with a start-and-stop system to be a hybrid vehicle, HEVs can be considered already largely diffused.

Table 14: Explanation of non-implementation of financially convenient abatement options according to McKinsey's MAC curve

Sector	Abatement Option	Abatement Cost [€/tCO_2e]	Y-value	Sum of Non-Financial Scores	% non-financial
Building	Building Efficiency New Build	-40.2	9	5	55.6 %
Energy	Geothermal	-3.9	16	10	62.5 %
Energy	Small hydro	-8.9	13	9	60.0 %
Forestry & Agriculture	Cropland nutrient management	-68.8	6	12	75.0 %
Fuels	Bioethanol lignocellulosic	-138.8	15	11	73.3 %
Household Changes	Lighting switch incandescent to LED (residential)	-253.1	2	1	50.0 %
Household Changes	Residential appliances	-195.8	10	7	70.0 %
Industrial Processes	Clinker substitution by fly ash	-32	6	4	50.0 %
Vehicles	Air Transport	-20.5	5	4	80.0 %
Vehicles	Cars full hybrid	-72.9	3	1	33.3 %
Waste	Electricity from landfill gas	-23.4	10	6	75.0 %

Detailed insights

For each of the 24 abatement options, whether characterized by a respective similar or different ranking to the one in McKinsey's MAC curve, the Y-curve provides new characterizing information which should be considered when debating the feasibility and implementation strategy of any of these abatement options. The most important new insights obtained for each abatement options are discussed below:

- The abatement option [Building]: Building efficiency new build has a different but consonant ranking in the two curves. It has a total Y-value of 9, consisting on the following four category-scores: A=4, B=2, C=1, D=2. Thus, *Cost and Financing* factors are recognized as dominant by the Y-factor method, which nevertheless highlights other-domain factors to be similarly relevant. The present but low scores of the three non-financial categories explain the different but consonant ranking of the option in the two curves.

- The abatement option [CCS]: Coal CCS new built and [CCS]: Coal CCS retrofit are placed by both curves on their far-right side, with both options assigned the maximum scores for the category *Cost and Financing*, and almost equally high scores for the other categories. Nevertheless, their relative ranking is swapped in the two curves, with McKinsey's MAC curve considering cheaper to retrofit a coal plant with CCS than building a new one. Two considerations are worth highlighting:
    1. The ranking in McKinsey's MAC curve is surprising, as both the interviewed experts highlighted repeatedly how retrofitting an existing coal plant with CCS is even more expensive than constructing a new plant already designed with CCS technologies, as spatial and interconnection constraints are very expensive to overcome.
    2. [CCS]: Coal CCS retrofit is assigned higher scores for two categories (*C, D*) than [CCS]: Coal CCS new build, 11 against 7, which unequivocally highlight the higher difficulty of retrofitting a spatially- and behaviorally-impactful CCS system on an operating coal plant.

- The ranking of the abatement option [Energy]: Geothermal is quite different in the two curves, as it is positioned in the first half of the McKinsey's MAC curve while it is one of the most difficult abatement options to implement according to the Y-curve. While the financial domain is recognized as the dominant one by the Y-curve, the *Multi-actor Complexity* is assigned a high relevance (score of 5 out of 6), while environmental impact and behavioral changes are present but minor issues. Different accidents as damages to households were cited by the interviewed experts, which created conflicts not only amongst the many stakeholders but especially with the population, as reported in the Italian newspaper *Corriere della Sera* (2013) informing over an earthquake in Switzerland caused by geothermal drilling: "Additional earthquakes in the coming days cannot be excluded in the region - is communicated from the Zurich Polytechnic - Thus, preoccupation raised amongst the population, while the those responsible for the project try reducing conflicts" (free-translation from Italian). Thus, it is recommended to focus on the stakeholders' interdependencies and conflict to increase the energy-supply from geothermal power.

- The ranking of the abatement option [Energy]: High penetration wind is very similar in the two curves, but the Y-curve estimates challenges about actors' interaction to be as relevant as financial ones. Additionally, the impact on the surrounding physical environment should also be adequately considered. Experts were surprised to consider for this abatement option a contribution >10% in the energy mix, highlighting the massive dimension of such figure.

- Similarly, the abatement option [Energy]: Nuclear has a very similar ranking in the two curves, were financial challenges are the most relevant (score of 6) but are closely followed by *Multi-actor Complexity* (score of 5), considering the negative public image nuclear energy has acquired over the years.

- Instead, [Energy]: PV panels home are ranked rather differently in the two curves, 19th/24 and on the right-hand side of McKinsey's MAC curve, and 8th /24 and in the middle of the left-half of the Y-curve. Considering the low-scores of the non-financial factors estimated by the Y-curve, a possible explanation for the large ranking difference is the year-of-publication of McKinsey's MAC curve. This was published in 2009, and since then PV-panel technology has become substantially cheaper, with pricing dropping 10% every year (Department of Energy, 2015), and a total drop of more than 70% since 2010 (SEIA, 2018). Such figures can explain the differences in the ranking, also considering the increasing amount of residential PV panels installations (SEIA, 2018).

- The abatement option [Energy]: Small hydro has a different but consonant ranking in the two abatement curves, both placing in the central part of the ranking. Nevertheless, McKinsey's MAC curve assigns to the option a negative abatement cost, while the interviews with experts have highlighted the relevance of investment cost: although lower than for standard hydropower plants due to the absence of mountaineering activities, investments are substantial and are expected to be paid back over 20 years, even with incentives for renewables. Moreover, an important part of the final Y-value of the option is caused by non-financial factors (categories *B*, *C*, and *D*), accounting for 8 of the total Y-value (13). Thus, it is suggested to not underestimate the investment costs of the small hydropower projects, which are attractive investments (as specified by *Dejonghe &* Sprengers from *Statkraft Markets BV*), but still require substantial funding. Moreover, project-specific needs as the modification of a river's flow-bed for improved stream-quality can cause considerable physical and behavioral impacts.

- [Forestry & Agriculture]: Agronomy practices is one of the abatement options for which the ranking in the two curves is most different, 3rd/24 for the Y-curve and 17th/24 for McKinsey's MAC curve. Such difference is explained but the low score (1 out of a maximum of 6) of the *Cost and Financing* category, while McKinsey's MAC curve estimates a relatively high abatement cost. Both interviewees agreed on the very limited implementation cost, and the figures of McKinsey's MAC curve are surprising. A possible explanation worth investigating further is the difference on opinion expressed by the interviewed experts over the effectiveness on such practices: while *Smith* mentioned higher land yields to be a consequence of agronomy practices, *Verhagen* highlighted how in certain areas these can often lead to lower productivity in the long term (after 10 years), thus causing a conceptually-negative pay-back time. This does not explicitly explain the high cost figures displayed by McKinsey's MAC curve but remarks uncertainties about this abatement option, which should be investigated further.

- [Forestry & Agriculture]: Cropland nutrient management has the exact same ranking in the two curves. McKinsey's MAC curve assigns it a negative abatement cost, somehow reflected in the score of 0 for the category *Cost and Finance* of the Y-curve. Thus, the abatement option is confirmed to be cheap to implement, and the Y-curve additionally suggests discussing actor-interactions, focusing on the ease of fertilizer supply, possible leaching of nitrate with consequent development of social conflicts, and the clarification of different tasks' performance.

- The abatement option [Forestry & Agriculture]: Grassland management has a different but consonant ranking in the two curves. McKinsey's MAC curve assigns it an Abatement Cost slightly above 0, comparable to the score of 0 assigned to the category *Cost and Financing*. Additionally, the Y-curve highlights the necessity of adapting some traditional practices regulating current grassland management procedures, and the possibility of social conflicts raising over shared portions of lands. These issues are nevertheless less relevant for [Forestry & Agriculture]: Grassland management than for other abatement options, and thus the positioning of the abatement option in the Y-curve is only slightly moved rightwards compared to the position in McKinsey's MAC curve.

- [Forestry & Agriculture]: Reduced deforestation from intensive agriculture conversion has a very similar ranking in the two curves, but non-financial factors are highlighted as relevant by the Y-curve. Considering the importance of the abatement options for developing countries, besides the financing capital needed to compensate land owners, it is necessary to account for the difficulties related to the involved of many institutions for the collection and distribution of the funds. Moreover, the disruptions of regular business-income for local population, invited to stop generational habits, should be strategically planned for.

- The ranking for the abatement option [Forestry & Agriculture]: Reduced deforestation from timber harvesting is more different in the two curves than the one of Reduced deforestation from intensive agriculture conversion but follows the same reasoning: the costs are present but limited, the crucial challenge is the management of the money-flow amongst stakeholders and the behavioral adaptations of local population. The main difference between the two options is the involvement of timber corporations, fact which introduces the additional complexity of lobbying and the need of considering the impact of reduced deforestation of wood-availability on the consumer-market.

- The drastically different ranking of the abatement option [Fuels]: Bioethanol lignocellulosic is difficult to interpret: it is assigned a highly negative Abatement Cost by McKinsey's MAC curve, while the Y-curve assigns it a complexity well-distributed across the four categories. In fact, the interviewed experts highlighted the high production costs, higher than common benzine, and the uncertainty of the market, besides the technical limit of 10-20 % mixing with regular benzine. Most problematic is the technical uncertainty recognized by both the interviewed experts, who highlighted how secondary-biofuels share some of the problematics affecting primary-biofuels, as their large-scale effectiveness and cost efficiency remains unproven.

- Fewer uncertainties seem characterizing the abatement option [Household changes]: Lighting switch incandescent to LED (residential), ranked as the option with smaller implementation barriers by both curves. Overall costs are very limited (10 €/bulb), but the perspective with which the Y-curve was constructed can help explaining the difficulty still hampering a large diffusion of LEDs: the cost of an abatement option should not only be considered in total, but also from the perspective of those having the power of implementing it, which in this case are the buyers. As the interviews with experts highlighted, buyers are not inclined to face an expense ten-times higher than otherwise possible in name of future savings, even with these are guaranteed. Moreover, the Y-curve highlights the existence of some educational barriers. Thus, while considering LEDs a viable, cheap technology for achieving energy-savings, it is pivotal to focus on reducing their market-price, or to provide incentives able to reduce buyers' fear and simplify the purchasing-process.

- Surprisingly, [Household Changes]: Residential appliances are ranked 2nd/24 in McKinsey's MAC curve, with a deeply negative implementation cost, while the abatement option is located in the middle of the Y-curve. A partial reason for this could be the definition issue highlighted in *section 4.3.*6: the interviewed experts agree on the high energy-efficiency of most residential appliances currently installed and available on the market; they highlighted how the technology able to increase the energy-efficiency of appliances is their smart-component, able to deal with increasingly fluctuating energy prices caused by renewables. These smart-components are not diffused yet and are still characterized by high prices. Additional implementation barriers which should be considered are: the collection and management of the energy-consumption data of the appliances, needed for the functioning of smart-components; the definition of behavioral changes (e.g.: is a dishwasher starting at 8am rather than 8pm a behavioral change?). The definition and the impact of behavioral changes are subjective and can obstacle the diffusion of appliances. Thus, it is suggested to update the definition of the abatement option to include current technological developments, and to consider carefully data-management and behavioral incentives to encourage the adoption of smart, energy-efficient appliances.

- The abatement option [Vehicle]: Air Transport has a different but consonant ranking in the two curves, both placing it in their left-most quarter. The major issue with this abatement option is its multi-form definition which, as remarked by *Blok*, actually entails multiple abatement options. This makes its discussion and implementation difficult, and it is thus recommended to decompose it. These sub-components are very different, but mostly centered on OE and Alternative Fuels, both still posing technical challenges. The international political scene, aiming to decrease pollution from air transport is a driving force which should first set the boundaries within which to develop technical and operational solutions.

- The abatement option [Vehicle]: Battery Electric Vehicles is not one of 50 options classified by McKinsey's MAC curve with the highest abatement potential and is thus not displayed in *Figure 20* nor considered by Chappin (2016). Nevertheless, an abatement cost of 90 €/tCO_2e is displayed in McKinsey's report (Nauclér & Enkvist, 2009, *Exhibit 8.6.4*, p. 100); this cost figure is by far the largest amongst the considered options, placing [Vehicle]: Battery electric vehicles on the far right-hand of McKinsey's MAC curve. Since 2009, BEV-technology has become cheaper, as witnessed by the market introduction in 2018 of the Nissan LEAF, with a price comparable to ICEs of its class. It is thus needed to revise the Abatement Cost figures for BEVs, and it is recommended to discuss the other implementation barriers highlighted by the Y-curve: dependency on the recharging infrastructure and the derived range-anxiety, and municipal landscape adaptation. A chicken and egg paradox arises: how to introduce the recharging infrastructure introduce while few BEVs using it are circulating, but which is necessary to encourage the diffusion of BEVs?

- The ranking of the abatement option [Vehicle]: Cars full hybrid in the two curves is very similar, with both curves considering it one of the abatement options with fewer implementation barriers to overcome. The increasing popularity proven by the figures from CBS (2015) is even underestimating the general diffusion of HEVs as defined by McKinsey's MAC, which include a variety of simple, highly diffused technologies such as start-and-stop systems.

- The abatement option [Vehicle]: Cars plug-in hybrid has a somewhat different ranking in the two curves, with the Y-curve positioning it in its center while McKinsey's MAC curve places it in the middle of its right-hand side. A first explanation relates to the financial costs of PHEVs, which have decreased since the release of McKinsey's MAC curve in 2009 thanks to the technological advancements, favoring their diffusion (CBS, 2018). Nowadays, financial drivers do not seem to be the main barrier to implementation, and the Y-curve suggests focusing on the reliability of the recharging infrastructure. This should be introduced organically with the other municipal needs (e.g.: division of parking slot between PHEVs and ICE vehicles), to minimize conflict and reduce the range-anxiety which risks hampering a large-scale adoption. This is the same chicken and egg paradox mentioned for BEVs.

- The two abatement options from the [Waste] sector, Composting new waste and Electricity from landfill gas have different but consonant rankings in the two curves. The costs of implementing waste composting do not seem the main challenge according to the Y-curve, which rather highlights the systemic interdependencies amongst stakeholders and the reliance on a qualitative waste-separation by the population, who incurs a clear disruptions and complication of regular waste disposal operations.

- Y-curve recognizes financial barriers as the most relevant ones for implementing the production of electricity from the collected biogas, because of the additional needed infrastructure to collect and burn the landfill gas and to connect the landfill to the power distribution grid. Surprisingly, McKinsey's MAC curve assigns a negative Abatement Cost to [Waste]: Electricity from landfill gas, and even more surprisingly, this is lower than the abatement cost assigned to [Waste]: Composting new waste. Besides the additional costs, the production of electric power augments the interaction between the landfill and the players of the energy sector, and it is thus important to consider power-producing landfills just as other small power plants.

Chapter 5: Applications for Energy Strategies

Discussion of applications with players developing energy strategies

This chapter presents the outcomes of discussions with players responsible and/or consulted for drafting energy strategies, and thus dedicating to the sustainable transformation of society. The goal of the discussions is to verify the relationship of the consulted players with emission abatement curves, their opinions and uses of MAC curves such as McKinsey's, and to introduce them to the Y-factor method and the validated Y-curve. The consulted players can provide indications on the possible applications they envision for the Y-factor method and the Y-curve, also highlighting strengths and weaknesses which can be remarked or improved. *Section 5.1* introduces the consulted players and the backbone-structure of the conversations, while *section 5.2* presents the individual remarks collected during the discussions.

5.1 Consulted players and Methodology

The validated Y-curve has confirmed how the Y-factor method is able to provide new insights to the emission abatement debate, and the relevance of the 12 factors has been verified relying on the opinions of the interviewed experts. Hence, the fit-for-purpose of the Y-factor method can be now further tested. In fact, the emission abatement debate has the goal of finding solutions effectively able to reduce GHG emissions; thus, it is interesting to verify if the insights provided by the validated Y-curve can support the efforts of energy strategists aiming to reduce air pollution. This entails attesting if energy strategists believe the Y-factor method is able to highlight relevant implementation barriers, which need to be tackled for implementing effective emission abatement options.

Three types of players responsible and/or consulted for the development of energy strategies can be identified: governments, governmental agencies advising the government, and energy service companies advising and/or providing energy solutions to private businesses and at times supporting governmental agencies and governments. These three types of players are not the sole existing ones but are three important types which can be clearly identified.
Thus, also considering the time constraints of this thesis research, a representative of each type active in The Netherlands was contacted to discuss the validated Y-curve and the Y-factor method and their potential applications. The consulted players are reported in *Table 15* (below).

The contact persons were provided a brief description (less than 100 words) of the theme of this master thesis research and asked for a 1-hour meeting. The meetings were performed face-to-face and as unstructured-interviews, to allow the consulted persons to provide their comments as freely as possible. Nonetheless, the conversations evolved around three main themes, and were aided by similar power-point slides: Opinion and use of MAC curves such as McKinsey's, opinion on the Y-factor method and the results displayed in the validated Y-curve, and possible envisioned usage of the Y-factor method.

Table 15: Consulted energy strategies and affiliations

Type	Player	Contact Person(s)	Role
Government body	Ministerie van Economische Zaken en Klimaat - The Netherlands -	Mr. Wouter Schaaf	Programmadirectie Energieuitdagingen 2020 - Directoraat Generaal Energie, Telecom en Markten
		Mr. Frans Duijnhouwer	
		Mr. Dennis Holtrop	
Governmental agency	Planbureau voor de Leefomgeving (PBL)	Mr. Robert Koelemeijer	Policy Researcher - Sector Klimaat, Lucht en Energie
Energy service - consulting	ECOFYS	Mr. Kees van der Leun	Managing Director

5.2 Potential Applications for the consulted players

This section presents and discusses the outcomes of the conversations with the consulted players. Each meeting is reported individually, to highlight the different perspectives collected; for each meeting, the collected comments are reported according to the themes touched during the consultation: Current approach to emission abatement, Opinion on the Y-factor method and the results displayed in the validated Y-curve, and possible Envisioned usage of the Y-factor.

After the presentation of the collected comments, a separate paragraph is dedicated to discussing the collected opinions.

DISCALIMER: All conversations with the indicated energy strategists had a personal connotation, and the reported comments should not be in any form considered as official positions of the institutions to which the contacted persons are affiliated.

5.2.1 Duijnhouwer, Holtrop, Schaaf - Ministerie van Economische Zaken en Klimaat

While the opinions expressed by the three interlocutors are reported per theme without distinguishing individual opinions, not every comment was supported and/or mentioned by all three persons. Nevertheless, all the comments reported below were explicitly mentioned during the conversation.
Duijnhoiwer and Holtrop have background in *Economics*, Schaaf in *Econometrics.*

Current approach to emission abatement

All the three interlocutors are familiar with the concept of emission abatement curves, and often utilize McKinsey's MAC curve in their works. They are also aware of the inability of McKinsey's MAC curve to capture the complexity characterizing the implementation of emission abatement options, as they recognize the difficulty in explaining why abatement options ranked as financially convenient are not implemented. Thus, depending on the projects, the interlocutors try to consider additional, non-financial factors which might be relevant for the specific project at hand; no systematic approach is used to discuss implementation barriers, but the interlocutors mentioned how they are aware of non-financial functions suggested by Hekkert et al. (2007), which they use as guideline to identify relevant problematics to consider.

Opinions on the Y-factor and the Y-curve

All the three interlocutors acknowledged the importance of including in the discussion implementation barriers hampering the introduction of emission abatement options, accepting the 12 factors proposed by the Y-factor method as relevant, and highlighting the validity of the ranking of the abatement options presented by the Y-curve.

Specifically, the interlocutors believe the Y-factor to be the result of a reasoning similar to the one of Hekkert et al. (2007), and consider the Y-factor method and the Y-curve as valuable additions to the emission abatement debate: they explicitly list those specific non-financial themes needing to be considered in the policy-debate, which the interlocutors are normally trying to consider project-specifically, without relying on any supporting framework.

Because of its structure, the interlocutors believed the Y-curve to be suggesting a quantitative comparison between the ranked abatement options, rather than the intended qualitative comparison of the difficulties of implementation.

The interlocutors considered factors capturing the impact of political and policy preferences on the ranking of abatement options to be missing in both the Y-factor method and McKinsey's MAC curve; the interlocutors remarked the importance of policy and political barriers by highlighting how subsidies are for instance often assigned by swinging political favor and how they can change entirely the implementation paths of different abatement options.
Moreover, they highlighted the importance of the reputation of McKinsey's MAC curve: this carries McKinsey's stamp which, associated to quantitative figures, allows McKinsey's global cost curve to be presented in a straightforward fashion, inspiring trust and facilitating its employment by politicians and parliamentarians who have little knowledge on GHG emissions and little time to investigate graphs. Besides having a lower ease-of-use, the Y-factor method does not currently have a reputation which can inspire users as McKinsey's curve does.

Envisioned usage of the Y-factor

The interlocutors believe that Y-factor method can effectively support the policy-making process, as it considers very different factors, which should be explicitly discussed. More than for comparing abatement options, the interlocutors believe the Y-factor method can be used to discuss individual issues which should be tackled to implement a new, specific emission abatement option or to modify an individual policy which is not returning the intended outcome.

Thus, the interlocutors envision the following use of the Y-factor method: McKinsey's MAC curve would be considered first, and successively the 12 factors could be used to a) explain and discuss why an abatement option which seems financially convenient is not effective or b) what themes should be discussed before releasing a new policy. For this, the 12 factors would have to first be weighted depending on the considered situation, and then specific policy-instruments can be selected to tackle the most problematic issue. The Y-factor method is considered to be specifically helpful in facilitating the debate of a broader set of policies: these are usually boxed depending to their relative domain, and it is thus challenging to jointly diverse policies; with its multi-domain approach, the interlocutors believe the Y-factor method to be helpful in identifying the institutional instruments better suited for a specific context, either leading to the introduction of new policies or to tuning existing ones.

The interlocutors commented how policy analysis and policy making for emission abatement is usually option-specific. Thus, they envision discussing the individual factors rather than the Y-curve, as the formers are more adequate for debating individual abatement options. In this perspective, it was remarked how many more factors than the ones highlighted in the Y-factor method ought to be considered for fully characterizing an individual abatement option.

Workshop

The discussion concluded with a brief workshop in which the interlocutors were asked to select one of the 24 ranked abatement options and to underpin every one of the 12 factors considered relevant (score $\neq 0$) with existing or proposed policies.
The selected option was [Energy]: High penetration wind, and the following measures were mentioned for tackling the 12 factors:

A1: FIT and tenders.
A2-A3: Policies (as FIT and tenders) to reduce pay-back to 15 years over the 30 years of turbines' lifetime; last tender won at 0 €/KW.
B1: Collaboration between stakeholders is prescribed in tenders' descriptions.

B2: Ad-hoc planning to consider and solve possible conflicts, before the tender is issued.
B3: See B1.
C1: "Milieu Effect Rapportage (MER)" = Assessment of Environmental Impact, project specific.
C2: Minor, thus not considered (score = 1).
C3: /
D1: No educational programs but shared benefits to involved communities.
D2: /
D1-D3: Considered upfront, to avoid problems due to environmental impact.

The interlocutors highlighted how *Cost and Finance* is the category which the *Ministerie van Economische Zaken en Klimaat* can impact the most, while the factors belonging to the category *Multi-actor Complexity* are the ones most difficult for the Ministry to consider. Moreover, environmental impact (which the interlocutors connected to the *Physical Interdependencies* category) is one of the major themes considered when drafting a policy, and *Behavioral* factors are normally considered up-front, to reduce the environment impact caused by the implementation of an abatement option or an environmental policy. During the discussion the following question was raised by the interlocutors: "Would it be possible to construct a more quantitative tool which also has space for the 12 factors?"

TAKEAWAY MESSAGE and COMMENTARY

The interlocutors are knowledgeable on the topic of emission abatement curves, and McKinsey's global cost curve is evidently a well-known tool to all of them. The goal and value of the Y-factor method were quickly understood and acknowledged, as a tool including non-financial themes in the debate; these seem to be recognized as important at the *Ministerie of Economishe Zaken and Klimaat* but are not discussed with any ad-hoc framework. In particular, the results of the workshop demonstrate how the Y-factor method is able to foster discussion on the measures implemented to tackle specific implementation barriers. As highlighted by the interlocutors, the Y-factor method helps considering a broader set of policies than usual, as policies belonging to different domains are more easily confronted; this supports the policy-making process.

While there can be similarities in the approaches, the Y-factor method and the 7 functions highlighted by Hekkert et al. (2007) have entirely different scopes and applications. In fact, the 12 factors are specific for the implementation of emission abatement options while the 7 functions are generic, and thus not directly applicable. Hekkert's 7 functions can be considered providing conceptual guidelines, while the Y-factor is a research method. Because of the additional effort needed to apply the highlighted the 7 functions to the specific emission abatement debates, implementation barriers risk to be only marginally and/or superficially discussed.

Political preferability and policies' impact are intentionally ignored by the Y-factor method as much as by McKinsey's analysis (Nauclér & Enkvist, 2009, p. 21); this is logical considering how emission abatement curves are a tool to take political and/or policies decision rather than graphs describing their consequences. While it is understandable the wish expressed by the interlocutors to visualize the consequences of implementing different policies, emission abatement curves are not the adequate tool for it. Rather, consequences of decisions and policies could be better captured by simulation models, such as Agent Based Models: describing the implementation barriers and how these are affected by different policies for multiple abatement options in a NetLogo model can provide additional guidance. In fact, such model could show how the ranking of the abatement options provided by the Y-curve changes according to the potential implementation of specific policies. Nevertheless, consequences are more dynamic concepts than barriers, and it is thus extremely complex to model the many variables which might influence/be influenced by them.

Some doubts on the direct employability of a Y-curve in the presented structure were raised: while an emission abatement curve cannot and does not intend to substitute a detailed per-option analysis, I believe the Y-curve can provide value in its current form, immediately pinpointing to the most critical themes to be further discussed. In fact, the brief workshop performed highlighted how the 12 factors can initiate a discussion on the existing policies and on which barriers they intend tackling.

5.2.2 Koelemeijer - Planbureau voor de Leefomgeving (PBL)

Current approach to emission abatement

Dr. Koelemeijer is an expert of MAC curves and is highly aware of financial approach they follow; amongst MAC curves, McKinsey's cost curves are recognized as the most popular. Koelemeijer personally uses McKinsey's MAC curves only in presentations, as they provide nice and indicative illustrations, but are not considered useful for detailed analysis. In fact, there are too many problems which hamper trust such as:

- many conceptual and financial assumptions have had to be taken to construct the curves, which reduce the generalizability of the displayed figures;
- geographical scopes are hard to define and have large impacts on financial figures. For instance, a policy to increase the market price of gas in the Netherlands might easily reduce GHG emissions from Germany, where the marginal, non-dispatched gas plants might be located;
- aggregation of abatement potentials is questionable, as interdependencies amongst abatement options are ignored.

Rather than on McKinsey's MAC, to perform energy analysis PBL relies on a self-developed modelling tool, called "Energy System Simulation": it models possible technological and GHG-emissions developments and tries to predict or justify investment decisions. The model combines the Net Present Value (NPV) of technologies to other relevant factors such as technological complexity and public opinion; these are scored individually and combined to achieve the "motivation factor" of each abatement option. The highest investment is and/or should be destined to the abatement option characterized by the highest motivation factor.

Opinions on the Y-factor and the Y-curve

Dr. Koelemeijer believes the Y-factor method to be very relevant for the emission abatement debate, as it provides a framework which can be employed to structurally considered implementation barriers. He acknowledged the importance and relevance of the 12 proposed factors, and accepted the Y-curve, recognizing it as valid and able to expose issues which need to be tackled. Moreover, Koelemeijer highlighted how these issues undoubtedly influence sustainable decision-making and are not captured by cost curves. In fact, he remarked how creating a tool tackling "soft" problem is a large struggle, but also a very important one.

Besides finding the Y-factor method simple to understand and able to foster relevant discussions, Koelemeijer mentioned how the factors belonging to the category *B. Multi-actor Complexity* can be considered tackling institutional problems, while the ones of the category *C. Physical Interdependencies* to focus more on technical issues. The Y-factor method was considered somewhat comparable to the previously mentioned modelling tool used at PBL, and the specific variables modelled into the PBL tool were conceptually considered sub-factors of 12 highlighted factors. While it is difficult to always consider many, very specific variables as the PBL model does, Koelemeijer mentioned how the 12 factors are able to expose relevant themes, from which potential sub-variables can be derived and discussed in more detail. Examples of specific similarities between the factors and the variables considered in the PBL's model are:

- *B3 Division of roles and responsibilities unclear* & "technology pick up over time";
- *D2 Frequency of opportunity* & "status on S-curve".

Table 7 (page 90) summarizing the validated scores and their uncertainty is considered extremely appealing, as more informative than the individual variables currently considered in PBL's model, whose scores always appear subjective to the user. Instead, such table is judged functional in highlighting the most critical and/or debated themes.

Finally, Koelemeijer suggested including an additional factor in the *Cost and Financing* category to capture "cost uncertainty", which is how much the implementation of an emission abatement option would finally cost. He remarked how this is particularly relevant for retrofit-technologies which, interfacing with existing structures, might entail unplannable costs.

Envisioned usage of the Y-factor

Koelemeijer believes the presented Y-curve, possibly expanded and relying on more numerous experts' opinions, can be used as global reference; multiple local Y-curves can be additionally developed to support decision-making in specific contexts. While the structure of the Y-factor method can remain the same, the scores would have to be changed depending on the analyzed context to construct locally-relevant Y-curves; similarly, weights could be assigned to the factors, tailoring their importance to the analyzed context. Nevertheless, fixed weights are considered inaccurate also for a specific context. Hence, rather than fixing them, Koelemeijer suggested to temporarily assign different weights to each factor, to see how different scores impact decisions, thus exposing the robustness and sensibility of a strategic-choice.

Moreover, the development of new tools combining different approaches to the emission abatement debate and studying a "best" approach to jointly consider the various insights (e.g.: figures provided by McKinsey's MAC, the barriers highlighted by the Y-curve, and the variables used in PBL's model) is suggested. While some tools combining the approaches can be helpful for the discussion, these should not be too elaborated to avoid confusions between intrinsically different approaches and information. More benefits are expected to be gained by jointly using the different approaches and some basic-combination tools.

Finally, Koelemeijer showed much interest in performing specific research to integrate the insights from the Y-factor method with the model(s) used at PBL, to ensure the most relevant aspects are covered in the models and to reflect the variability of the opinions as in scores & uncertainty table.

TAKEAWAY MESSAGE and COMMENTARY

Koelemeijer positively welcomed the Y-factor method and the Y-curve, as he already is skeptical about the usefulness of cost curves such as McKinsey's for the performance of specific analyses. Besides the presented Y-curve and the approach to emission abatement it encourages, Koelemeijer was rather enthusiastic about the possibility of structurally compare the opinions of different experts on "soft" topics, which PBL already considers relevant and tries to model in its tool; nevertheless, these variables are normally assigned subjective values. Instead, it was particularly satisfactory how Koelemeijer did not only appreciate the Y-curve but also remarked how the scores displayed in *Table 7* provide new information, by highlighting the differences of opinions of experts.

The suggestion by Koelemeijer of adding an additional factor is interesting as it highlights the relevance of an additional variable, which is how much the necessary investment is unknown/variable. This proposal clearly belongs to the category of *Cost and Financing* and it captures a relevant barrier, mirroring the factor *C3 Technology Uncertainty* and to a lesser extent *B3 Division of roles and responsibilities unclear*. The proposal should be further investigated to understand if this theme is already incorporated in an existing factor or how to include it if it is not. I believe the factor *A3 Difficulty in financing the investment* does already capture part of the barrier, as investment uncertainty brings more financing difficulties as a frequent consequence.

Overall, the presented results were considered functionally able to structure the emission abatement debate, supporting the drafting of effective energy strategies. The specific investigation for integrating the Y-factor method with PBL's modeling tool is highly intriguing and promising.

5.2.3 Van der Leun - ECOFYS

Current approach to emission abatement

Mr. van der Leun confirmed the popularity of MAC curves and in particular of McKinsey's global cost curves in the emission abatement debate. He recognizes the purely-financial approach proposed and supported by these curves, approach which he also considers to be dominant in the emission abatement debate. While acknowledging the importance of working with accurate financial figures, van der Leun criticized the uncontested dominance of financial arguments in the emission abatement debate and in the entire context of sustainable development, disputing their ability to explain reality: McKinsey's MAC curve is evidently not sufficient to discuss the implementation of emission abatement options, and the emission abatement debate ought to include non-financial factors.

Moreover, van der Leun added how adjusting the *Discount Rate* has become a procedural practice to account for implementational, non-financial difficulties. This results in reports only highlighting financial figures, with non-financial issues relegated under an asterixis next to them, and thus most often disregarded.

Opinions on the Y-factor and the Y-curve

Mr. van der Leun strongly believes in the importance of considering implementation barriers besides financial costs and thus positively welcomed the Y-factor as a method capturing relevant barriers and fostering their explicit consideration; he remarked how discussing these barriers can effectively help implementing abatement options. Moreover, he recognized the validity of the validated Y-curve, crediting it to display a genuine ranking of the abatement options able to support useful discussions.

In particular, van der Leun considered the Y-factor method and the conceptual approach it proposes of easy understanding, and immediately judged it as valuable. He also added how the systematic structure proposed by the Y-factor method and resulting in the Y-curve is fundamental to avoid reducing the non-financial features to a disregarded asterixis. Van de Leun judged the 12 factors to be a good amount, sufficient to stimulate a rich discussion but not too numerous to discourage it; he recommended not to weight the factors as long as they have "the same order of magnitude". Van der Leun also believes the Y-factor method not only to facilitate the analysis and comparison of emission abatement options, but also to help ideating strategies to improve the definition/design of the discussed abatement options, as relevant problems are exposed. The importance of using the same actor-perspective when scoring abatement options on such different criteria was also highlighted, confirming the relevance of *Scope 1* in *section 4.3*.

Then, van der Leun suggested some possible ideas for the improvement of the Y-factor method:

- Including in the Y-factor method not only the problems hampering the implementation of abatement options but also of the "co-benefits" caused by their implementation, either as a separate category/factor or as negative scores of existing factors. Co-benefits represent the attractiveness of an emission abatement option, which van der Leun explained with the following example: in the traffic-clogged city of Cairo, the proposal of BEVs does not solve any of the population problems on its own. Instead, implementing better, sustainable public transport alongside BEVs reduces not only GHG emissions but also traffic and bad-smelling air, thus co-benefitting the population.
- Including the abatement potential displayed on the X-axis of McKinsey's MAC on the X-axis of the Y-curve.
- Highlighting if and/or how much some of the scores can be adaptable depending on the considered situation.

Envisioned usage of the Y-factor

Van der Leun mentioned how he can envision using the Y-factor method in his company's activities; he imagines employing the Y-factor method to identify the most promising solutions from a numerous pool, and thus direct available resources on the identified, most promising solutions. Within the theme of strategic resource allocation, the Y-factor method would be used differently, dpending on the users' target:

- Governmental bodies could use the Y-factor method to focus the debate on the most problematic issues and/or to select specific abatement measures to support with policy.
- An energy service company, like ECOFYS could use it to:
  - Perform a selection of the potentially-interesting services to further analyze and sponsor, thus in the early stage of strategy-development process (Strategy). E.g.: Advising about hydrogen-technology applications, currently at the niche status;
  - Direct marketing funds on truly promising/implementable service offers (Financing);
  - Explain products' sales-trends and modify products' design to modify some of their features highlighted as limiting for the products' market performance (Product Development).

Van der Leun commented how users of the Y-factor method and the Y-curve are most likely willing to assign their own scores, depending on the context at hand. Hence, a general Y-curve could be used for comparison and reference. From this perspective, van der Leun enphasized the need of providing accurate definitions not only of the 12 factors but also of the possible alternative values to assign to each of them; users could be guided in assigning the scores, developing a detail recipe-guide or an ad-hoc software.

The discussion concluded asking van der Leun what he would personally do with the Y-factor method. He mentioned how he is keen to learn more about it and highlighted three successive steps:

1. Study the factors to master them;
2. Consider if he envisions some general/specific methodological and definitional tweaking (e.g.: new scale values);
3. Add the Y-factor method to his own toolbox, discussing it with other consultants at ECOFYS so that it can become a commonly-available tool. No immediate applications for ongoing projects were evident.

TAKEAWAY MESSAGE and COMMENTARY

Van der Leun welcomed very positively the Y-factor method, considering it a new approach to emission abatement curve able to expand its current focus beyond financial parameters; he believes the current purely-financial approach to be limiting the debate on sustainable development. He proposed to consider some methodological modifications which are mostly relatable to the personalization of the Y-factor method, as additionally considering how much an emission abatement option is attractive for a specific context and the flexibility of individual scores.

In particular, the proposal of including the co-benefits deriving from the implementation of an emission abatement option is very interesting and relevant: co-benefits can increase the attractiveness of an emission abatement option, favoring its implementation. The range of possible co-benefits is likely to be broader than the list of implementation barriers considered by the Y-factor method: while the factors refer to a specific moment (the implementation) and to an individual abatement option, co-benefits may be experienced over a more extended time and are likely not to be exclusively related to abatement to the considered abatement option. Thus, it is difficult to imagine analyzing co-benefits related for each of the 12 factors, possibly in the form of negative scores as proposed by van der Leun. A fifth category might be better suited to include co-benefits, as it would suggest a reasoning different from evaluating the relevance of a specific implementation barrier. This fifth category could possibly comprise *Financial benefits*, *Societal benefits* and *Technical benefit*.

It is exiting to reflect on the multiple applications of the Y-factor which van der Leun envisions for an energy service company, as they prove how the Y-factor method is a flexible tool, which can support a very diverse range of activities. Particularly, it is worth to further investigate the elaboration of a recipe/software able to guide users in applying the Y-factor method; this could allow a more rapid analysis, while favoring a rigorous and accurate application.

The envisioned possible applications of the presented results for ECOFYS' activities and the proposal of developing a recipe/software to score emission abatement options emphasize how van der Leun considers the Y-factor method ready for implementation.

5.3 Combined takeaway and Proposal of a combined tool

The consultations with players regularly involved in the emission abatement debate provided many different insights and comments. The first and most important takeaway-message is how every one of the consulted players recognized the relevance of the 12 factors, remarking the importance of explicitly discussing implementation barriers of emission abatement options. Moreover, all the consulted energy strategists accepted the Y-curve as a valid ranking, although some are doubtful on its possible direct employment.

More specifically, the following conclusions can be drawn from the three conversations reported in the previous paragraph:

Emission abatement cost curves, and in particular McKinsey's global cost curves, were confirmed to be the dominant tool in the emission abatement debate; the extent to which these are used and trusted is variable, depending on personal opinions the projects' specifics. Nevertheless, the importance of adding a non-financial perspective to the emission abatement debate was emphasized in all discussions, as the financial figures showed in McKinsey's MAC curve are recognized as insufficient for developing effective strategies.

Besides of easy understanding and employment, the Y-factor method was recognized able to capture relevant themes which are normally not tackled and/or reported explicitly. The consulted players expressed the interest of using it in their professional activities, in different fashions and tweaking it according to the contextual needs.
Three main applications for the Y-factor method are envisioned:

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Three points for further reflections were highlighted:

- Is there worth in considering extending the tripartite scale? Two possible extensions are:
  - 5-value scoring scale (No/Zero, Little, Medium, Much, Yes/High), as often remarked in the experts interviewed for the Y-scores validation;
  - negative values to include the attractiveness of an abatement options depending on the co-benefit it enables.
- In which way can a validated Y-curve provide useful insights to the emission abatement debate? The consultations with energy strategists have suggested that the Y-curve can mainly be used as a reference for users who tweak and apply the Y-factor method themselves, according to the specific situation at hand, possibly assigning a weight to the individual factors.
- Is it possible to construct a tool which combines the insights provided by both the Y-curve and McKinsey's MAC curve? How could this look and what uses might it enable?

One of the reasons for which McKinsey's MAC curve is extremely popular is McKinsey's reputation, which encourages immediate trust in the displayed figures. Thus, to be able to complete weaknesses in MAC curves such as McKinsey's, the reputation of the Y-factor should be sponsored. Effective and rapid strategies to increase the reputation of the Y-factor method remain to be investigated; an option could be to partner with McKinsey and/or with other renowned corporations which can hopefully endorse the Y-factor method, thus enhancing its reputation and participating in its diffusion.

Concluding, the implementation barriers highlighted by the Y-factor method have been recognized as relevant and handy for strategy-making. The consulted players showed interested in a tool able to combine the information from the two curves (McKinsey's MAC curve and Y-curve); a detailed investigation on the most effective structure and applications of such tool shall be the object of future research. A possibility is to jointly display in a graph the overall Y-value of each abatement option alongside their Abatement Cost from a MAC curve; the Y-values could then be used as warning-flags, highlighting those abatement options which is fundamental to debate beyond their differently promising financial figures.
Critical would be to update the financial figures of developing technologies regularly, to account for technological developments.

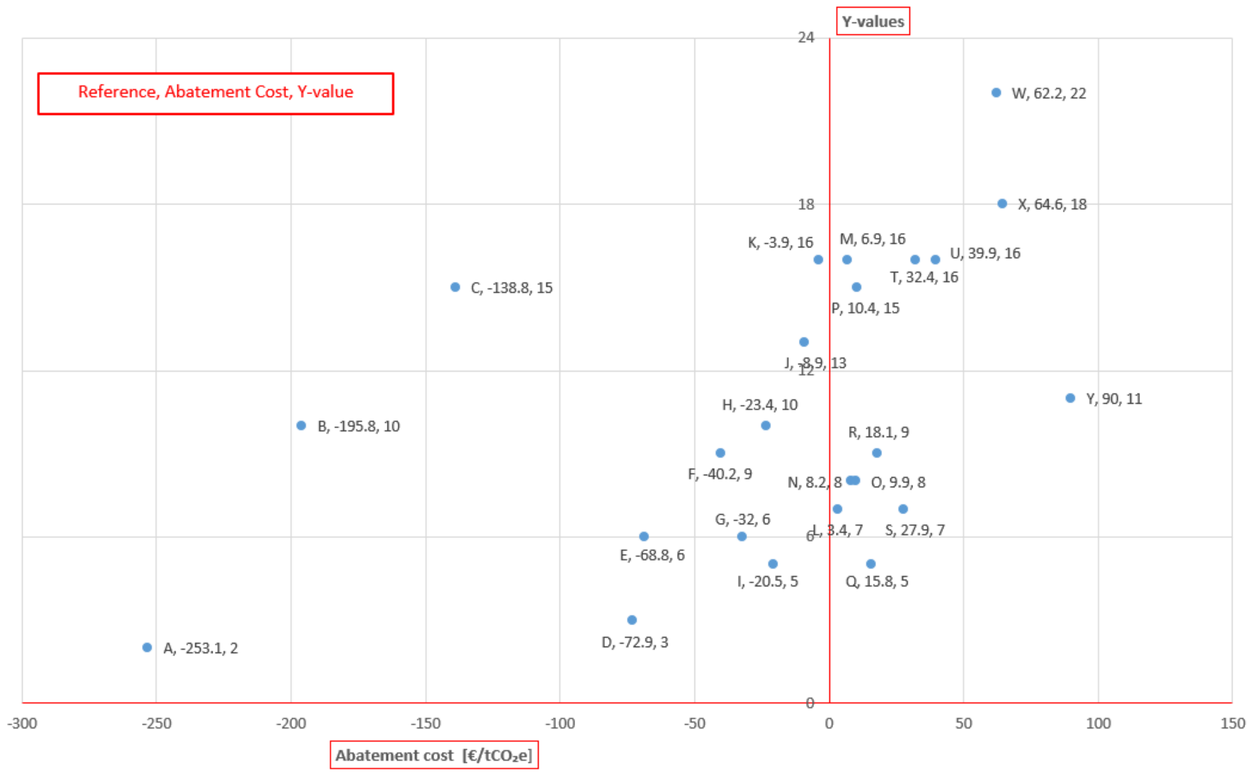
This first proposal of a tool combining the information displayed in the validated Y-curve with the financial figures provided by McKinsey's curve is presented in *Table 16* and *Figure 21* below.

The letters introduced in *Table 16* are used as reference for an improved visualization of *Figure 21*. Each dot represents an abatement option, characterized by its (reference letter, Abatement Cost, and Y-value).

Table 16: McKinsey's MAC curve and Y-curve: combined figures for a new tool

Abatement option	Graph Reference	Abatement cost [€/tCO_2e]	Y-value
Lighting switch incandescent to LEDs, residential	A	-253.1	2
Residential appliances	B	-195.8	10
Bioethanol lignocellulosic	C	-138.8	15
Cars full hybrid	D	-72.9	3
Cropland nutrient management	E	-68.8	6
Building efficiency new built	F	-40.2	9
Clinker substitution by fly ash	G	-32	6
Electricity generation from landfill gas	H	-23.4	10
Air transport	I	-20.5	5
Small hydro	J	-8.9	13
Geothermal	K	-3.9	16
Grassland management	L	3.4	7
Reduced deforestation from timber harvesting	M	6.9	16
Energy efficiency 1 Iron & Steel	N	8.2	8
Composting new waste	O	9.9	8
Nuclear	P	10.4	15
Agronomy Practices	Q	15.8	5
Cars plugin hybrid	R	18.1	9
PV panels homes	S	27.9	7
High penetration wind	T	32.4	16
Reduced deforestation from intensive agriculture conversion	U	39.9	16
Coal CCS retrofit	W	62.2	22
Coal CCS new built	X	64.6	18
Battery electric vehicles	Y	90	11

Figure 21: Proposal of new tool, combining abatement costs and Y-value



The abatement options in the top right corner of the graph are the least appealing ones, expensive and difficult to implement. The abatement options in the bottom-left corner (O= LED lights, and T= Cars full hybrid) are the most appealing, cheap and rather easy to implement. Of the abatement options distributed around the Y-axis of the graph, the ones position towards the bottom of the graph are more appealing, as characterized by lower implementation barriers against a comparable implementation cost. The missing variable, which depending on the pursued strategy can justify ignoring the insights provided by this new tool, is the Abatement Potential; this should be added to the tool in the future. Nevertheless, the abatement potential of an abatement option is dynamic, depending on which other options are implemented: this is highlighted both in the literature on MAC curves (*section 1.1.2*) and by some of the consulted energy strategists. Thus, the investigation should next be directed to tackle the third limitation of MAC curves, not tackled by the Y-factor method: emission reduction is path-dependent and dependent for abatement cost and abatement potential on the combination of the implemented emission abatement options.

The proposed tool was also presented to Koelemeijer during the discussion at PBL (reported in *section 5.2.3*), who welcomed it very positively as an additional tool able to provide new, useful insights which can further enrich and structure the strategy-drafting process.

The 12 factors have been proven relevant (end of *Chapter 4*); the consulted energy strategists have accepted the validated Y-curve and have acknowledged the ability of the Y-factor method to provide new insights previously missing to the emission abatement debate. Hence, the Y-factor method can be considered as a new, *heuristic tool* (Smith et al., 2005): by pinpointing to the many diverse challenges of implementation, the Y-factor method increases the richness of the debate on air pollution, highlighting financial, managerial, technical and behavioral problems which should be addressed.

In particular, the Y-factor is a *heuristic tool* which aims to create a *purposive transition* (Smith et al., 2005): the energy transition and the reduction of GHG emissions are topics extensively debated , and there is an increasing awareness of their impelling urgency; thus, the debate has the explicit intention of implementing sustainable changes. MAC curves are the prominent tool available for the governance of the sustainable transformation of society, to which this research offers a new, validated tool. This can be used by those responsible and/or consulted for the sustainable transformation of society to draft effective energy strategies able to achieve the intended sustainable societal development.

5.4 Overview of obtained results

The performance of the consultations with energy strategists, amongst the possible users of the Y-factor, concludes this investigation. Before recapping the research process in the following *Conclusion* chapter, it is worth to explicitly highlight its main results:

1. A reliable Y-curve ranking the 24 selected emission abatement options was constructed relying on the combined opinions of experts. These were retrieved via 12 semi-structured interviews: 19 abatement options were discussed with two or more experts, the remaining 5 only with one. The presented Y-curve is robust, as the vast majority of its characterizing scores could be easily validated combining consonant experts' opinions; only about ¼ of the scores is somewhat or significantly uncertain. The Y-curve is more robust over time than McKinsey's MAC curve, which is solely based on financial analysis proven to be volatile (e.g.: high Abatement Cost for the options PV panels homes and Battery electric vehicles); nevertheless, the Y-curve is robust only in a short/medium time-horizon: implementation barriers such *B1 Dependence on other actors, B2 Diversity of actors involved incl. conflicts*¸ and *D2 Frequency of opportunity* are likely to persist over time, while barriers such as *C3 Technology uncertainty, D1 Absence of knowledge of actors and D3 Requires change in behaviour* change over time.
2. Adding to the previous works on the Y-factor method from Chappin (2016), Arensman (2018) and Cheung (2018), this investigation has verified the relevance of the 12 factors composing the Y-factor method following the strategy proposed by Hekkert and Negro (2009). In fact, each of the 12 factors was considered by the interviewed experts to capture some relevant barriers hampering the implementation of the 24 considered abatement options. In particular, the barriers captured by the factors in the *Cost and Financing* category, the most-financial category of the four, have been found to account for approximately 30% of all implementation barriers, while the remaining 70% is related to non-financial factors.
3. The obtained Y-curve provides many new insights for each of the considered 24 abatement options, adding to the financial figures which characterized them in McKinsey's MAC curve. 9 options are ranked respectively similar in McKinsey's global cost curve and in the Y-curve, 5 are ranked extremely different, and the remaining 10 have a somewhat different ranking.
   Moreover, the Y-curve can explain why all the 11 considered abatement options characterized by a negative Abatement Cost in McKinsey's MAC curve are not yet largely diffused; in fact, for 10 of these 11 options non-financial scores [overall Y-value - ∑scores belonging to category *A. Cost and Financing*)] account for 50% or more of the overall Y-value. The 11th option is Cars full hybrid, for which the non-financial scores account for a third of the overall score and is to be considered regularly implemented considering its McKinsey's definition.
4. The Y-factor method and the obtained Y-curve were positively welcomed by strategists working for three players responsible and/or consulted for drafting energy strategies in The Netherlands (Ministerie van Economische Zaken en Klimaat, PBL, ECOFYS). All the consulted energy strategists accepted the Y-factor method and the presented Y-curve as tools able to aid their decision-making efforts, highlighting relevant barriers which need to be tackled to effectively reduce GHG emissions. All envisioned possible applications of the Y-factor method and the Y-curve, very much differing in extent and intention. These include the development of new tools combining insights from different approaches to emission abatement, such as MAC curves and the Y-factor; thus, a first example of such new tools is proposed, combining the figures in McKinsey's global cost curve and the presented Y-curve.
5. The consulted energy strategists accepted the Y-curve, confirming the validity of the insights it exposes; thus, the Y-factor method is identified as a *heuristic tool* for the *purposive transition* of sustainable strategy-making, using the framework of Smith et al. (2005). This further adds to the theoretical characterization of the Y-factor method for future applications.

Concluding, this master thesis research has verified how the Y-factor method can validly contribute to the emission abatement debate, currently dominated by purely-financial discussions and frameworks which are fundamental but insufficient. The need for new, diversified approaches to the debate is evident and impellent; having been validated and accepted, the Y-factor method can be the tool, or one of the tools, able to effectively support strategic decision-making for sustainable societal development.

Chapter 6: Conclusion

Overview of answers to research questions, limitations and reflection

This chapter concludes this master thesis report by remarking the logic and the results in each of the different investigation steps performed, as reported in the Research Flow Diagram presented at the end of *Chapter 1*: the construction of the preliminary Y-curve investigating the literature, its validation via multiple interviews with experts, and the discussion of possible applications of the Y-factor method for drafting sustainable energy strategies (*section 6.1*). Then, the main limitations characterizing the performed research and possible directions for future research are discussed. The chapter concludes with a reflection on the scientific and societal contribution provided by the results of this investigation, and a personal reflection on the aim of the Y-factor method and the obtained results, discussing how these can hopefully be the next small drop in the oceanic strive towards a sustainable future.

6.1 Obtained Results

This section recapitulates the logical steps followed in the investigation and the results achieved by each.

The goal of this master thesis research was to construct a reliable emission abatement curve using the Y-factor method, able to provide new insights on relevant economic and non-economic barriers hampering the implementation of emission abatement options. The implementation barriers considered in this research are the ones proposed by the Y-factor method, initially developed by Chappin (2016); thus, a secondary goal of the research was the verification of the relevance of the 12 factors composing the Y-factor method.
The only emission abatement curve previously constructed applying the Y-factor method is the one presented by Chappin (2016), presenting subjective, self-assigned score. Thus, this research aimed to construct a first, reliable emission abatement curve employing the Y-factor method.

To be reliable, the Y-curve must display reliable scores. The reliability of the individual scores cannot be achieved by performing extensive quantitative research on the individual factors, as these are typologically different, and such differences prevent quantitative comparisons of the scores assigned to different factors. Hence, the reliability of the scores shall be achieved relying on the opinions of multiple experts, knowledgeable on the abatement options' topics; considering multiple experts' opinions reduces the subjectivity of each score and thus of the consequent ranking of abatement options displayed in the Y-curve.

The main research question which guided this investigation was:
RQ: *What emission abatement curve can reliably capture not only economic but also relevant non-economic implementation barriers?*

The main conclusions achieved by this investigation are the following:

1. A reliable Y-curve ranking the 24 selected emission abatement options could be constructed relying on the combined opinions of experts. These were retrieved via 12 semi-structured interviews: 19 abatement options were discussed with two or more experts, the remaining 5 only with one.

The presented Y-curve is significantly robust, as the vast majority on its characterizing scores could be easily validated synthesizing consonant experts' opinions; only about ¼ of the scores is somewhat or significantly uncertain. The Y-curve is more robust over time than McKinsey's MAC curve, as it considers variables more stable than costs over time such as actors-interdependencies and frequencies of opportunities; nevertheless, the inclusion of evolving barriers such as behavioural and technological changes render the Y-curve robust only on for a short/medium time-horizon.

2. The Y-factor and the obtained Y-curve were positively welcomed by strategists working for three players responsible and/or consulted for drafting energy strategies in The Netherlands (Ministerie van Economische Zaken en Klimaat, PBL, ECOFYS). All the consulted energy strategists accepted the Y-factor and the presented Y-curve as tools able to aid their decision-making efforts, highlighting relevant barriers which need to be tackled to effectively reduce GHG emissions. All players envisioned applications for the Y-factor method and the Y-curve, widely differing in extent and intention. These include the development of new tools combining insights from different approaches to emission abatement, such as MAC curves and the Y-factor; thus, a first example of such new tools is proposed, combining the figures in McKinsey's global cost curve with the overall Y-values assigned to the abatement options in the presented Y-curve.
3. Adding to the previous works on the Y-factor from Chappin (2016), Arensman (2018) and Cheung, (2018) this investigation has verified the relevance of the 12 individual factors composing the Y-factor method following the strategy employed by Hekkert and Negro (2009), and has defined it as an *heuristic tool* for *purposive transition* using the framework from Smith et al. (2005). These additions expand the theoretical background of the Y-factor method for future applications.

Combining the previous three conclusions, this master thesis research has verified how the Y-factor can provide valid contributions to the emission abatement debate. This is currently dominated by purely-financial discussions and frameworks which are fundamental but insufficient, as many financially-convenient abatement options are not implemented; thus, the need for new diversified approaches to the debate is evident and impellent. Having been validated and accepted, the Y-factor can be the tool, or one of the tools, able to effectively support strategic decision-making for sustainable societal development.

Three main logical steps guided the research: the construction of a preliminary Y-curve, its validation and the discussion of its possible applications. These research steps are recapitulated below, to highlight how answering to the respective sub-research questions defined in *Chapter 1* helped achieving the results presented above and answering to the main research question. The main results of each research step are summaries in a colored text-box, and structurally elaborated according to the Research Flow Diagram at the end of *Chapter 1*.

6.1.1 Step 1: Creation of the preliminary Y-curve

The following sub-research question guided this first research step:

Q1: *What scores can be assigned to the considered abatement options basing on information from the existing literature?*

24 emission abatement options were initially selected from set of options considered by McKinsey's MAC curve. Performing an overview of the options' most characterizing features discussed in the literature, preliminary subjective scores were assigned applying to the Y-factor method. These enabled the construction of a preliminary Y-curve, to be employed in the remainder of the investigation.

Three actions were performed to answer this first research step:

a) Selection of the abatement options to consider in the investigation

24 abatement options were selected to be analyzed in this investigation from the pool of abatement options ranked by McKinsey's MAC curve. 20 abatement options were initially selected using a multi-criteria selection process from the sub-pool of 50 option ranked by McKinsey's MAC curve with the highest abatement potential and included in the research of Chappin (2016); the selection process pursued the diversity (sectors and

positive/negative abatement cost) characterizing the options ranked in McKinsey's MAC curve. The following abatement options were initially selected:

Building efficiency new build, Coal CCS new built, Coal CCS retrofit, Geothermal, Small hydro, PV panels homes, High penetration wind, Cropland nutrient management, Reduced intensive agriculture conversion, Reduced deforestation from timber harvesting, Grassland management, Agronomy Practices, Bioethanol lignocellulosic, Lighting switch incandescent to LED (residential), Residential appliances, Energy efficiency 1 Iron & steel, Clinker substitution by fly ash, Air transport, Electricity from landfill gas, Composting new waste.

To these selected 20 emission abatement options, four others were arbitrarily added for their current societal relevance: Nuclear energy, Cars full-hybrid (HEVs), Cars plug-in hybrid (PHEVs), and Battery Electric Vehicles (BEVs), the latter not belonging to the pool of the 50 options with highest abatement potential in McKinsey's MAC curve, but still discussed in McKinsey's report (Nauclér & Enkvist, 2009).

b) Overview of the selected abatement options

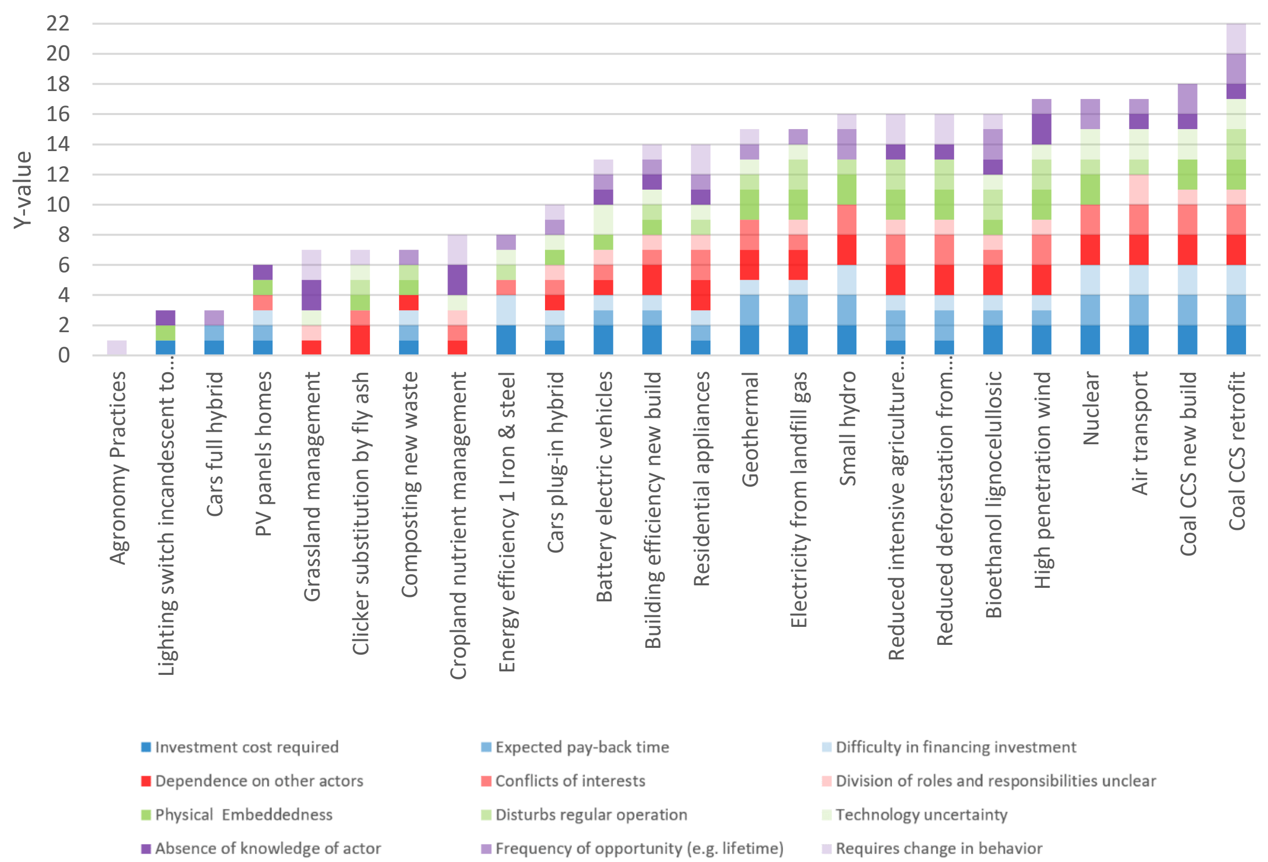
The main features of the selected abatement options discussed in the existing literature were reviewed. For each of the considered abatement option, the following information was highlighted: the definition used by Chappin (2016), gathered from McKinsey's report, highlight-features frequently mentioned in the literature, the potential for GHG emissions reduction and their implementation-cost estimates, and the most important barriers hampering implementation.

c) Scoring of the abatement options

Basing on the information retrieved in the literature, the scores displayed in *Figure 22* were preliminary assigned. These are summed for comparison and graphical purposes as in the research of Chappin (2016), to form the preliminary Y-curve, answering to the first sub-research question:

Q1: *What scores can be assigned to the considered abatement options basing on information from the existing literature?*

Figure 22: The preliminary Y-curve constructed with information from the existing literature



6.1.2 Step 2: Validation of the Y-curve

Once assigned, the preliminary scores were validated via interviews with experts, to answer to the second sub-research question: **Q2:** *How are the preliminary scores validated by interviews with experts?*

The interviews with experts enable the collection of experts' opinions, synthetized in final, validated scores. These were combined to construct the validated Y-curve. The Y-curve is robust, as the majority of the scores it contains could be easily validated combining consonant experts' opinions; only about ¼ of the scores is somewhat or significantly uncertain. Moreover, the relevance of each of the 12 factors composing the Y-factor method could be verified; this adds to the results of previous researches focused on the development of the Y-factor. Then, the Y-curve was compared to McKinsey's MACC.

5 of the 24 abatement options could be debated only with one interviewee: Energy efficiency 1 Iron & Steel, Clinker substitution by fly ash, Air transport, Composting new waste and Electricity from landfill gas. The scores characterizing the remaining 19 abatement options were discussed with at least two experts.
Following an explicit validation procedure, the collected experts' opinions were synthesized to obtain final, validated scores. Each score is reported as "certain", "somewhat uncertain", or "significantly uncertain", depending on the differences between experts' opinions and on the narratives provided by the experts.

Table 17: Validated scores and uncertainties: certain (green), somewhat uncertain (yellow), significantly uncertain (red)

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	sum
Lighting switch incandescent to LED (residential)	1	0	0	0	0	0	0	0	0	1	0	0	2
Cars full hybrid	1	1	0	0	0	0	0	0	0	0	1	0	3
Air Transport*	1	0	0	1	0	0	1	0	1	0	0	1	5
Agronomy Practices	0	1	0	0	1	0	0	1	1	0	0	1	5
Cropland nutrient management	0	0	0	1	1	1	0	0	1	1	0	1	6
Clinker substitution by fly ash*	0	0	0	2	1	0	1	1	0	0	0	1	6
Grassland management	0	0	0	1	1	1	0	0	1	1	0	1	6
PV panels homes	1	1	1	0	1	0	1	0	0	1	0	1	7
Composting new waste*	1	1	0	2	1	0	1	1	0	0	0	1	8
Energy efficiency 1 Iron & steel*	2	0	2	0	1	0	0	1	1	0	1	0	8
Cars plug-in hybrid	1	1	0	1	1	1	1	0	0	1	1	1	9
Building Efficiency New Build	2	1	1	1	1	0	1	0	0	1	1	0	9
Residential appliances	1	1	1	1	1	0	0	1	1	1	1	1	10
Electricity from landfill gas*	2	1	1	2	1	1	1	0	0	0	1	0	10
Battery Electric Vehicles	1	1	1	2	0	1	1	0	0	1	1	2	11
Small hydro	2	2	1	2	1	0	2	1	0	0	1	1	13
Nuclear	2	2	2	2	2	1	1	0	1	0	2	0	
Bioethanol lignocellulosic	1	2	1	1	1	1	1	1	2	1	1	1	15
Geothermal	2	2	2	2	2	1	1	1	1	0	1	1	16
High penetration wind	2	2	1	2	2	1	2	1	1	1	1	0	16
Reduced intensive agriculture conversion	1	2	1	2	2	1	2	2	0	1	0	2	16
Reduced deforestation from timber harvesting	1	2	1	2	2	1	2	2	0	1	0	2	16
Coal CCS new build	2	2	2	2	2	1	2	0	2	1	2	0	18
Coal CCS retrofit	2	2	2	2	2	1	2	2	2	1	2	2	22

The validated Y-curve is composed by 288 scores (24 abatement options x 12 factors), of which 60 rely on the opinion of one expert and 228 on the opinion of at least two experts. Of these 228, 168 (74%) are classified as "certain", 41 (18%) are classified as "somewhat uncertain", and 19 (8%) as "significantly uncertain". Combining the validated scores enabled the creation of the validated Y-curve.

Figure 23: The validated Y-curve - factor-scores

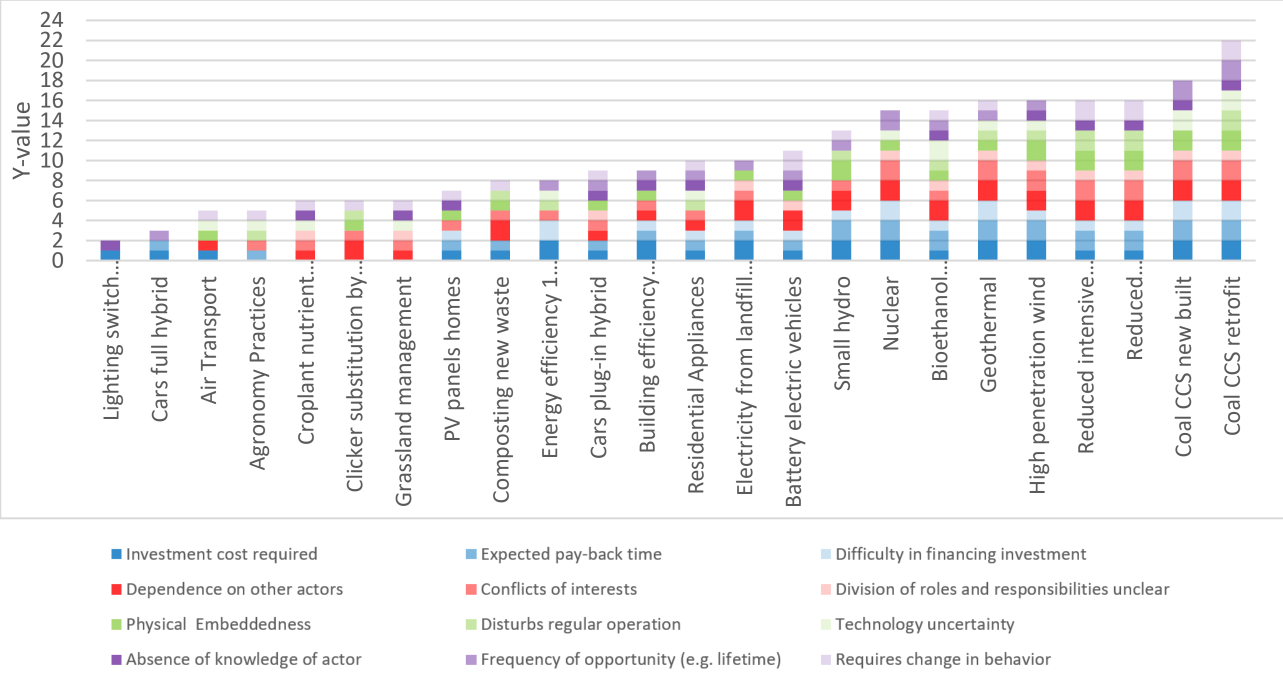
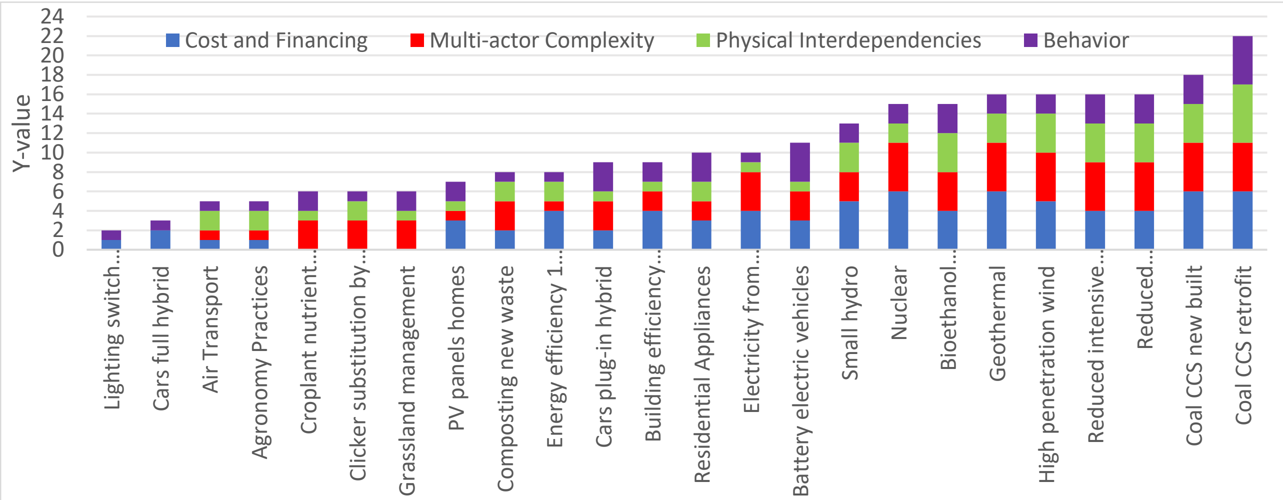


Figure 24: The validated Y-curve - category-scores



Following the procedure proposed by Hekkert and Negro (2009), remarking how it is possible to validate the importance of specific variables by observing their relevance across different case studies, it is possible to validate the relevance of each of the 12 factors, adding to the previously achieved theoretical embedding of the Y-factor method. In fact, each of the 12 factors was considered a relevant implementation barrier during the interviews with experts, as proved by *Table 18*, reporting the average contribution of each factor to the collected overall Y-values. These figures also highlight the importance of including non-financial analysis in decision-making, as the factors not belonging to the category *Cost and Financing* account on average for 70% of the discussed implementation barriers.

Table 18: Average contribution of each factor to overall scores

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
AVERAGE CONTRIBUTION - per Y-factor	**12.4**	**10.4**	**7.3**	**12.5**	**10.6**	**4.9**	**8.7**	**5.7**	**6.1**	**6.4**	**6.7**	**8.4**
AVERAGE CONRIBUTION – per category	**30.1**			**27.9**			**20.5**			**21.4**		

The overall ranking displayed in the validated Y-curve and the scores assigned to each abatement option were briefly compared to the relative ranking of the considered abatement options displayed in the research of Chappin (2016) to verify the impact of experts' interviews, and successively to McKinsey's MAC curve.

Comparing the Y-curve to McKinsey's global cost curve, the following general conclusions are drawn:

- 9 abatement options are assigned a "most similar" ranking in the two curves (color green in *Table 19* below), 5 others have a "most different" one (color red); the remaining 10 abatement options have a "somewhat different" ranking (color yellow).
- Coal CCS technologies are recognized as the most challenging options to implement by both curves, and LED and HEVs among the easiest.
- The options PV panels homes and Battery electric vehicles are characterized by a substantially higher ranking in McKinsey's MAC curve than in the Y-curve. For these options, the outdated cost-figures available in 2009 (year of publication of McKinsey's MAC curve) are most evident, and large technological developments have occurred since then.
- Bioethanol lignocellulosic and Residential appliances are also amongst the most differently ranked abatement options; both have a category-score ≥ 2 for each category in the Y-curve, which highlights the relevance of non-financial barriers, not considered by McKinsey's cost curve.
- Agronomy practices are characterized in McKinsey's MAC curve by an Abatement Cost bigger than for the other options related to land-management practices (Cropland nutrient management and Grassland management), but such higher costs were not highlighted by experts in the interviews and are thus not reflected in the Y-curve.

Table 19: Comparison McKinsey's global cost curve v. Y-curve

#	Abatement Option	Abatement Cost [€/tCO_2e]	Y-value [out of 24]	Ranking MAC → Ranking Y-curve	Financial ranking Y-curve
A	Lighting switch incandescent to LEDs, residential	-253.1	2	1 → 1	4
B	Residential appliances	-195.8	10	2 → 13	10
C	Bioethanol lignocellulosic	-138.8	15	3 → 17	13
D	Cars full hybrid	-72.9	3	4 → 2	7
E	Cropland nutrient management	-68.8	6	5 → 5	1
F	Building efficiency new built	-40.2	9	6 → 11	13
G	Clinker substitution by fly ash	-32	6	7 → 5	1
H	Electricity from landfill gas	-23.4	10	8 → 13	13
I	Air Transport	-20.5	5	9 → 3	4
J	Small hydro	-8.9	13	10 → 16	19
K	Geothermal	-3.9	16	11 → 19	21
L	Grassland management	3.4	7	12 → 7	1
M	Reduced deforestation from timber harvesting	6.9	16	13 → 19	13
N	Energy efficiency 1 Iron & Steel	8.2	8	14 → 9	13
O	Composting new waste	9.9	8	15 → 9	7
P	Nuclear	10.4	15	16 → 17	21
Q	Agronomy Practices	15.8	5	17 → 3	4
R	Cars plug-in hybrid	18.1	9	18 → 11	7
S	PV panels homes	27.9	7	19 → 7	10
T	High penetration wind	32.4	16	20 → 19	19
U	Reduced deforestation from intensive agriculture conversion	39.9	16	21 → 19	13
W	Coal CCS retrofit	62.2	22	22 → 24	21
X	Coal CCS new built	64.6	18	23 → 23	21
Y	Battery electric vehicles	90	11	24 → 15	10

Substantial ranking differences also exist comparing McKinsey's cost curve to the ranking obtained only considering the "financial-factors" in the Y-curve, which are those belonging to the *Cost and Financing* category. The ranking differences can be are caused by three main reasons: the Y-curve considers multiple financing factors, but these can only assume 7 different values (from 0 to 6), while the variable Abatement

Cost has a scale much more sensitive thus overlapping less in the ranking; McKinsey's figures are largely outdated, and thus costs are considered by experts to have reduced; the financial-factors of the Y-factor method do not capture cost-savings, which are instead included in the McKinsey's financial figures. Hence, while few conclusions on the similarities between the financial factors and the financial analysis of McKinsey's MAC curve can be drawn, the ranking differences between the Y-curve and the "financial Y-curve" confirm how much the ranking of abatement options changes when considering also non-financial factors.

Nevertheless, the scores presented by the Y-curve can explain why all the 11 abatement options ranked with a negative Abatement Cost in McKinsey's curve and considered in this investigation are not yet fully implemented. In fact, non-financial implementation barriers (factors not belonging the category: *Cost and Financing*) account for 50% or more of the total barriers relevant for 10 of these 11 options. The missing option, Cars full hybrid, which in McKinsey's report include any vehicle with a start-and-stop system, can be considered already largely diffused.

While new insights are highlighted for each of the investigated abatement options, the following ones are the most evident:

- The abatement option Coal CCS new built and Coal CCS retrofit are placed by both curves on their far-right hand, with both options assigned the maximum scores for the category *Cost and Financing,* and almost equally high scores for the other categories. Nevertheless, their relative ranking is swapped in the two curves, as McKinsey's curve considers cheaper to retrofit a coal plant with CCS than building a new one designed including CCS technologies.
- Lighting switch incandescent to LED (residential), is the abatement option ranked as having the fewer implementation barriers by both curves. Overall costs are very limited (10 €/bulb), but the Y-curve highlights how buyers are not inclined to face an expense ten-times higher than otherwise possible in name of future savings, even with these are proven. Moreover, the Y-curve remarks the relevance of some educational barriers.
- PV panels home are ranked very differently in the two curves: 19th/24 and on the right-hand side of McKinsey's MAC curve, and 8th/24 and in the middle of the left-half of the Y-curve. Considering the low-scores of the non-financial factors estimated by the Y-curve, a possible explanation for the large ranking difference is the year of publication of McKinsey's curve (2009); since then, PV panel technology has become substantially cheaper, with prices dropping of more than 70% since 2010 (SEIA, 2018).
- Agronomy practices is one of the abatement options for which the ranking in the two curves is most different, 3rd/24 in the Y-curve and 17th/24 in McKinsey's curve. Such difference is explained but the low score (1 out of a maximum of 6) for the *Cost and Financing* category, while McKinsey's curve estimates a relatively high implementation cost. This abatement option is one of the most controversial ones, as the interviewed experts disagree over the effectiveness on such practices. While not explicitly explaining the high cost-figures displayed by McKinsey's curve, the uncertainties of multiple scores remark the importance of further analysis.
- The drastically different ranking of the abatement option Bioethanol lignocellulosic is surprising: it is assigned a highly negative abatement cost by McKinsey's MAC curve, while the Y-curve assigns it a complexity well-distributed across its four categories. In fact, the interviewed experts reported high production costs and the uncertainty of the market as challenging issues, besides the technical limit of 10-20% mixing with regular benzine and the similarities of secondary-biofuels to their disappointing predecessors.
- Similarly, Residential appliances are ranked 2nd/24 in McKinsey's curve, with a negative abatement cost, while this abatement option is located in the middle of the Y-curve. A partial reason for this could be definitional: the interviewed experts agreed on the high energy-efficiency of most residential appliances currently installed and remarked the inevitability of focusing smart-appliances, able to deal efficiently with increasingly fluctuating energy prices consequence of renewables. Additional factors which should be considered relate to the collection and management of energy-consumption data from appliances' owners, and a reflection on the definition and management of behavioural changes.

- Differently from all the other 23 considered abatement options, Battery Electric Vehicles (BEVs) are not part of the 50 abatement options ranked by McKinsey's curve with the highest abatement potential (whose figures were available for this research), but an abatement cost of 90 €/tCO_2e can be retrieved from McKinsey's report (Nauclér & Enkvist, 2009, *Exhibit 8.6.4,* p. 100). This figure is the largest amongst the considered options, placing BEVs on the far-right hand of McKinsey's curve. Since 2009, the technology has become cheaper, allowing in 2018 the market introduction of the Nissan LEAF, with a price comparable to ICE of its class. It is thus needed to revise the abatement cost figures for BEVs, and to focus on the other barriers hampering their implementation highlighted by the Y-curve: dependency on the recharging infrastructure and the derived range-anxiety, and municipal landscape adaptation. A chicken and egg paradox arises: how to introduce the recharging infrastructure while few BEVs are circulating, but which is necessary to encourage the diffusion of BEVs?

6.1.3 Step 3: Applications for energy strategies

The last sub-research question wondered about ***Q3:*** *How do players responsible and/or consulted for the development of energy strategies envision applications of the Y-curve and of the Y-factor method?*

Three players responsible and/or consulted for drafting energy strategies in The Netherlands were then contacted to discuss the validated Y-curve and how they believe the Y-factor method can be applied to support the emission abatement debate.

All the consulted energy strategists accepted the Y-factor and the presented Y-curve as tools able to aid their decision-making efforts, highlighting relevant barriers which need to be tackled to effectively reduce GHG emissions. All envisioned possible applications for the Y-factor method and the Y-curve, which very much differ in extent and intention. Thus, the Y-factor method can now be considered a *heuristic tool* able to support a *purposive transition* towards an effective, rather than solely cost-efficient, debate on sustainable development. This also adds to the development of the Y-factor, further grounding it in existing transition theories and frameworks.

The discussions highlighted the importance of adding a non-financial perspective to the emission abatement debate, able to support strategy-making towards the effective implementation of emission abatement options, as the financial figures showed in McKinsey's MAC curve are recognized by the interviewed players useful but insufficient. The Y-factor method was recognized as simple to understand and employ, capturing relevant themes which are normally not tackled and/or reported explicitly. Three main applications for the Y-factor method were highlighted:

1) **For governmental bodies: Selection and Discussion of policies**
The Y-factor method is considered to be specifically helpful in debating a broader set of policies: these are normally boxed depending on their relative domain, and it is thus challenging to jointly evaluate and compare the impact of policies with very different nature.
The Y-factor method can be used to analyze individual abatement options which are not implemented according to the cost figures in a MAC curve as McKinsey's, discussing the relevance of the 12 factors for a specific abatement option. Discussing the 12 factors can help to understand why an abatement option which seem financially convenient is not effective; in particular, the Y-factor method helps pinpointing which existing and/or intended policies address a specific implementation barrier.

2) **For governmental agencies: Comprehensive analysis**
The Y-factor method provides a structured approach for debating non-financial barriers, which are already recognized as fundamental. Different tools similar to PBL's are probably existing, but the Y-factor method can effectively be used for the collection and comparison of different opinions, to expose the most problematic issues. The global Y-curve can be used as reference, and multiple local Y-curves can be developed for supporting context-specific analyses. Moreover, the approaches of different emission abatement curves (e.g.: McKinsey's MAC curve and the Y-curve) can be combined

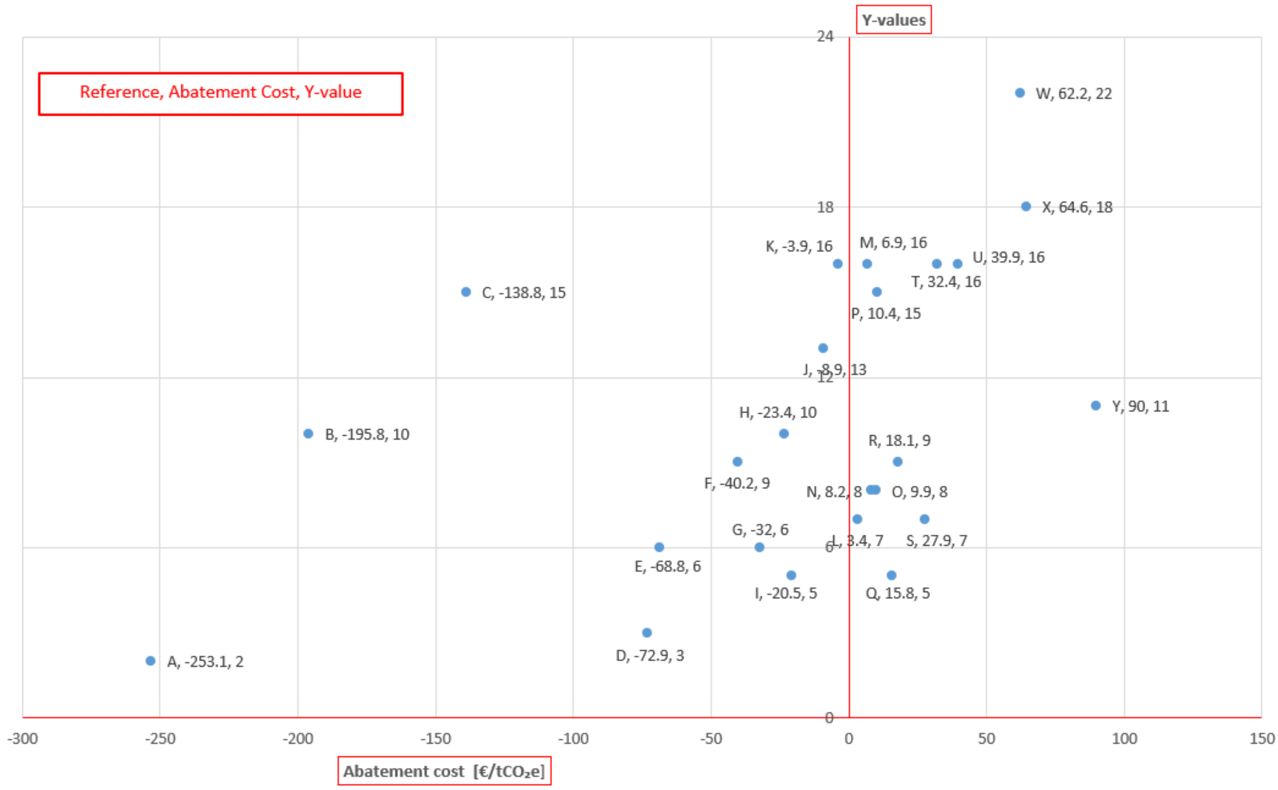
to construct new, informative tools. Finally, the Y-factor method facilitates the comparison of different opinions on implementation barriers, which is valuable for sound advices.

3) **For energy service companies- consulting: Allocation of resources**
An energy service company can apply the Y-factor method for the following three operations:
   - Perform a selection of the potentially-interesting services to further analyze and sponsor, thus in the early stage of strategy-development process (Strategy). E.g.: Advising about hydrogen-technology applications, currently at the niche status;
   - Direct marketing funds on truly promising/implementable service offers (Financing);
   - Explain products' sales-trends and modify products' design to modify some of their features highlighted as limiting for the products' market performance (Product Development).

As users of the Y-factor method are likely to assign scores themselves to capture the features of the specific situation at hand, a recipe or a software able to guide users in the clear and rapid assignation of scores able to reflect the situation at hand could be developed.

The comparison of McKinsey MAC curve to the Y-curve enables the proposal of the first, simple tool combining the information provided by both emission abatement curves: the abatement cost in €/tCO_2e on the X-axis and the Y-value of each abatement option on the Y-axis (see *section 5.3)*. Each abatement option is identified in the graph via a reference letter for improved visualization. The reference letters are provided in *Table 17* above.

Figure 25: Proposed new tool combining figures from McKinsey's MAC curve and overall Y-values



6.2 Limitations and Recommendations for Future Research

This investigation has ambitiously pursued a two-fold main goal: the validation of the Y-factor method constructing a Y-curve analyzing numerous, very different emission abatement options, and the discussion of its possible applications with some of the most important players responsible and/or consulted for energies strategies in The Netherlands. Building on the works of Arensman (2018) and Cheung (2018), this thesis also tried to further ground the validity of the Y-factor method in the emission abatement debate and in *transition theory*. This investigation process imposed different methodological choices, and some of these constitute the main limitations of this investigation:

1) The investigation considered a limited number of abatement options, fewer than the two other abatement curves to which it compares, namely the one presented by Chappin (2016) and McKinsey's MAC curve. The limited number of considered options reduces the possibilities of result-comparison and might have led to conclusions which would not be as valid and/or relevant for a larger Y-curve. Nevertheless, this limitation is not considered functional; in fact, the goal pursued with the construction of a Y-curve was to verify the ability of the Y-factor to construct a reliable emission abatement, which was achieved also with the limited number of analyzed emission abatement options.

2) To facilitate and accelerate the time-intensive interviews with experts, these were asked to validate preliminary scores rather than assigning scores themselves, which would have been a more realistic application of the Y-factor method, as successively confirmed by the consulted energy strategists. Referring to a preliminary score avoided digressional comments from the interviewees but might have induced a somewhat bounded reasoning, rather than allowing an entirely-free approach to the proposed topics. This might have affected the final scores to a minor extent; in fact, clarificatory comments about the preliminary scores were provided only when explicitly requested by the interviewees. Thus, the researcher is confident the validation process did not impact significantly the final scores; this holds especially for those scores classified as "certain" in *Table 17* reported above, as these were validated by two or more interviewees without significant doubts. Instead, there are chances that those scores reported as "somewhat"- or "significantly uncertain" might variate following a different scoring strategy.

3) Considering the time constraints, a limited number of experts could be consulted to validate the preliminary scores. For 5 abatement options, only one expert could be interviewed, for 18 two experts were consulted and for one option three. While the presented Y-curve is evidently less subjective than the curve proposed by Chappin (2016), it still nevertheless suffers of a certain degree of subjectivity, especially for those abatement options and factors which most frequently displayed uncertainty in the scores. While interviewing more or different experts might have led to different scores, the "certain" scores are unlikely to radically change. Moreover, the performed investigation achieved its goal of obtaining an emission abatement curve applying the Y-factor, which can obviously be improved in the future.

Different themes needing further investigation have been highlighted over the course of the research and can be classified in three main categories: Further investigation on the obtained results, Investigation on the further development of the Y-factor method, and Applications of the Y-curve and of the Y-factor method.

<u>Further investigation on the obtained results</u>

The abatement options and the factors highlighted in *section 4.5.1* as being the most uncertain deserve a specific analysis. In particular:

The definition and the implementation barriers of the abatement options most characterized by uncertain scores should be discussed in detail with numerous experts, to understand the origin of the uncertainty: Is it mostly depending of the subjective opinions of the interviewed experts, or are there issue which are more generally dividing? If the latter is the case, the problem would no longer be which scores is best to assign, but rather how to overcome the disagreements to either achieve a conciliatory framing of the options' features and implications or to stop considering the abatement options as a viable.

The factors most often assigned uncertain scores (*D1: Absence of knowledge of actors*, *A3: Difficulty in financing the investment*, *C2: Disturbs regular operations*, and *D3: Requires change in behavior*) should be re-discussed, to verify if the uncertainties can be reduced by improving the definition and the corresponding value-scale. An example of methodological refinement is proposed by Arensman (2018), who suggested modifications to the definition and scales of the Y-factor method as initially proposed by Chappin (2016). To verify possible improvements, alternative definitions of the uncertain factors could be discussed with experts, who could be invited to attempt assigning a score to a few different abatement options using the possible factors' definitions.

Further development of the Y-factor

Suggestions and ideas for further developing the Y-factor were collected during the interviews with experts and the consultations with energy strategists.

The interviewed experts frequently expressed the dependency of the scores on the considered actor-perspective and geographical-scope. A strategy to tackle the perspective-issue has already been implemented in this investigation, specifying *Scope 1* in *section 4.3*: The Y-factor method looks at the barriers hampering the implementation of abatement options, and thus the assigned scores should always refer to those actors with the power of implementation. For example, the physical embeddedness (factor *C1*) caused by the implementation of PV panels should only refer to the changes experienced by the purchasers, and not to the changes in operations caused by the intermittency of solar energy to the DSO handling the power grid. As also validated by the consultations with energy strategists, a different Y-curve could be constructed accounting for the experiences of the DSO.

Instead, the scope-issue remains to be solved: while it was more explicitly noticeable for specific abatement options and factors (e.g.: *D1: Absence of knowledge of actors* and *D3: Requires change in behavior*), non-financial barriers have often a more context-specific relevance than financial ones. Thus, it is interesting to investigate how context-specific Y-curves can increase the specificity and effectiveness of the analysis, applying the Y-factor method to characterize peculiar situations. In this regard, the presented Y-curve could be conceptually compared the McKinsey's global cost curve, to which this research has repeatedly referred. Having proven its relevance, this global Y-curve could be juxtaposed to multiple local Y-curves, for instance reflecting diverse national-situations. In this way, those employing the Y-factor method could still create their own curve while relying on a reference, validated Y-curve, intrinsically more relevant for their analysis than the one global one proposed in this research. The global Y-curve could be used as trendline connecting the local Y-curves.

Another specific methodological adjustment proposed by the interviewed experts and the consulted energy strategists is the expansion of the tripartite scale. Specifically, two possible extensions are a 5-value scoring scale (No/Zero, Little, Medium, Much, Yes/High) for each factor, and the inclusion of negative values to account for the attractiveness of an abatement options, depending on the co-benefit it enables. The impelling question to be answered is whether there is worth in considering extending the tripartite scale.

A tripartite scale forces those applying the Y-factor method to categorize in a clearly distinguished fashion the relevance of the highlighted barriers, while a longer scale might allow a more comfortable categorization and shorten stalling discussions.

Instead, considering the attractiveness and co-benefits enabled by an abatement option forces a further reflection on the perspective considered when assigning the scores, as co-benefits are often more relevant for and perceived by the collectivity than for specific actors.

The inclusion of three additional factors was suggested during the experts' interviews, namely *Governance, Regulation*¸ and *Emotional decision making.*

Of all the collected methodological suggestions, the following ones are believed to be beneficial for an increased accuracy and clarity of the Y-factor method:

It is suggested to include these three factors in the definition of existing factors, namely *Governance* and *Regulation* in the factor *B3: Division of roles and responsibilities unclear*, thus changing the name of category B into *Multi-actor and institutional complexity*. Moreover, it is suggested to expand the current tripartite value scale into a four-value scale; this could contain a negative score, to account for co-benefits, and the current three value.

The Y-factor method has been developed with the purpose of complementing weaknesses in MAC curves, of which McKinsey's global cost curve is the most famous and popularly employed representative, also thanks to the reputation of McKinsey. Thus, the Y-factor method should be sponsored to increase its own reputation, aspiring to become a tool similarly trusted as all McKinsey's products, and in particular of the global cost curve. Endorsement of the Y-factor method from famous experts and organizations (e.g.: McKinsey & Company, Delft University of Technology, etc.) could possibly be the quickest and most empowering strategy to equip the Y-factor method with an appealing reputation.

Applications of the Y-factor

It is extremely interesting to investigate the potential benefits brought by a tool jointly displaying the financial figures proposed by McKinsey's MAC curve and the implementation barriers highlighted by the Y-factor method, and the most effective outlook such tool might have. A first attempt was proposed in *section 5.3*, but further investigation on the possible benefits brought by the simultaneous display of two such different approaches should be verified, to achieve an effective design.

Finally, the implementation barriers and the impact different policies might have on them could be modeled into an Agent Based Model, for instance built using the software NetLogo, to simulate the possible consequences of a specific decision. This would provide a more dynamic tool to the emission abatement debate, able to highlight how the ranking of different emission abatement options displayed in a Y-curve might change as a consequence of political preferences and/or policies decisions.

6.3 Reflection

Concluding this report of a five-month master thesis project, this paragraph reflects on the scientific contributions and societal applications of the achieved results and embeds the themes of this research in the current global situation.

Scientific contribution to the development of emission abatement curves and of the Y-factor method

Besides a method to construct emission abatement curves, the Y-factor proposes a radically different approach to the debate on GHG emissions reduction.
The Y-factor method was proposed by Chappin (2016). Before this investigation, two other researchers dedicated to its study, namely Arensman (2018) and Cheung (2018): these two researches underpinned the four categories of the Y-factor method in the existing literature on implementation barriers and transition literature and tested the ability of the Y-factor method to analyze a few, specific emission abatement options and thus guide discussions.

Firstly, this investigation has verified the Y-factor method is fit-for-purpose, applying it for the first time to construct an emission abatement curve validated relying on experts' opinions. This result has generic scientific relevance, as it advances the development of a new framework, performing an application never tested before and thus adding to the scientific body of knowledge on emission abatement curves.

While enabling the construction of a validated Y-curve, the collected experts' opinions have confirmed the relevance of the 12 proposed factors; in fact, each of the factors was found to be capturing relevant implementation barriers, as discussed in *section 4.5.2* and summarized below. The displayed average contributions of the factors to the overall Y-values can be considered validating the relevance of each of the 12 factors following the reasoning proposed by Hekkert and Negro (2009), as all the "functions used in the empirical analyses can be related to actual events that took place" (p. 590).

This is the second specific scientific contribution offered by this master thesis research, which strengthens the theoretical background of the Y-factor method, expanding the contributions of Arensman (2018) and Cheung (2018).

Lastly, the consulted energy strategists accepted the presented Y-curve and acknowledged the ability of the Y-factor method to effectively contribute to sustainable strategy-making. Thus, the Y-factor method could be described using the framework proposed by Smith et al. (2005) as a *heuristic tool* able to support the *purposive transition* of the emission abatement debate.

Societal implications: Contribution to sustainable policy and decision making

Players responsible and/or consulted for the drafting of energy strategy were consulted to verify if and what support the validated Y-curve can provide to the emission abatement debate and to the related decision-making process. As reported in *section 5.2* and *5.3*, very different comments were collected, but all the interviewed players confirmed the relevance of the multi-domain approach proposed by the Y-factor method. This exposes implementation barriers which should be discussed but are marginal in the current debate, because an approach enabling a structural discussion is missing.

In particular, this research has verified how the Y-factor method can be employed for three different activities:

4. Support to policy-making: The Y-factor method fosters the discussion on the policies measures implemented to tackle specific implementation barriers and facilitates the comparison of policies belonging to different domains, which is usually challenging.
5. Support to research analyses: The Y-factor method facilitates the comparison of different opinions on implementation barriers, valuable for providing sound advices, and enables the construction of multiple new tools integrating quantitative and qualitative insights on emission abatement options.
6. Support to business strategy: The Y-factor method helps a business active in the energy market in the strategic allocation of available resources, highlighting the most promising products or services and supporting their design in tackling existing implementation barriers.

These conclusions add societal relevance to the results presented in this report: the Y-factor method has been found able to construct valid and insightful emission abatement curves; these can help in effectively implementing emission abatement options for the reduction of air pollution, one of the greatest challenges of the 21st century. Moreover, three specific applications for the Y-factor method can be highlighted.
Repeating the terminology characterizing the framework of Smith et al. (2005), the Y-factor can be considered as a *heuristic tool*, created outside the current emission abatement debate, but able to contribute to it and hopefully initiating a *purposive transition* towards a more comprehensive and conclusive debate for the sustainable development of societies.

Personal reflection on the Y-factor

The aim of the Y-factor method is noble: it aims to contribute to the betterment of the world and societies by aiding the implementation of solutions to reduce GHG emissions. It has been developed to complement weaknesses in MAC curves; in fact, they are insufficient for explaining the implementation conditions, as discussed in this report for their most popular representative, McKinsey's global cost curve.

The Y-factor method does not and cannot substitute McKinsey's MAC curve, whose value has become progressively clearer to me during the performance of this investigation: McKinsey's global costs curve brings into one framework an extremely numerous number (218) of abatement options which are very often treated in separate, isolated discussions; this provides immediately-comparable information, and contextualizes them in a comprehensive frame. Moreover, the report in which the global cost curve is reported (Nauclér & Enkvist, 2009) provides a formidable collection of figures characterizing the ongoing sustainability debate; this ranges from the development of global emissions over the years, to their translations in GHG atmospheric concentration and to overall possible future evolution scenarios. Most of all, McKinsey's global cost curve is remarkable for its ability to synthesize in a bar-graph the very complex theme of cost-efficiency of emission abatement options; the curve is of immediate reading and understanding, and thus has an extraordinary ease of use considering the complex topics. This, together with the reputation characterizing the works of McKinsey & Company, explains its popularity.

The Y-factor method proposes a radically different approach to emission abatement curves and to the ongoing discussion on emission abatement. To complement financial figures typical of MAC curves and of straightforward understanding, the Y-factor wants to initiate and structure the debate around barriers hampering the implementation of abatement options.
The tradeoff is evident: the scores displayed in the Y-curve do not provide objective, quantitative indications, but rather highlight those barriers which are fundamental to further discuss and tackle for an effective implementation of abatement options. On one hand this reduces the ease of use of the Y-curve with respect to McKinsey's MAC curve, while on the other hand enriching the discussion.

The current emission abatement debate is inconclusive, as new, more challenging emission reduction targets continue to be set and are regularly failed, global GHG emissions continue raising (IEA, 2017), and discussed abatement options do not reach the implementation phase. I believe it is fundament to add new perspectives which can help un-stalling the debate and support effective decision-making. The construction of a valid Y-curve to which this research has dedicated is an essential developmental passage, which proves the functionality of the Y-factor method. This can and should be employed alongside MAC curves in the emission abatement debate.

As I believe the local MAC curves developed by McKinsey (see info-box in *section 1.1.1*) provide more realistic information than the global cost-curve, the same is even more valid for the Y-curve presented in this research. In fact, implementation barriers are likely to be more location-specific than financial costs, which might vary to a more limited extend and can be more accurately broken down into their root-causes. Hence, I believe the Y-curve constructed in this investigation without a specific geographical scope can provide some initial guidance, highlighting general barriers-trends, but cannot be directly employed to draw conclusions for specific decision-making. This concept was indirectly highlighted in the consultation at the Ministerie van Economische Zaken en Klimaat, where the interlocutors doubted about a structured used of the presented Y-curve: I believe this comment would be much less relevant for a Y-curve specific for the situation in The Netherlands. Nevertheless, constructing a "global" Y-curve in this investigation was a fundamentally necessary to proof the concept of applying the Y-factor, which can now be further and more specifically applied.

The major critique which I believe can still be moved to the Y-factor method regards the justification of not including more factors: while Arensman (2018) proposed to remove one factor from the list of 13 proposed by Chappin (2016), and this investigation has proven the relevance of these 12 factors, why should we consider specifically these 12 instead of others? This appraisal does not impact the ability of the current 12-factors method to aid the emission abatement discussion, but can be used to contradict its employment, with the excuse of partiality. I believe the underpinning of the factors of the Y-factor method in the implementation barriers discussed in literature, as the IPCC's report (2014) proposed by Arensman (2018), is a good strategy to justify the selected factors; such justifications should be expanded and explicitly proposed when introducing the Y-factor method, to further encourage its use.

Concluding, I strongly endorse the noble intentions of the Y-factor method, which I believe this investigation has proven to be fit-for-purpose; I was positively surprised by the enthusiastic reactions of the majority of the people on whose expertise I relied to perform this investigation. These prove the existing need and interest for another approach to discuss the theme of emission abatement, and the ability of the Y-factor method to at least partially satisfy such appetite. The results obtained in this investigation have largely progressed the development status of the Y-factor, as this has not only been applied to construct a robust, reliable emission abatement curve but has also be discussed with some of the most experienced and authoritative experts in the field of emission abatement curve and sustainable strategies in The Netherlands.

And I am convinced the Y-factor method is now ready for use, and that it will become a popular tool while stimulating the embracement of its multi-domain, socio-technical approach.

Reflection on the energy transition

This master thesis research has focused on the validation of a method to construct emission abatement curves; more than merely testing a method, this entailed the translation of different expertise and opinions on sustainable development into an explicitly structure tool, which can help strategic decision-making. Thus, this research has been inspired and guided by the need of orienting societal development towards a sustainable future. In recent years, the strive towards sustainable societal development, and the collection of measures enabling it, have been named *energy transition*. Its impellent urgency is becoming more and more evident, as the increasing air pollution figures and the consequently increasing number of deaths introduced in *Chapter 1* show.

New international treaties and national policies are being introduced, landscapes are being modified by the introduction of new technological solutions such as solar panels, wind turbines, and EVs; these are shaping a new societal outlook, impacting existing infrastructure (e.g.: smart grids) and encouraging behavioral changes for the population. Basically, all business-as-usual activities are or are going to be re-discussed under the light of a new variable, sustainability.

Considering the limited amount of resources available, and the difficulty of governing such a profound change, it is fundamental to elaborate effective and cost-efficient strategies able to govern and implement sustainable development. McKinsey's cost curves are excellent tools which, besides some possibly outdated figures, can elegantly summarize the cost-efficiency part, characterizing potential options for striving towards sustainable development. Nevertheless, these curves do not consider how to effectively implement such options; thus, they should be treated as one rather than the only considered tool for decision making, as it is currently often happening with unsatisfactory results.
The Y-factor method and the investigation presented in this master thesis report want to provide a new perspective on the implementation of GHG-abatement options, exposing its complexity. The constructed Y-curve stresses the importance on not only focusing on the fundamental but insufficient cost-efficiency perspective, but also on how diverse implementation barriers need to be overcome for effectively achieving sustainable development.

The validated Y-curve object of this investigation and its discussion with energy strategists have shown how the Y-factor method is relevant and helpful in supporting sustainable decision-making, which aims to reduce current GHG emissions while implementing new technologies and shaping the future of societies.

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Appendices

Appendix A: Scientific Article

Exposing the Complexity of GHG Reduction

Validation of a multi-criteria emission abatement curve constructed with the Y-factor to support sustainable energy strategies

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Marginal Abatement Cost (MAC) curves rank emission abatement options according to their marginal implementation cost and are an extremely popular tool to draft energy strategies. Although relevant and elegant, MAC curves are often insufficient to justify the implementation of abatement options, as many of the ones ranked financially convenient are not fully realized. The Y-factor method is an alternative approach to emission abatement curves, highlighting the relevance of 12 implementation barriers related to costs, multi-actor complexity, physical interdependencies and behavioral changes. This investigation applies the Y-factor method to construct a new emission abatement curve, validating its characterizing scores with experts. The obtained Y-curve exposes the relevance of many implementation barriers not capture by MAC curves, as financial barriers are found to account for only 30% of all the considered implementation barriers; the relevance of non-financial barriers helps explaining the reasons for which abatement options considered financially convenient are not implemented. The interviews with experts also verify the relevance of each of the 12 considered factors, each of which is found to be explicitly hampering the implementation of abatement options. Lastly, the newly constructed emission abatement curve enables the combination of cost curves such as the ones developed by McKinsey & Company with the multi-domain approach of the Y-factor method, which can be integrated to expose hidden complexities and thus further support the elaboration of effective and cost-efficient energy strategies.

Keywords: marginal abatement cost curves; emission abatement; sustainable transition; energy strategy.

1. Introduction

On October 30th, 2017, the World Meteorological Organization (WMO) launched a new warning: a record-breaking atmospheric CO_2 concentration of 403.3 ppm was measured for 2016, increasing from the 400 ppm of 2015 and the average annual increase of 2.0 ppm/year, establishing the largest increase over 30 years (WMO, 2017). Air pollution is at the core of the environmental debate, impacting societies across the globe: an increasing amount of people is considered dying because of poor air quality (IHME, 2016), and there is a large agreement in the international political and scientific community on the impelling need to reduce atmospheric concentration of Green House Gasses (GHG): pre-industrial emissions (1990) of GHG are estimated at 36-38 $GtCO_2e$/year (IPCC, 2014) and global emission figures raised to 49 $GtCO_2e$/year in 2010, year of the latest assessment of the UN Intergovernmental Panel on Climate Change (IPCC). Global energy-related CO_2 emissions grew by 1.4% in 2017, reaching a historic high of 32.5 $GtCO_2$/year (IEA, 2017).

Countermeasures such as banning oil-consuming vehicles from metropoles (BBC, 2016), and new regulations are being drafted and implemented, progressively affecting the outlooks of societies. While with the Paris Agreements (IPCC, 2014) the 195 signatory nations have committed for the first time in history to lowering national emissions of GHG, national and international strategies to reduce such emissions have yet to be developed and implemented. A vast debate is ongoing to understand which abatement options are most promisingly able to effectively and cost-efficiently reduce emissions of CO_2 and other GHG.

Marginal Abatement Cost (MAC) curves are the most prominent tool used in the emission abatement debate: a MAC curve is a bar-graph ranking emission abatement options according to their "marginal abatement cost" (€/tCO_2e), which is the cost of eliminating the last-achievable unit of CO_2 given the incurred investment, displayed against the abatement potential (tCO_2e) of each of the ranked options. McKinsey & Company's global cost curve (Nauclér & Enkvist, 2009) is a most popular MAC curve, which elegantly ranks more than 200 emission abatement options belonging to very different economic sectors in one graph of straightforward understanding.

Different authors have highlighted the limitations of MAC curves such as McKinsey's (Chappin, 2016), (Kesicki, 2010), (Kesicki & Ekins, 2012), remarking a lack of reporting transparency with regards to their fundamental underlying assumptions, their inability to account for the interdependent, dynamic character emission abatement, and especially the insufficiency of their financial analysis. In fact, many abatement options ranked as financially convenient in McKinsey's MAC curve have still not been implemented, such as LED lights, buildings insulation and sustainable air transport. This suggests there shall be are other factors besides abatement costs influencing the implementation of abatement options, which ought to be considered when constructing emission abatement curves.

The "Y-factor" is a new method to construct emission abatement curves, firstly presented by Chappin (2016) and further studied by Arensman (2018) and Cheung (2018). The Y-factor aims to qualitatively expose the relevance of 12 socio-technical criteria, or "factors", in hampering the implementation of emission abatement options. The 12 factors are grouped in four categories: *Cost and Financing*, *Multi-actor Complexity*, *Physical Interdependencies*, and *Behavior*. Each of the factors is characterized over an ad-hoc, tripartite scale; to enable comparisons across the factors, all the 12 factor-scales refer to a general scale, which is characterized by three values: Value 0, Value 1, and Value 2. The relevance of each factor for a specific abatement measure is established classifying it with one of the three possible scores. Successively, the scores can be summed to obtain the overall Y-value of each abatement option; these can be used to rank them in a comparative fashion, thus constructing a multi-factorial emission abatement curve. The 12 factors are presented in the table below *(Table 1)*, alongside their relative scales.

Considering the intrinsic differences amongst the 12 factors, the scores assigned with the Y-factor method do not propose a numerical correlation. Rather, they enable a qualitative comparison of abatement options, highlighting the respective relevance of the 12 considered factors: a high score signifies the relevance of the specific barrier for the abatement option, and suggests the importance of discussing it for an effectively implementation. Hence, a high overall Y-value assigned to an abatement option indicates its high difficulty of implementation.

Table 1: The Y-factor method

Category	Factor	Value 0	Value 1	Value 2	Definition
(A) Costs and Financing	Investment cost required **(A1)**	Absent	Medium	Large	Degree to which the investment in an abatement measure is significant
	Expected pay-back time **(A2)**	< 5 years	5-12 years	> 12 years	Expected time required to earn back the investment for an abatement measure
	Difficulty in financing investment **(A3)**	Low	Medium	High	The degree to which it is difficult to finance the abatement or attract appropriate financial means
(B) Multi-actor Complexity	Dependence on other actors **(B1)**	No	Little	Much	Degree of dependence on actions of other actors to successfully implement and execute the abatement measure
	Diversity of actors involved incl. conflicts **(B2)**	Low	Medium	Large	Degree of diversity of interests, values, roles, skills and expectations of the actors involved. Degree of public acceptance. When opposing interests from the (local) public to the implementation of the abatement option are (expected to be) present, a high score should be given'
	Division of roles and responsibilities unclear **(B3)**	Clear	Slightly	Unclear	The extent to which the roles and responsibilities for the realization of the abatement option are clear
(C) Physical Interdependences	Physical embeddedness **(C1)**	No	Medium	High	Degree to which the abatement measure requires physical changes to the environment it is placed in
	Disturbs regular operation **(C2)**	No	Slightly	Strongly	Degree (duration, intensity) to which status quo/regular operation is disrupted to successfully apply the abatement measure
	Technology uncertainty **(C3)**	Fully proven	Small	Large	Degree to which the technological performance of the abatement measure is uncertain
(D) Behavior	Absence of knowledge of actor **(D1)**	High Knowledge	Low Knowledge	No Knowledge	Level of knowledge of the parties responsible for the abatement measure
	Frequency of opportunity **(D2)**	Often	Medium	Rarely	Number of opportunities for the responsible party to realize the abatement measure
	Requires change in behavior **(D3)**	No	Slight	Severe	Degree to which the actors involved need to change their day to day behavior

This article wants to verify if the Y-factor method can be employed to construct a reliable emission abatement curve, able to enrich the emission abatement debate and structuring it around topics relevant for the effective implementation of emission abatement options in society.

The research of Chappin (2016) also proposes an emission abatement curve constructed applying the Y-factor method, but this is not reliable as it presents subjective, self-assigned scores; thus, the reliability of the curve is a fundamental characteristic of this investigation, guided by the following research question:
RQ: *What emission abatement curve can reliably capture not only economic but also relevant non-economic implementation barriers?*

This question is answered considering the implementation barriers highlighted by the Y-factor method, which is thus employed to score different emission abatement options and rank them in an emission abatement curve, called the Y-curve.

To be reliable, the Y-curve must display reliable scores. The reliability of the individual scores cannot be achieved by performing extensive quantitative research on the values of the individual factors, as only some of them are numerically quantifiable (for instance, the factors *A1: Investment cost required* and *A2: Expected payback time*), and the factors have intrinsic, typological differences. Hence, the reliability of the scores shall be achieved relying on the opinions of multiple experts, knowledgeable on the abatement option topic, which can reduce the subjectivity of scores and consequently of the Y-curve.

By constructing the first-ever validated Y-curve and verifying the Y-factor method is fit-for-purpose, this investigation wants to propose it as a new tool for the governance of sustainable societal development, which can initiate a "purposive transition" (Smith et al., 2005): currently MAC curves are the mainstream tool used in the emission abatement debate, but they are an insufficient support for strategic decision-making.

Moreover, the construction of a validated Y-curve enables verifying the relevance of the 12 factors composing the Y-factor method, according to the procedure proposed by Hekkert and Negro (2009), thus enhancing its theoretical background.

2. Methodology

Due to the limited time available for this investigation, 24 abatement options were selected for analysis. Following a multi-criteria selection process pursuing information richness (Patton,1990), 20 options were initially selected from the pool of options analyzed by Chappin (2016); this consists of the 50 abatement options ranked with the highest abatement potential in McKinsey's MAC curve and classified in 9 different economic sectors. The three criteria supporting the selection were sectorial-diversity (at least one option per sector selected), diversity of Abatement Cost diversity (selection of 10 abatement options ranked with a negative abatement cost in McKinsey's MAC curve and 10 with a positive abatement cost), and the scores assigned by Chappin (2016) applying an older version of the Y-factor method. The selection process led to the following 20 selected abatement options, as named by Chappin (2016):

Building efficiency new build, Coal CCS new built, Coal CCS retrofit, Geothermal, Small hydro, PV panels homes, High penetration wind, Cropland nutrient management, Reduced intensive agriculture conversion, Reduced deforestation from timber harvesting, Grassland management, Agronomy Practices, Bioethanol lignocellulosic, Lighting switch incandescent to LED (residential), Residential appliances, Energy efficiency 1 Iron & Steel, Clinker substitution by fly ash, Air transport, Electricity from landfill gas, Composting new waste.

To these selected 20 emission abatement options, four others were subsequently added for their current societal relevance: Nuclear energy, Cars full-hybrid (HEVs), Cars plug-in hybrid (PHEVs), and Battery Electric Vehicles (BEVs). Hence, a total of 24 emission abatement options was included in the investigation.

Considering the time-intensive character of experts' interviews, to accelerate the discussion it was decided to assign preliminary scores to the selected abatement options, basing on information in the existing literature, and successively to ask experts to validate them. A total of 12 interviews with experts were conducted; the scores preliminarily assigned to 19 of the 24 considered abatement options were discussed with a minimum of two experts, while the remaining 5 abatement options were discussed with one expert. People knowledgeable on specific emission abatement options, professionally-active in academia, research institutes, and energy service companies were interviewed.

Experts were not always confident with assigning one of the three possible values; in these cases, an uncertainty score was recorded. With the explicit consent of the interviewee, each interview was recorded and successively reviewed to obtain an interview summary. All interview summaries can be found in *Appendix F* of thesis report. The tables below highlight the experts interviewed.

Table 2: List of interviewed experts

Expert	Affiliation
Blok, Kornelis Prof. dr.	ECOFYS & Delft University of Technology – The Netherlands
Barthel, Claus dr.	Wuppertal Institut für Klima, Umwelt, Energie gGmbH – Germany
Dejonghe, Koen MA.	Statkraft Markets BV – The Netherlands
Elizondo, Cordero Alejandra dr.	Centro de Investigatiòn y Docencia Economicas – Mexico
Jasper, Jörg Prof. dr.	EnBW – Germany
Morelli, Gargiulo Vittorio MSc.	Bain & Company – The Netherlands
Smith, Pete Prof. dr.	University of Aberdeen – United Kingdom
Sprengers, Peter MSc.	Statkraft Markets BV – The Netherlands
Vaessen, Peter Prof. ir.	DNV GL & Delft University of Technology- The Netherlands
Viebhan, Peter dr.	Wuppertal Institut für Klima, Umwelt, Energie gGmbH – Germany
Verhagen, Jan dr.	Wageningen University & Research – The Netherlands

Once at least two interviews per abatement option had been performed, the collected experts' opinions were reviewed and synthesized into final, validated scores. For the sake of transparency, a collection of guidelines for synthesizing experts' opinions was established, consisting of two scopes (inspired by experts' interviews) and multiple validation requirements.

Scope 1: The 12 factors are barriers potentially hampering the implementation of emission abatement options; thus, the scores should refer to those actors who could proactively implement the respective abatement option, to reflect how the barriers highlighted by the factors might impact actors' decision-making. E.g.: A person who buys an EV does not experience the conflicts between the oil-producing corporations, lobbying for benzine-vehicles, and government parties pushing for sustainable transport (factor *B1: Diversity of actors involved incl. conflicts*).

Scope 2: Most of the considered abatement options propose a change to current practices and/or existing habits. Thus, the scores should reflect the relevance of the changes compared to business-as-usual rather than in any sort of absolute value. E.g.: The construction of a new building requires the interaction of multiple actors, and so does the constructing an energy-efficient one, which should thus be considered as having no/minor superior dependency on other actors (factor *B1: Dependence on other actors*).

The following validation-requirements (to each of which is assigned a color used in the next *Results* section) enabled the synthesis of the collected experts' opinions into validated scores:

- If all experts validated the preliminary score, this is confirmed as final score; [GREEN]
- If all experts proposed the same score, different from the preliminary one, the proposed score is accepted as final; [GREEN]
- If one or more expert validated the preliminary score, while one or more experts were uncertain between two score, one of which being the preliminary score, the latter is validated for absence of a clear argument against it; [GREEN]
- If experts were uncertain about scores similar to each other, (e.g.: I-1 proposes 2, I-2 is uncertain between 1 or 2), or different from each other but similar to the preliminary score (p.s. = 1, I-1 uncertain between 0-1, I-2 uncertain between 1-2) the most "popular" score is validated as final (e.g.: 2 and 1), but reported as "somewhat uncertain", as different from the preliminary score and not proposed by experts without any uncertainty; [YELLOW]
- If experts proposed different score (either with one validating the preliminary score or not), the arguments presented by the experts are compared:
    - If the argument of one expert is not aligned with either Scope 1 or Scope 2, the argument and the score proposed by the other expert(s) is preferred; [GREEN]

- If all arguments are aligned with both *Scope 1* and *Scope 2*, the dilemma can be solved in three ways:
  1. Justifying the predominance of one of the arguments and/or scores, and reporting it as "somewhat uncertain" for the sake of transparency; [YELLOW]
  2. Arbitrary selecting one of the proposed scores, and reporting it as "significantly uncertain" for the sake of transparency; [RED]
  3. Arbitrary selecting a medium between the proposed scores and reporting it as "significantly uncertain" for the sake of transparency. [RED]

Summing the individual scores characterizing each abatement option as in Chappin's research (2016) returns the overall Y-value characterizing each of them; Y-values can be ranked to obtain the validated Y-curve.

3. The validated Y-curve and Relevance of the 12 factors

The validated scores are reported in the *Table 3* (below), which highlights their uncertainty, depending on the collected experts' opinions and referring to the colors characterizing the validation requirements introduced in the previous section: the scores highlighted in green are considered "certain", as the interviewed experts provided very similar judgements; the ones in yellow are considered "somewhat uncertain", as the collected opinions of experts were slightly conflicting; the ones highlighted in red are "significantly uncertain", as the opinions of experts were conflicting and the reported scores act as medium. The scores assigned to the 5 abatement options validated by one expert (highlighted with an "*") are reported as somewhat uncertain.

Considering the 19 abatement options validated by two or more experts, the most contentious ones are: High penetration wind, Nuclear, and Bioethanol lignocellulosic, which have 6 of their 12 scores reported as somewhat or significantly uncertain; other dubious abatement options (4/12 scores uncertain) are: Building efficiency new built, Geothermal, Small hydro, Cropland nutrient management, Agronomy practices, and Cars plug-in hybrid. Similarly, the factors over which the interviewed experts provided most often uncertain and conflicting opinions are: *D1 Absence of knowledge of actors* (uncertain for 9 of the 19 abatement options) and three other factors *ex-equo* (7/19 times uncertain): *A3: Difficulty in financing the investment*, *C2: Disturbs regular operations*, and *D3: Requires change in behavior*.

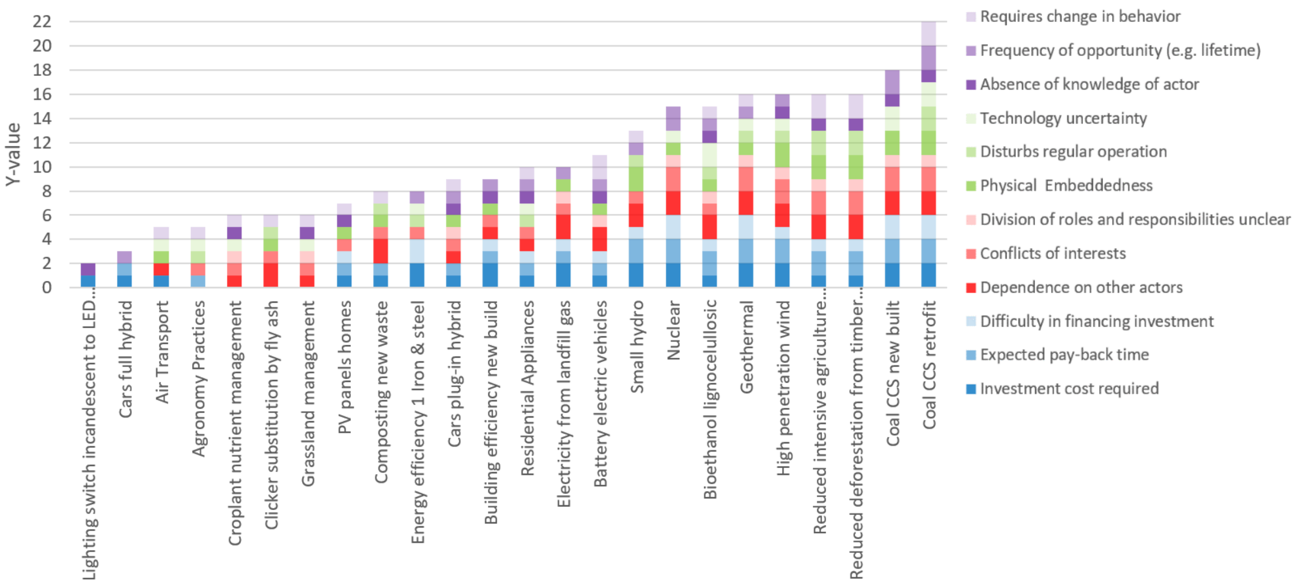
Table 3: Validated Y-scores and uncertainty

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	sum
Lighting switch incandescent to LED (residential)	1	0	0	0	0	0	0	0	0	1	0	0	2
Cars full hybrid	1	1	0	0	0	0	0	0	0	0	1	0	3
Air Transport*	1	0	0	1	0	0	1	0	1	0	0	1	5
Agronomy Practices	0	1	0	0	1	0	0	1	1	0	0	1	5
Cropland nutrient management	0	0	0	1	1	1	0	0	1	1	0	1	6
Clinker substitution by fly ash*	0	0	0	2	1	0	1	1	0	0	0	1	6
Grassland management	0	0	0	1	1	1	0	0	1	1	0	1	6
PV panels homes	1	1	1	0	1	0	1	0	0	1	0	1	7
Composting new waste*	1	1	0	2	1	0	1	1	0	0	0	1	8
Energy efficiency 1 Iron & steel*	2	0	2	0	1	0	0	1	1	0	1	0	8
Cars plug-in hybrid	1	1	0	1	1	1	1	0	0	1	1	1	9
Building Efficiency New Build	2	1	1	1	1	0	1	0	0	1	1	0	9
Residential appliances	1	1	1	1	1	0	0	1	1	1	1	1	10
Electricity from landfill gas*	2	1	1	2	1	1	1	0	0	0	1	0	10
Battery Electric Vehicles	1	1	1	2	0	1	1	0	0	1	1	2	11
Small hydro	2	2	1	2	1	0	2	1	0	0	1	1	13
Nuclear	2	2	2	2	2	1	1	0	1	0	2	0	
Bioethanol lignocellulosic	1	2	1	1	1	1	1	1	2	1	1	1	15
Geothermal	2	2	2	2	2	1	1	1	1	0	1	1	16
High penetration wind	2	2	1	2	2	1	2	1	1	1	1	0	16
Reduced intensive agriculture conversion	1	2	1	2	2	1	2	2	0	1	0	2	16
Reduced deforestation from timber harvesting	1	2	1	2	2	1	2	2	0	1	0	2	16
Coal CCS new build	2	2	2	2	2	1	2	0	2	1	2	0	18
Coal CCS retrofit	2	2	2	2	2	1	2	2	2	1	2	2	22

The uncertainty characterizing the factors *D1* and *D3* was most often caused by the different contexts (geographical scope mainly) to which the scores could refer.

Coherently with the curve presented by Chappin (2016), the validated scores characterizing each abatement option are summed to obtain the Y-value characterizing it; ranking the Y-values enables the construction of the validated Y-curve, intended by the research question.

Figure 1: Validated Y-curve



Besides validating the scores, interviewing experts had also the goal to underpin the relevance of the 12 factors proposed by the Y-factor method. The relevance of the 12 factors could be verified following the procedure proposed by Hekkert and Negro (2009): to validate the relevance of the seven system functions proposed by Hekkert et al. (2007), they propose to "First, based on the different event databases we can count how many events are allocated to each system function and calculate the share of each system function per case study and in total. Second, based on the earlier described cases, we argue what the relative importance is of the different system functions" (p. 590). Comparing these seven functions to the 12 factors considered in this investigation, their relevance can be verified following the same procedure. The procedure can be applied to the validated scores following two numerical strategies

A) Relevance per Abatement Option:

The share-contribution of each individual score to the overall Y-value of each abatement option can be easily calculated. Averaging the share-contributions of each factor over all the abatement options provides the average contribution of each factor to all Y-values, thus highlighting their relevance.

Table 4: Relevance of the 12 factors – per option

Abatement Option	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
Building Efficiency New Build	22.2	11.1	11.1	11.1	11.1	0.0	11.1	0.0	0.0	11.1	11.1	0.0
Coal CCS new build	11.1	11.1	11.1	11.1	11.1	5.6	11.1	0.0	11.1	5.6	11.1	0.0
Coal CCS retrofit	9.1	9.1	9.1	9.1	9.1	4.5	9.1	9.1	9.1	4.5	9.1	9.1
Geothermal	12.5	12.5	12.5	12.5	12.5	6.3	6.3	6.3	6.3	0.0	6.3	6.3
High penetration wind	12.5	12.5	6.3	12.5	12.5	6.3	12.5	6.3	6.3	6.3	6.3	0.0
Nuclear	13.3	13.3	13.3	13.3	13.3	6.7	6.7	0.0	6.7	0.0	13.3	0.0
PV panels homes	14.3	14.3	14.3	0.0	14.3	0.0	14.3	0.0	0.0	14.3	0.0	14.3
Small hydro	15.4	15.4	7.7	15.4	7.7	0.0	15.4	7.7	0.0	0.0	7.7	7.7
Agronomy Practices	0.0	20.0	0.0	0.0	20.0	0.0	0.0	20.0	20.0	0.0	0.0	20.0
Cropland nutrient management	0.0	0.0	0.0	16.7	16.7	16.7	0.0	0.0	16.7	16.7	0.0	16.7
Grassland management	0.0	0.0	0.0	16.7	16.7	16.7	0.0	0.0	16.7	16.7	0.0	16.7
Reduced deforestation from timber harvesting	6.3	12.5	6.3	12.5	12.5	6.3	12.5	12.5	0.0	6.3	0.0	12.5
Reduced intensive agriculture conversion	6.3	12.5	6.3	12.5	12.5	6.3	12.5	12.5	0.0	6.3	0.0	12.5

Bioethanol lignocellulosic	6.7	13.3	6.7	13.3	6.7	6.7	6.7	6.7	13.3	6.7	6.7	6.7
Lighting switch incandescent to LED (residential)	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0
Residential appliances	10.0	10.0	10.0	10.0	10.0	0.0	0.0	10.0	10.0	10.0	10.0	10.0
Clinker substitution by fly ash	0.0	0.0	0.0	33.3	16.7	0.0	16.7	16.7	0.0	0.0	0.0	16.7
Energy efficiency 1 Iron & steel	25.0	0.0	25.0	0.0	12.5	0.0	0.0	12.5	12.5	0.0	12.5	0.0
Air Transport	20.0	0.0	0.0	20.0	0.0	0.0	20.0	0.0	20.0	0.0	0.0	20.0
Cars full hybrid	33.3	33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	0.0
Cars plug-in hybrid	11.1	11.1	0.0	11.1	11.1	11.1	11.1	0.0	0.0	11.1	11.1	11.1
Battery Electric Vehicles	9.1	9.1	9.1	18.2	0.0	9.1	9.1	0.0	0.0	9.1	9.1	18.2
Composting new waste	12.5	12.5	0.0	25.0	12.5	0.0	12.5	12.5	0.0	0.0	0.0	12.5
Electricity from landfill gas	20.0	10.0	10.0	20.0	10.0	10.0	10.0	0.0	0.0	0.0	10.0	0.0
AVERAGE CONTRIBUTION - per factor (%)	**13.4**	**10.2**	**6.6**	**12.3**	**10.4**	**4.7**	**8.2**	**5.5**	**6.2**	**7.3**	**6.6**	**8.8**
AVERAGE CONTRIBUTION – per category (%)		**30.1**			**27.3**			**19.9**			**22.6**	

While the relevance of each factor seems evident, the obtained figures could be biased because of the employed calculation method. In fact, for an abatement option characterized by a low overall Y-value (e.g.: Lighting switch incandescent to LED, Y-value = 2), a factor having a score of 1 (e.g.: *A1: Investment cost required*) contributes to the overall Y-value for 50% and would thus be assigned a relevance of 50%. While this is valid to establish the relevance of each factor, it might be considered having an excessively relative character, capturing the factor's relevance for a specific abatement option rather than its generic relevance.
Thus, a second numerical method can be used to verify these figures.

B) Relevance per Factor

In this case, the scores assigned to a specific factor for all the 24 abatement options can be summed, and the overall sum can be divided by, thus obtaining the score assigned on average to each factor.
The *Average score – per factor* figures display the share-contribution of each factor to the total overall Y-values over the considered abatement options; these can be grouped also by category.

Table 5: Relevance of the 12 factors – per factor

Factors	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	Total
Average score - per factor	1.2	1.1	0.8	1.3	1.1	0.5	1.0	0.6	0.6	0.6	0.7	0.8	10.5/24
Average score - per category		3.2			3.0			2.2			2.1		10.5/24
AVERAGE CONTRIBUTION -per factor (%)	**11.5**	**10.7**	**7.9**	**12.7**	**10.7**	**5.2**	**9.1**	**6.0**	**6.0**	**5.6**	**6.7**	**7.9**	100 %
AVERAGE CONTRIBUTION – per category (%)		**30.2**			**28.6**			**21.0**			**20.2**		100 %

Comparing the same variables in the two tables (matching over the same color), shows how the relevance figures are not identical, but very similar. The factor-relevance figures with the two calculations can be averaged to a final relevance-figure per factor.

Table 6: Relevance of the 12 factors

Factors	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
AVERAGE CONTRIBUTION - per factor (%)	**12.4**	**10.4**	**7.3**	**12.5**	**10.6**	**4.9**	**8.7**	**5.7**	**6.1**	**6.4**	**6.7**	**8.4**
AVERAGE CONRIBUTION – per category (%)		**30.1**			**27.9**			**20.5**			**21.4**	

The following can be concluded: Each of the 12 factors is verified to be relevant. In fact, all the "functions used in the empirical analyses can be related to actual events that took place" (Hekkert & Negro, 2009, p. 590), which translates to each factor having been considered able to capture existing implementation barriers by the interviewed experts. This conclusion was sought by this research as previous researches could only underpin in the existing literature the relevance of the four categories composing the Y-factor method. Following a very different approach, this result adds to the theoretical reliability of the Y-factor method, showing the relevance of the 12 individual factors and connecting them to the methodology proposed by Hekkert and Negro (2009).

4. Comparison and Integration with McKinsey's global cost curve

The goal of this investigation was the construction of the validated Y-curve, to verify the ability of the Y-factor method to construct an emission abatement curve able to provide new insights to the emission abatement debate. Thus, the validated Y-curve was compared to McKinsey's global cost curve.

The Abatement Cost figures characterizing the 24 considered abatement options in McKinsey's global cost curve were provided by McKinsey & Company to the investigation of Chappin (2016), who made them available for this research. While "Battery electric vehicles" is not one of the 50 top-abatement potential options in McKinsey's curve and was thus not included in the research of Chappin (2016), it is possible to retrieve its Abatement Cost from McKinsey's report (Nauclér & Enkvist, 2009) which, in *Exhibit 8.6.4* on page 100, is reported to be about 90 €/tCO_2e, the highest marginal cost among the considered abatement options. The abatement potential is not unequivocally reported; as it is also not relevant for the comparison in object, it is not reported.

Considering the intrinsic differences between the two curves, the only possible comparison is between the relative ranking of the considered options; thus, the 24 considered abatement options are extracted from McKinsey's global cost curve and relatively ranked to obtain a 24-option cost curve.

A ranking-difference of more than 8-spots (1/3) is considered to be "substantially different"; ranking differences up to 8 spots are divided in 2 classes-of-similarities. Of the considered 24 abatement options, 9 are assigned a "most similar" (color green in *Table 7* below) ranking in the two curves, while 5 others have a "most different" one (color red). The remaining 10 abatement options are ranked "significantly differently" (color yellow). In *Table 4*, the "non-financial Y-value" is the sum of the scores assigned to the factors belonging to the categories *B Multi-actor complexity*, *C Physical Interdependencies* and *D Behavior*.

Table 7: Comparison Y-curve & McKinsey's global cost curve

Abatement Option	Abatement Cost [€/tCO_2e]	Y-value [out of 24]	Ranking MAC → Ranking Y-curve	Financial Y-value [out of 6]	Ranking Financial Y-curve
Lighting switch incandescent to LEDs, residential	-253.1	2	1 → 1	1	4
Residential appliances	-195.8	10	2 → 13	3	10
Bioethanol lignocellulosic	-138.8	15	3 → 17	4	13
Cars full hybrid	-72.9	3	4 → 2	2	7
Cropland nutrient management	-68.8	6	5 → 5	0	1
Building efficiency new built	-40.2	9	6 → 11	4	13
Clinker substitution by fly ash	-32	6	7 → 5	0	1
Electricity from landfill gas	-23.4	10	8 → 13	4	13
Air Transport	-20.5	5	9 → 3	1	4
Small hydro	-8.9	13	10 → 16	5	19
Geothermal	-3.9	16	11 → 19	6	21
Grassland management	3.4	7	12 → 7	0	1
Reduced deforestation from timber harvesting	6.9	16	13 → 19	4	13
Energy efficiency 1 Iron & Steel	8.2	8	14 → 9	4	13
Composting new waste	9.9	8	15 → 9	2	7
Nuclear	10.4	15	16 → 17	6	21
Agronomy Practices	15.8	5	17 → 3	1	4
Cars plug-in hybrid	18.1	9	18 → 11	2	7
PV panels homes	27.9	7	19 → 7	3	10
High penetration wind	32.4	16	20 → 19	5	19
Reduced deforestation from intensive agriculture conversion	39.9	16	21 → 19	4	13
Coal CCS retrofit	62.2	22	22 → 24	6	21
Coal CCS new built	64.6	18	23 → 23	6	21
Battery electric vehicles	90	11	24 → 15	3	10

While the Y-curve provides new insights for each of the 24 abatement options, the most evident similarities and differences in the ranking of the two curves are reported below:

The abatement option Coal CCS new built and Coal CCS retrofit are placed by both methods on the far-right of the curves, with both options assigned the maximum scores for the category *Cost and Financing*, and almost equally high scores for the other categories. Their relative ranking is swapped in the two curves, with McKinsey's MAC curve considering cheaper to retrofit a coal plant with CCS than building a new one.

The ranking of the abatement options High penetration wind and Nuclear energy is very similar in the two curves; the Y-curve estimates actors-interaction challenges to be as relevant as the financial ones.

McKinsey's curve assigns a negative implementation cost to the abatement option Cropland nutrient management, somehow reflected in a score of 0 for the category *Cost and Financing*. The Y-curve additionally urges to focus on the ease of fertilizer supply, possible leaching of nitrate with consequent social conflicts and the clarification of different task-performance to reduce the relevant multi-actor complexity.

Reduced deforestation from intensive agriculture conversion has a very similar ranking in the two curves; besides the financing needed to compensate land owners, the Y-curve highlights difficulties related to the involved of many institutions for the distribution of the funds. Moreover, disruptions of regular business income for local population, invited to stop generational habits, should be strategically planned for.

Lighting switch incandescent to LED (residential) is the abatement option ranked as having the fewer implementation barriers by both curves. Overall costs are very limited (10 €/bulb), but the Y-curves remarks how buyers are not inclined to face an expense ten times higher than otherwise possible in name of future savings, even with these are proven. Moreover, the existence of some educational barriers is highlighted.

Cars full hybrid are also ranked very similarly in the two curves and is considered one of the abatement options with fewer barriers to overcome.

PV panels home and Battery electric vehicles are ranked amongst the most expensive options by McKinsey's MAC curve, while they are located in the central section of the Y-curve. Considering the limited relevance of non-financial barriers, the large ranking difference is likely to be caused by outdated cost-figures: McKinsey's curve was published in 2009 and since then, costs of PV technology have dropped more than 70% (SEIA, 2018) and BEVs price-competitive with ICEs of their respective classes have been introduced on the market, such as the 2018 introduction of the Nissan LEAF. The Y-curve highlights the existence of a chicken and egg paradox: how to introduce the recharging infrastructure necessary to encourage the diffusion of BEVs, while few are circulating?

Agronomy practices is ranked 3rd/24 in the Y-curve and 17th/24 in McKinsey's curve. Such difference is explained but the low score (1 out of a maximum of 6) of the *Cost and Financing* category, while McKinsey's curve estimates a relatively high implementation cost. This abatement option is one of the most controversial ones as the interviewed experts disagree over the effectiveness on such practices. While not explicitly explaining the high cost-figures displayed by McKinsey's curve, the uncertainties of multiple scores remark the importance of further analysis.

The negative abatement costs assigned by McKinsey's MAC curve to the abatement options Bioethanol lignocellulosic and Residential appliances are surprising. For the former, the Y-curve remarks implementation barriers well-distributed across the four categories of the Y-factor method, and the interviewed experts reported complexities caused by high production costs, uncertainty of the market and similarities between secondary-biofuels and their disappointing predecessors. Instead, a partial reason for the ranking differences for Residential appliances is definitional: the interviewed experts remarked the inevitability of focusing on smart, energy-efficient appliances rather than solely efficient ones, making the management of energy-consumption data from appliances' owners the most relevant barrier, and imposing a reflection on the definition and management of behavioral changes.

Substantial ranking differences also exist comparing McKinsey's cost curve to the ranking obtain only considering the "financial-factors" in the Y-curve, which are those belonging to the *Cost and Financing* category. The ranking difference between McKinsey's MAC curve and the Y-curve substantially reduces (changing class-of-similarity) considering only the "Financial Y-curve" for four abatement options, namely Reduced deforestation from timber harvesting and Energy efficiency 1 Iron & Steel and Battery electric vehicles and Residential appliances. Nevertheless, for many other options the ranking differences do not reduce or even increase. The ranking differences can be caused by: the lower sensibility of the three financial factors considered by the Y-curve (7 possible values, from 0 to 6) which facilitates score-overlaps impactful for the ranking; outdated cost figures in McKinsey's 2009 cost curve; the inclusion of cost-savings in McKinsey's MAC curve, not captured by the Y-factor method.

Nevertheless, the scores presented by the validated Y-curve can explain why all the 11 abatement options ranked with a negative Abatement Cost in McKinsey's global cost curve and considered in this investigation are not yet implemented on a large scale. In fact, non-financial implementation barriers (factors belonging three non-financial categories: *Multi-actor Complexity*, *Physical Interdependencies*, and *Behavior*) account for 50% or more of the total barriers relevant for 10 of these 11 options, highlighted by their summed-scores. The missing option, Cars full hybrid, is characterized by a low overall Y-value (3), of which a third consists of non-financial barriers; considering its definition in McKinsey's report considers any vehicle with a start-and-stop system to be a hybrid vehicle, HEVs can be considered already largely diffused.

Table 8: Relevance of non-financial Y-factors for abatement options with abatement cost < 0 in McKinsey's MAC curve

Abatement Option	Abatement Cost [€/tCO_2e]	Y-value [out of 24]	Non-Financial Y-value [out of 18]	Non-Financial %
Building Efficiency New Build	-40.2	9	5	55.6
Geothermal	-3.9	16	10	62.5
Small hydro	-8.9	13	9	60.0
Cropland nutrient management	-68.8	6	12	75.0
Bioethanol lignocellulosic	-138.8	15	11	73.3
Lighting switch incandescent to LED (residential)	-253.1	2	1	50.0
Residential appliances	-195.8	10	7	70.0
Clinker substitution by fly ash	-32	6	4	50.0
Air Transport	-20.5	5	4	80.0
Cars full hybrid	-72.9	3	1	33.3
Electricity from landfill gas	-23.4	10	6	75.0

Lastly, acknowledging the difference of approach to emission abatement proposed by McKinsey's MAC curve and the Y-factor and the importance of both perspectives to draft effective and cost-efficient energy strategies, a first, simple tool combining the two perspectives is constructed. This wants to further highlight the new insights which can be obtained employing the Y-factor and sets an example for further investigations which can develop new tools able to integrate the two perspectives. The data used to construct this tool is provided in *Table 9*, where the letters used as reference for graphical purposes are also specified.

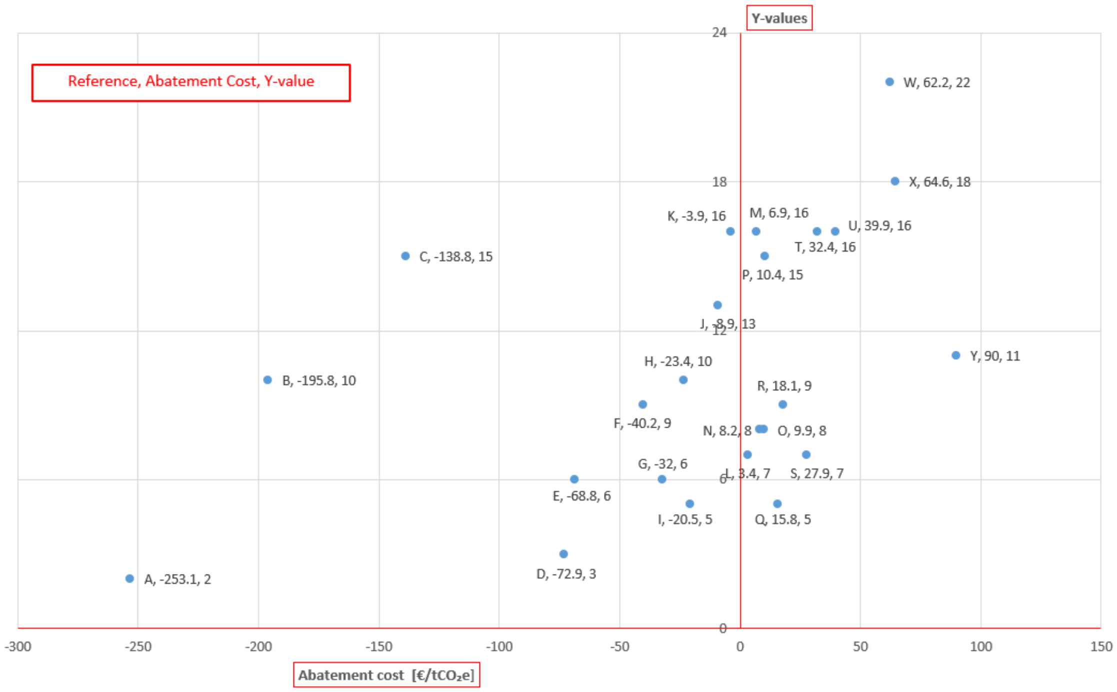
Table 9: Data set for new tool combining insights from McKinsey's MAC and the Y-factor

Abatement option	Graph Reference	Abatement cost [€/tCO_2e]	Y-value [out of 24]
Lighting switch incandescent to LEDs, residential	A	-253.1	2
Residential appliances	B	-195.8	10
Bioethanol lignocellulosic	C	-138.8	15
Cars full hybrid	D	-72.9	3
Cropland nutrient management	E	-68.8	6
Building efficiency new built	F	-40.2	9
Clinker substitution by fly ash	G	-32	6
Electricity generation from landfill gas	H	-23.4	10
Air transport	I	-20.5	5
Small hydro	J	-8.9	13
Geothermal	K	-3.9	16
Grassland management	L	3.4	7
Reduced deforestation from timber harvesting	M	6.9	16
Energy efficiency 1 Iron & Steel	N	8.2	8
Composting new waste	O	9.9	8
Nuclear	P	10.4	15

Agronomy Practices	Q	15.8	5
Cars plugin hybrid	R	18.1	9
PV panels homes	S	27.9	7
High penetration wind	T	32.4	16
Reduced deforestation from intensive agriculture conversion	U	39.9	16
Coal CCS retrofit	W	62.2	22
Coal CCS new built	X	64.6	18
Battery electric vehicles	Y	90	11

The proposed tool is presented in *Figure 2* below. Each dot represents an abatement option, characterized by its (reference letter, Abatement Cost, and Y-value).

Figure 1: New tool combining insights from McKinsey's MAC and the Y-factor



The abatement options in the top right corner of the graph are the least appealing ones, expensive and difficult to implement. The abatement options in the bottom-left corner (O= LED lights, and T= Cars full hybrid) are the most appealing, cheap and rather easy to implement. Of the abatement options distributed around the Y-axis of the graph, the ones position towards the bottom of the graph are more appealing, with lower implementation barriers against a comparable implementation cost.

5. Conclusion

The current emission abatement debate is dominated by MAC curves, which propose purely financial analyses; a most popular MAC curve is McKinsey & Company's global cost curve which is useful, elegant but insufficient to explain why emission abatement options financially convenient are not implemented. The goal of this research was to construct a reliable emission abatement curve applying the Y-factor method, to verify its ability to provide new insights to the emission abatement debate, and to verify the relevance of its 12 factors. The scores assigned with the Y-factor method are not quantitively comparable given the typological differences of the factors; hence, the reliability of scores in the Y-curve scores shall be achieved relying on the opinions of multiple experts, knowledgeable on the abatement option topic which can reduce the subjectivity of scores. Thus, the main research question which guided this investigation was:

RQ: *What emission abatement curve can reliably capture not only economic but also relevant non-economic implementation barriers?*

24 emission abatement options were selected from the pool considered by McKinsey's MAC curve and assigned preliminary scores basing on the information available in the literature. Successively, 12 interviews with experts knowledgeable on the emission abatement options were performed to validate the preliminary assigned scores.

The most controversial abatement options are found to be: High penetration wind, Nuclear, and Bioethanol lignocellulosic, Building efficiency new built, Geothermal, Small hydro, Cropland nutrient management, Agronomy practices, and Cars plug-in hybrid. Similarly, the Y-factors over which the interviewed experts provided the most conflicting opinions are: *D1: Absence of knowledge of actors*, *A3: Difficulty in financing the investment*, *C2: Disturbs regular operations*, and *D3: Requires change in behavior*.

The interviews with experts enabled the validation of the scores, which were used to create the intended validated Y-curve and thus answer to the main research question.

All the 12 factors contribute differently but significantly to the Y-values assigned to the considered abatement option, representing its difficulty of implementation; thus, following the procedure proposed by Hekkert and Negro (2009), remarking how it is possible to validate the importance of specific variables by observing their relevance across different case studies, it is possible to validate the relevance of each of the 12 factors, adding to the previously achieved theoretical embedding of the Y-factor method.
On average, the factors belonging to category *Cost and Financing* are found to account only for about 30% of the total implementation barriers considered.

The curve provides many new insights not captured by the financial figures of McKinsey's MAC curve for each of the considered options and is especially able to highlight the relevance of non-financial barriers for those abatement options ranked in McKinsey's cost curve with negative abatement cost but surprisingly not implemented.

Comparing the Y-curve to McKinsey's MAC curve also allowed to construct a first simple tool combining the abatement cost of abatement options and their difficulty of implementation, which can provide new insights on the complexity of overcoming implementation barriers hampering emission abatement, thus further structuring the emission abatement debate.

Thus, it is concluded that the Y-factor method is a relevant method to construct emission abatement curves, which can provide new insights to the emission abatement debate, exposing relevant complexities. Moreover, the approach of the Y-factor method can be integrated with other approaches to the debate to develop new insightful tools.

Three main limitations characterized this investigation:

The consideration of limited number of abatement options was considered, fewer than the two other abatement curves to which it compares, namely the one presented by Chappin (2016) and McKinsey's MAC curve; this reduces the possibilities of result-comparison and might have led to conclusions which would not be as valid and/or relevant considering more abatement options.

To facilitate and accelerate the time-intensive interviews with experts, these were asked to validate preliminary scores rather than applying the Y-factor method themselves, which is a more likely utilization for potential users; this avoided digressional comments from the interviewees but might have induced a somewhat bounded reasoning rather than allowing an entirely-free approach to the proposed topics. Nevertheless, the impact is considered minor: clarificatory comments were added to the preliminary scores only when explicitly asked by the interviewees, and the majority of the scores are considered "certain" as they smoothly synthesize similar opinions of different experts.

Considering the time constraints, a limited number of experts could be consulted to validate the preliminary scores: for 5 abatement options only one expert could be consulted, while for the other 19 options two or more experts were consulted; thus, a certain degree of subjectivity could still be contested to the presented scores, especially for those abatement options and factors which most frequently displayed uncertainty in the scores.

Future research should focus on further investigating those abatement options found to be the most contentious, and the factors for which the assigned scores are most uncertain. Moreover, additional efforts could be oriented towards including more abatement options in the Y-curve and consulting more experts to further reduce the subjectivity of the scores to create a more reliable global Y-curve. From this, multiple local Y-curves better able to capture more specific (e.g.: national) situations cold be constructed, following the example of McKinsey's local cost curves. Finally, new tools combining the financial approached proposed by MAC curves with the multi-criteria approach of the Y-factor method should be developed, to maximize the information and insights which can be used for drafting energy strategies, able to guide societies along sustainable development.

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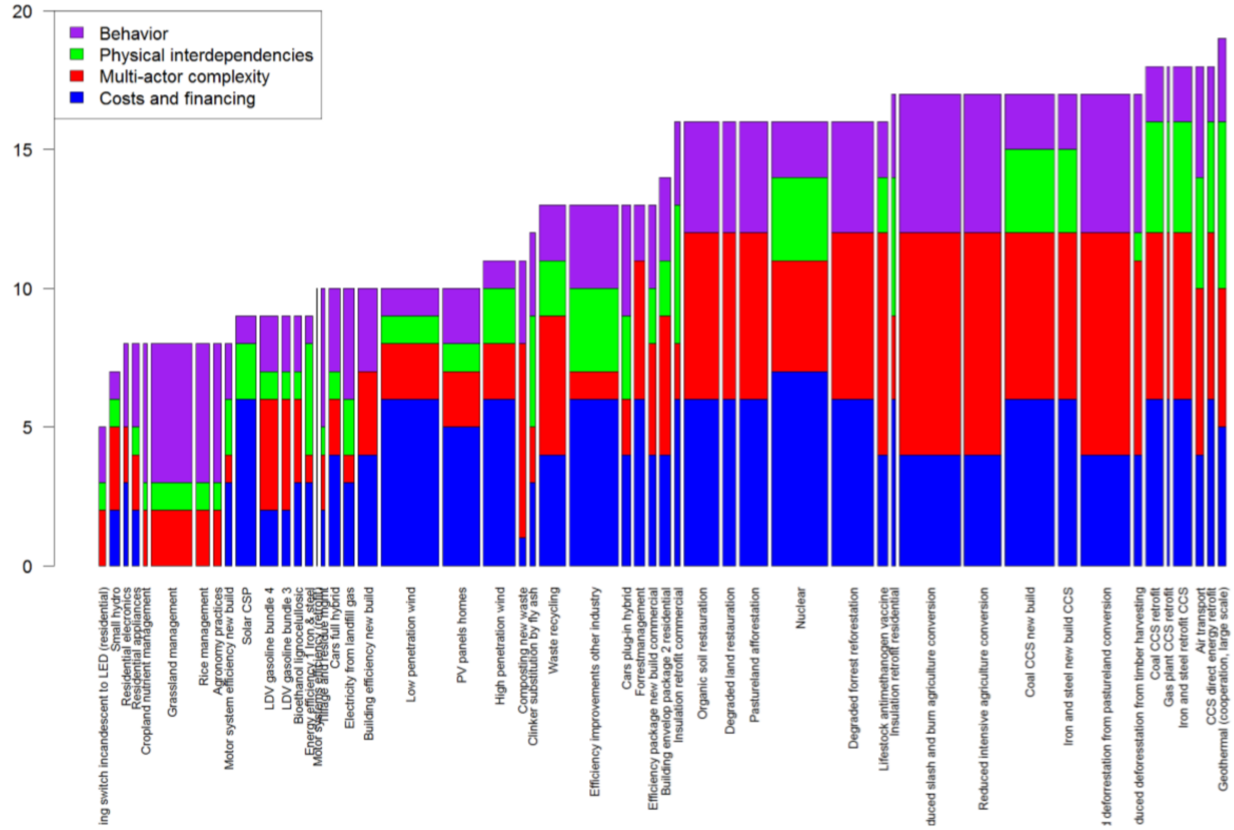
Appendix B: Results from (Chappin, 2016)

Curve from (Chappin, 2016)



Individual Y-scores assigned by (Chappin, 2016) to the selected abatement options

Abatement Option	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	D3
Building Efficiency New Build	1	2	1	1	0	1	1	0	0	0	1	2	0
Coal CCS new build	2	2	2	2	0	2	2	2	0	1	0	2	0
Coal CCS retrofit	2	2	2	2	1	2	1	2	1	1	0	2	0
Geothermal	2	2	1	2	1	1	1	2	2	2	1	2	0
Small hydro	1	1	0	1	1	1	0	1	0	0	0	1	0
PV panels homes	1	2	2	0	2	0	0	1	0	0	1	1	0
High penetration wind	2	2	2	0	0	2	0	1	1	0	0	1	0
Nuclear	2	2	3	1	0	2	1	2	0	1	0	2	0
Cropland nutrient management	0	0	0	0	2	0	0	0	1	0	2	1	2
Reduced intensive agriculture conversion	1	2	1	2	2	2	2	0	0	0	2	1	2
Reduced deforestation from timber harvesting	1	2	1	2	2	2	1	0	1	0	2	1	2
Grassland management	0	0	0	0	2	0	0	0	1	0	2	1	2
Agronomy Practices	0	0	0	0	2	0	0	0	1	0	2	1	2
Bioethanol lignocelullosic	1	2	0	1	1	1	0	0	1	0	0	1	1
Lighting switch incandescent to LED (residential)	0	0	0	0	2	0	0	1	0	0	1	1	0
Residential appliances	1	0	1	0	2	0	0	1	0	0	1	2	0
Energy efficiency 1 Iron & steel	1	1	1	0	1	0	0	2	2	0	0	1	0
Clinker substitution by fly ash	1	1	1	1	0	1	0	1	2	1	0	2	1
Air Transport	1	2	1	2	2	2	0	2	1	1	1	1	2
Cars full hybrid	1	1	2	0	2	0	0	0	0	1	1	2	0
Cars plug-in hybrid	1	1	2	0	2	0	0	1	1	1	1	2	1
Electricity from landfill gas	1	2	0	0	0	0	1	1	1	0	2	2	0
Composting new waste	1	0	0	2	2	1	2	0	0	0	1	0	2

Appendix C: Selection Process for the Abatement Options to consider

This section presents the selection process follow to identify the abatement options to include in this investigation. The selection process is presented below without the illustrations of the Y-factor scores from (Chappin, 2016) supporting each selection step but providing the overall Y-score next to the abatement options, which are thus mentioned in the following fashion: [Sector]: Abatement option (overall Y-score). Selection criteria are highlighted in *italics*. The Y-scores from (Chappin, 2016) are presented in *Appendix B.*

Step 1: Most Similar and Most Different overall Y-scores per sector

[Building]:

Most Similar:

(a) Insulation Retrofit Commercial (16) - Insulation Retrofit Residential (17)

(b) Building envelop package 2 residential (14) - Efficiency package new build commercial (13).

Most Different:

Insulation Retrofit Residential (17) - Building Efficiency New Build (10).

As two pairs of options equally match the *Most Similar* selection criteria, a choice has to be made. Pair (a) is preferred as it contain one option (Insulation Retrofit Residential) also matching the *Most Different* selection criteria.

Selected abatement options:

[Building]: Insulation Retrofit Commercial; Insulation Retrofit Residential; Building Efficiency New Build.

[CCS]

Most Similar:

Coal CCS new build (17) - Iron and steel new build CCS (17)

Coal CCS retrofit (18) - Gas plant CCS retrofit (18) - Iron and steel retrofit CCS (18) - CCS direct energy retrofit (18).

Most Different:

Coal CCS new build (17) / Iron and steel new build CCS (17) - Coal CCS retrofit (18) / Gas plant CCS retrofit (18) / Iron and steel retrofit CCS (18) / CCS direct energy retrofit (18).

As it is not possible to exclude any of the abatement options belonging to the [CCS] sector using the Most Similar and Most Different criteria, all are momentarily selected, and will be filters during the successive filtering steps.

Selected abatement options:

[CCS]: Coal CCS new build; Iron and steel new build CCS; Coal CCS retrofit; Gas plant CCS retrofit; Iron and steel retrofit CCS; CCS direct energy retrofit.

[Energy]

Most Similar:

(a) Low penetration wind (10) – Solar CSP (9)
(b) PV panels homes (10) – High penetration wind (11)

Most Different:

Small hydro (7) – Geothermal (cooperation, large scale) (19)

Two pairs of options equally match the *Most Similar* selection criteria. It is decided to select pair (b) as the option Solar CSP has a score of 0 for the category Multi-actor complexity, thus making it different from the other abatement options.

Selected abatement options:

PV panels homes; High penetration wind; Small hydro; Geothermal (cooperation, large scale).

[Forestry & Agriculture]

Most Similar:

(a) Reduced slash and burn agriculture (17) - Reduced intensive agriculture conversion (17) – Reduced deforestation from timber harvesting (17) - Reduced deforestation from pastureland conversion (17)
(b) Organic soil restauration (16) – Degraded land restauration (16) – Pastureland afforestation (16) – Degraded forest reforestation (16) – Lifestock antimethanogen vaccine (16)
(c) Cropland nutrient management (8) – Grassland management (8) – Rice management (8) – Agronomy Practices (8)

Most Different

Any option in group (a) – Any option in group (c)

Because the abatement options part of group (a) and group (c) respect both the *Most Similar* and the *Most Different* criteria, they are preferred to the options in group (b).

Selected abatement options:

Reduced slash and burn agriculture; Reduced intensive agriculture conversion; Reduced deforestation from timber harvesting; Reduced deforestation from pastureland conversion; Cropland nutrient management; Grassland management; Rice management; Agronomy Practices.

[Fuels], [Household Changes], [Industrial Processes], [Waste]

Only three abatement options are included in (Chappin, 2016) for each of the following sectors [Fuels], [Household Changes], [Industrial Processes]: They are all selected, as the selection of three abatement options is the minimum outcome of the two selection criteria *Most Similar* and *Most Different*, which renders unecessary to check their Y-factor scores.

Selected abatement options:

[Fuels]:	LDV gasoline bundle 4; LDV gasoline bundle 3; Bioethanol lignocellulosic.
[Household Changes]:	Lighting switch incandescent to LED (residential); Residential electronics; Residential appliances.
[Industrial Processes]:	Clinker substitution by fly ash; Efficiency improvements other industry; Energy efficiency 1 Iron & steel.
[Waste]:	Waste recycling; Electricity from landfill gas; Composting new waste.

[Vehicles]

Most Similar:

Motor systems efficiency (retrofit) (10) – Cars full hybrid (10)

Most Different:

Air Transport (18) – Motor system efficiency new build (8)

Selected abatement options:

<u>Motor systems efficiency (retrofit)</u>; <u>Cars full hybrid</u>; <u>Air Transport</u>; <u>Motor system efficiency new build.</u>

Options selected in Step 1:

Abatement options selected in Step 1 and entering in Step 2

#	Option	Sector	Preliminary Y-Value	McKinsey's Abatement Cost
1	Insulation Retrofit Commercial	Building	16	< 0
2	Insulation Retrofit Residential	Building	17	< 0
3	Building Efficiency New Build	Building	10	< 0
4	Coal CCS new build	CCS	17	> 0
5	Iron and steel new build CCS	CCS	17	> 0
6	Coal CCS retrofit	CCS	18	> 0
7	Gas plant CCS retrofit	CCS	18	> 0
8	Iron and steel retrofit CCS	CCS	18	> 0
9	CCS direct energy retrofit	CCS	18	> 0
10	PV panels homes	Energy	10	> 0
11	High penetration wind	Energy	11	> 0
12	Small hydro	Energy	7	< 0
13	Geothermal (cooperation, large scale)	Energy	19	< 0
14	Reduced slash and burn agriculture conversion	Forestry & Agriculture	17	> 0
15	Reduced intensive agriculture conversion	Forestry & Agriculture	17	> 0
16	Reduced deforestation from timber harvesting	Forestry & Agriculture	17	> 0
17	Reduced deforestation from pastureland conversion	Forestry & Agriculture	17	> 0
18	Cropland nutrient management	Forestry & Agriculture	8	< 0
19	Grassland management	Forestry & Agriculture	8	> 0
20	Rice management	Forestry & Agriculture	8	< 0
21	Agronomy Practices	Forestry & Agriculture	8	> 0
22	LDV gasoline bundle 4	Fuel	9	< 0
23	LDV gasoline bundle 3	Fuel	9	< 0
24	Bioethanol lignocellulosic	Fuel	9	< 0
25	Lighting switch incandescent to LED (residential	Household Changes	5	< 0
26	Residential electronics	Household Changes	8	< 0
27	Residential appliances	Household Changes	8	< 0
28	Clinker substitution by fly ash	Industrial Processes	12	< 0
29	Efficiency improvements other industry	Industrial Processes	13	< 0
30	Energy efficiency 1 Iron & steel	Industrial Processes	9	> 0
31	Motor systems efficiency (retrofit)	Vehicles	10	< 0
32	Cars full hybrid	Vehicles	10	< 0
33	Air Transport	Vehicles	18	< 0
34	Motor system efficiency new build	Vehicles	8	< 0
35	Waste recycling	Waste	13	< 0
36	Electricity from landfill gas	Waste	10	< 0
37	Composting new waste	Waste	11	> 0

Step 2: Marginal implementation cost in McKinsey's MAC curve

Of the remaining 37 options, 21 are ranked in McKinsey's MAC curve with a Marginal Abatement Cost [€/tCO_2e] < 0, and 16 with a Marginal Abatement Cost [€/tCO_2e] > 0. Coherently with the selection criteria delineated in *section 2.1.1*, the 37 options are divided in two sub-groups depending on their positive or negative Marginal Abatement Cost.

In each of the two sub-group, 10 abatement options should be selected, with Step 3 of the selection procedure, performed below.

Step 3: Sectorial diversity and Most Similar and Most Different overall Y-scores

Marginal Abatement cost [€/tCO_2e] > 0

Abatement options with Marginal Abatement Cost > 0 in McKinsey's MACC

Option	Sector	Preliminary Y-Value	McKinsey's Abatement Cost
Coal CCS new build	CCS	17	> 0
Iron and steel new build CCS	CCS	17	> 0
Coal CCS retrofit	CCS	18	> 0
Gas plant CCS retrofit	CCS	18	> 0
Iron and steel retrofit CCS	CCS	18	> 0
CCS direct energy retrofit	CCS	18	> 0
PV panels homes	Energy	10	> 0
High penetration wind	Energy	11	> 0
Reduced slash and burn agriculture conversion	Forestry & Agriculture	17	> 0
Reduced intensive agriculture conversion	Forestry & Agriculture	17	> 0
Reduced deforestation from timber harvesting	Forestry & Agriculture	17	> 0
Reduced deforestation from pastureland conversion	Forestry & Agriculture	17	> 0
Grassland management	Forestry & Agriculture	8	> 0
Agronomy Practices	Forestry & Agriculture	8	> 0
Energy efficiency 1 Iron & steel	Industrial Processes	9	> 0
Composting new waste	Waste	11	> 0

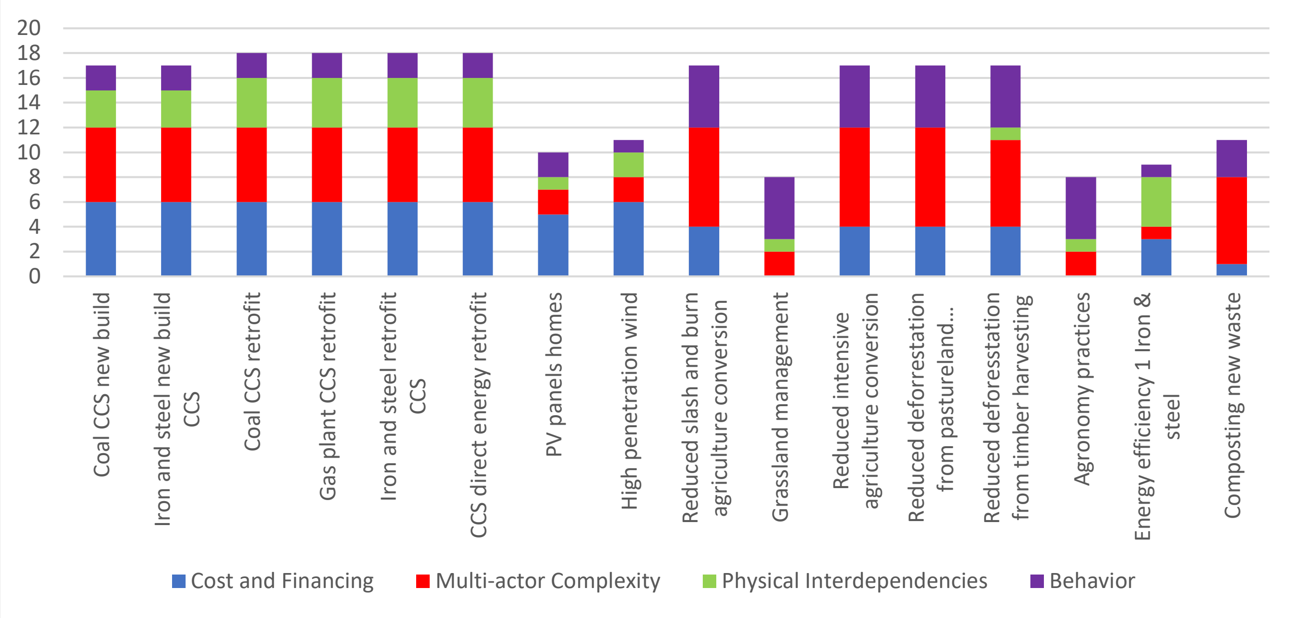
(a) Select first the abatement options which are the only representative of their sector

Of the 16 abatement options with Abatement cost [€/tCO_2e] > 0, 10 need to be selected and thus 6 are to be filtered. The 16 options belong to 5 different sectors; [Industrial Processes]: Energy efficiency 1 Iron & steel and [Waste]: Composting new waste are are the only representative of their sectors and are thus immediately selected.

(b) The options remaining for reaching a pool of 10 selected options per group should be selected considering the Most Similar and Most Different Y-scores. Differently from Step 1, abatement options are not selected per-sector.

Thus, the *Most Similar* and *Most Different* overall Y-score criteria are applied to select the remaining 8 abatement options.

Preliminary overall Y-score of abatement options with Abatement cost [€/tCO_2e] > 0 in McKinsey's MACC



Multiple abatement options have the same overall Y-score, and thus are eligible for selection under the *Most Similar* criterion. The abatement options with *Most Different* overall Y-score are the four CCS retrofit (score of 18) options compared to Grassland management (8) and Agronomy practices (8). As this analysis still leaves different selection options, further, arbitrary considerations are needed.

[Energy]: High penetration wind and PV panels homes are selected. They are the only representative of their sector and respect the *Most Similar* criterion.

Amongst the six abatement options belonging to the [CCS] sector, the two options related to new build technology have the same Y-factor scores, and so do the four options involving retrofit solutions. Thus, both groups are eligible for selection under the *Most Similar* criterion. The options [CCS]: Coal CCS new built and Coal CCS retrofit: they involve the same technology and material and are hence interesting to compare.

The remaining four options are to be selected from the [Forestry & Agriculture] sector.

The options [Forestry & Agriculture]: Grassland management and Agronomy practices are selected as they have the lowest overall Y-score, thus respecting the *Most Different* criterion when compared to [CCS]: Coal CCS retrofit. The other four options from the [Forestry & Agriculture] sector have the same overall Y-score; of the four, three have identical Y- score for all four categories (Cost and Financing, Multi-actor Complexity, Physical Interdependencies, and Behavior), while Reduced deforestation from timber harvesting has a different score in the Multi-actor Complexity category. The latter is thus selected, along with Reduced intensive agriculture conversion, arbitrarily selected amongst the other three.

Selected abatement options:

[Energy]:	PV panels homes; High penetration wind.
[CCS]:	Coal CCS new build; Coal CCS retrofit.
[Forestry & Agriculture]:	Grassland Management; Agronomy practices;
	Reduced deforestation from timber harvesting;
	Reduced intensive agriculture conversion.
[Industrial Processes]:	Energy efficiency 1 Iron & steel.
[Waste]:	Composting new waste.

Marginal Abatement Cost [€/tCO_2e] < 0

Abatement options with Abatement cost < 0 in McKinsey's MACC

Option	**Sector**	**Preliminary Y-Value**	**McKinsey's Abatement Cost**
Insulation Retrofit Commercial	Building	16	< 0
Insulation Retrofit Residential	Building	17	< 0
Building Efficiency New Build	Building	10	< 0
Small hydro	Energy	7	< 0
Geothermal (cooperation, large scale)	Energy	19	< 0
Cropland nutrient management	Forestry & Agriculture	8	< 0
Rice management	Forestry & Agriculture	8	< 0
LDV gasoline bundle 4	Fuel	9	< 0
LDV gasoline bundle 3	Fuel	9	< 0
Bioethanol lignocellulosic	Fuel	9	< 0
Lighting switch incandescent to LED (residential)	Household Changes	5	< 0
Residential electronics	Household Changes	8	< 0
Residential appliances	Household Changes	8	< 0
Clinker substitution by fly ash	Industrial Processes	12	< 0
Efficiency improvements other industry	Industrial Processes	13	< 0
Motor systems efficiency (retrofit)	Vehicles	10	< 0
Cars full hybrid	Vehicles	10	< 0
Air Transport	Vehicles	18	< 0
Motor system efficiency new build	Vehicles	8	< 0
Waste recycling	Waste	13	< 0
Electricity from landfill gas	Waste	10	< 0

(a) Select first the abatement options which are the only representative of their sector

As there is no sector represented by only one abatement option, this first part of Step 3 does not lead to the selection of any abatement option.

(b) The options remaining for reaching a pool of 10 selected options per group should be selected considering the Most Similar and Most Different Y-scores. Differently from Step 1, abatement options are not selected per-sector.

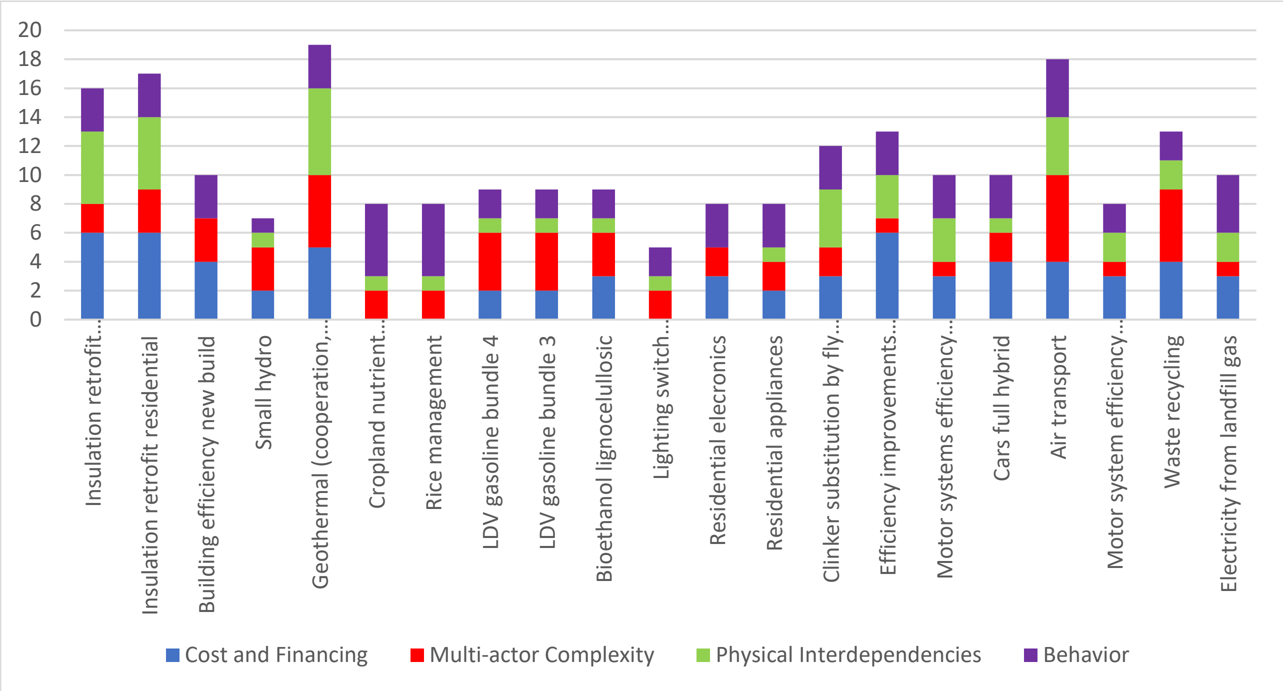
Of the 21 listed, ten need to be selected, with the constraint of selecting at least one option for each of the 8 represented sectors.

Applying the *Most Different* criterion, the options [Energy]: Geothermal (cooperation, large scale), and [Household Changes]: Lighting switch incandescent to LED (residential) are selected, with the first two options having the highest overall Y-score and the latter having the lowest.

Multiple pairs of abatement options satisfy the *Most Similar* criterion in terms of overall Y-score, but only a few do across different sectors; this is important as it is the differentiating feature of Step 3b compared to Step 1, which thus adds to the pursued diversity of selection.

The following abatement options have the same overall Y-score, specifically of 10: [Building]: Building efficiency new built, [Waste]: Electricity from landfill gas, [Vehicles]: Cars full hybrid, Motor system efficiency (retrofit).

Preliminary Y-Categories scores of abatement options with Abatement cost [€/tCO_2e] < 0 in McKinsey's MACC



Instead, the following ones have the same overall Y-score of 8: [Forestry & Agriculture]: Cropland nutrient management, Rice management, [Household Changes]: Residential electronics, Residential appliances, [Vehicles]: Motor system efficiency new built.

As the only sectors for which an abatement option with Abatement cost > 0 has been selected are [Energy], and [Household Changes], the sectors having only one representative in the two groups above are selected, namely: [Building]: Building efficiency new built, [Waste]: Electricity from landfill gas.

To select the remaining six abatement options, the pre-established selection criteria are not sufficient. Thus, the remaining selection is performed following the principle of "Convenience" sampling (Patton, 1990), highlighted by the performed literature review from *section 2.1.1*.

Coherently with the sectorial diversity pursue in Step 1, the following abatement options are selected for the still un-represented sectors:

[Vehicles]: Air Transport is selected for its Y-score, second highest; being substantially above average, this Y-score adds to the diversity of the selection, and promises to make an interesting topic of investigation, allowing further testing of the Y-factor on an abatement measure allegedly difficult to implement. For the sector [Forestry & Agriculture], Cropland nutrient management is selected over Rice management for its higher comprehensiveness and lower location-specificity.

For the sector [Fuels], the option Bioethanol lignocellulosic is selected, for the higher specificity of its definition, which will be helpful in the interviews. Similarly, for the sector [Industrial Processes], the option Clinker substitution by fly ash is selected over Efficiency improvements other industry.

[Energy]: Small hydro and [Household Changes]: Residential appliances are arbitrarily selected to reach the intended pool of 10 selections: the latter play a very popular role in the ongoing smart grid development, as they are needed for the efficient and smart handling of renewables volatility for the management of the frequency of electricity. The former might be particularly relevant for Western countries, which have reportedly short of locations suitable for large-scale hydropower production.

Selected abatement options:

[Building]:	Building efficiency new build.
[Energy]:	Geothermal (cooperation, large scale); Small hydro.
[Forestry & Agriculture]:	Cropland Nutrient Management.
[Fuels]:	Bioethanol lignocellulosic.
[Household Changes]:	Lighting switch incandescent to LED (residential); Residential appliances.
[Industrial Processes]:	Clinker substitution by fly ash.
[Vehicles]:	Air Transport.
[Waste]:	Electricity from landfill gas.

Appendix D: Definition of the selected Abatement Options, from (Chappin, 2016)

Sector	#	Option	Definition
Building	1	Building Efficiency New Build	Achieve energy consumption levels comparable to passive housing: Reduce demand for energy consumption through improved building design and orientation, Improved building insulation and airtightness; improve materials and construction of walls, roof, floor and windows, Ensure usage of high efficiency HVAC and water heating systems.
CCS	2	Coal CCS retrofit	Using CCS (Carbon Capture and Sequestration) on existing coal power plants by capturing the CO_2 from the point source of exhaust gases. The CO_2 is then permanently stored in deep geological formations.
	3	Coal CCS new build	Using CCS in the same way as mentioned above, but now it is incorporated in the design and building of a new coal power plant.
Energy	4	Geothermal	Large scale geothermal energy generation.
	5	Small hydro	Small scale hydro energy generation.
	6	PV panels homes	Solar energy installed on homes of individual home owners.
	7	High penetration wind	Wind energy, with a penetration of the energy mix higher than 10%.
	8	Nuclear	Energy generation in nuclear power plants.
Forestry & Agriculture	9	Cropland nutrient management	Management of cropland to reduce GHG emissions consists of improved nutrient management (such as slow-release fertilizer forms, nitrification inhibitors, and improved application rates and timing).
	10	Reduced intensive agriculture conversion	The decrease of deforestation for agricultural use. This is done through compensation of landholders for the lost revenue from one-time timber extraction and future cash flow from agriculture.
	11	Reduced deforestation from timber harvesting	Reduction of emissions from deforestation due to unsustainable timber extraction through compensation to landholders for lost timber revenue.
	12	Grassland management	Increased grazing intensity, increased productivity (excluding fertilization), irrigating grasslands, fire management and species introduction.
	13	Agronomy Practices	Improved agriculture mechanisms, such as: crop varieties; extended crop rotations, less intensive cropping systems, extended use of cover crops. This is a more long-term measure for soil treatment.
Fuel	14	Bioethanol lignocellulosic	A second-generation biofuel: Modelled as lignocellulosic ethanol (25gCO_2e per MJ). Other second-generation biofuels are: (lignocellulosic (LC) ethanol, Fisher-Troph (FT) diesel, and dimethyl ether (DME)). It is derived from feedstock such as bagasse, wheat straw, corn stover, or dedicated energy plants such as switch grass, and have a CO_2 reduction potential of up to 90 percent.
Household Changes	15	Lighting switch incandescent to LED (residential)	Switching incandescent lighting for LEDs in residences. Conversion to LEDs complete by 2030.
	16	Residential appliances	Replacing residential appliances with high efficiency models (when former expired): refrigerator/freezer, washer/dryer, dishwasher and fans.
Industrial Processes	17	Energy efficiency 1 Iron & steel	Higher energy efficiency in the iron and steel industry due to mechanisms such as: structural production shifts, better preventive maintenance, improved process flow (management, logistics, IT-systems), better motor systems, new efficient

			burners, pumping systems, capacity utilization management, heat recovery, coal moisture control, sinter plant heat recovery, or pulverized coal injection.
	18	Clinker substitution by fly ash	Reducing the clinker content in cement, by substituting clinker with slag, fly ash, and other mineral industrial components, reduces process and fuel combustion emissions as well as electric power from clinker production.
Vehicles	19	Air Transport	Technology solutions including alternative fuels, Operations-efficiency improvements and Infrastructure and air-traffic management.
	20	Cars full hybrid	Hybrids on the road today range from mild, simply incorporating some form of a stop-start system, to full, where an electrical drive system is packaged in parallel to the ICE drive system and is calibrated to run when conditions best suit electrical driving. In addition, full hybrids are typically engineered in such a way that aerodynamic drag, rolling resistance, and weight are all reduced to varying degrees.
	21	Cars plug-in hybrid	Full-hybrids that can be recharged both by the vehicle-driving cycle and by external sources, enabling the vehicle to run more frequently on electrical power.
	22	Battery electric vehicles	Vehicles that "are powered by an electric motor that receives power, via a controller, from a battery of significant capacity" (Nauclér & Enkvist, 2009, p. 95)
Waste	22	Electricity from landfill gas	Capture landfill gas to generate electricity.
	23	Composting new waste	Solid waste can be sorted for the recycling of glass, paper/cardboard, plastic, and metal waste, and the composting of organic waste. Recycling and composting reduce the introduction of new waste to landfills, thereby avoiding landfill and industry emissions. Composting avoids methane emissions from new organic waste.

Appendix E: Interview Template - Example

			CCS: Coal CCS Retrofit			
Category	**Factor**	**Definition**	**Value 0**	**Value 1**	**Value 2**	**Comments**
Costs and Financing	Investment cost required	Degree to which the investment in an abatement measure is significant	Absent	Medium	Large	Adding a Carbon Capture installation to an existing coal plant is very expensive ($1.5 bil. for average size plant) given the new equipment and the integration with existing infrastructure, considered in the same order of magnitude as constructing a new coal plant. Thus, the payback time is long and it's even more difficult to finance the investment than for New built coal CCS.
	Expected pay-back time	Expected time required to earn back the investment for an abatement measure	< 5 years	5-12 years	> 12 years	
	Difficulty in financing investment	The degree to which it is difficult to finance the abatement or attract appropriate financial means	Low	Medium	High	
Multi-actor Complexity	Dependence on other actors	Degree of dependence on actions of other actors to successfully implement and execute the abatement measure	No	Little	Much	Given the size of the investment, many players are involved for the financing and construction, besides the various energy market parties (TSO, DSO, Regulator). All investment in non-renewable/sustainable energy are complex, with parties having very contrasting opinions, and the population and media also weighting in the debate. The division of responsibilities is not as problematic as actually agreeing on the technology.
	Diversity of actors involved incl. conflicts	Degree of diversity of interests, values, roles, skills and expectations of the actors involved. Degree of public acceptance. When opposing interests from the (local) public to the implementation of the abatement option are (expected to be) present, a high score should be given'	Low	Medium	Large	
	Division of roles and responsibilities unclear	The extent to which the roles and responsibilities for the realization of the abatement option are clear	Clear	Slightly	Unclear	
Physical Interdependences	Physical embeddedness	Degree to which the abatement measure requires physical changes to the environment it is placed in	No	Medium	High	The changes needed to retrofit an operating coal plants with CCS technology are substantially change its outlook, adding pipelines and other transportation equipment for the recovered CO2, besides changing the flaring apparatus. Thus, operations are heavily interrupted. All CCS technologies are still much debated, because of their few implementations and the doubts of its effectiveness and price.
	Disturbs regular operation	Degree (duration, intensity) to which status quo/regular operation is disrupted to successfully apply the abatement measure	No	Slightly	Strongly	
	Technology uncertainty	Degree to which the technological performance of the abatement measure is uncertain	Fully proven	Small	Large	
Behavior	Absence of knowledge of actor	Level of knowledge of the parties responsible for the abatement measure	High Knowledge	Low Knowledge	No Knowledge	CCS is not known to the large public but energy experts have been debating over it for a long time without reaching a predominant opinion. The lack of experience is also a characterizing factor. Considering the large investment and long lifetime (30+ years), the frequency of opportunity is rare. Moreover, on-site operations which have possibly been the routine for many years (materials routing, safety procedures, spacing, etc.) have to change to adapt to the newly installed technology.
	Frequency of opportunity	Number of opportunities for the responsible party to realize the abatement measure	Often	Medium	Rarely	
	Requires change in behavior	Degree to which the actors involved need to change their day to day behavior	No	Slight	Severe	

Pre-selected Value

Appendix F: Characterization of Interviews

Barthel - [Building]: Building efficiency new built		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Large investments are required for constructing a building but depends on standards. Extra costs are probably higher than 8%.
A2. Expected pay-back time	1	Normally longer than 12 years. Proposed score = 2
A3. Difficulty in financing investment	1	Different programs supporting the construction of energy efficient buildings, as the ones from the KFW, supporting buildings following the KFW standards.
B1. Dependence on other actors	2	There are many parties required, but dependence should be only slightly higher than for the construction of a normal buildings. Uncertainty score = 1-2
B2. Diversity of actors involved incl. conflicts	1	Some conflicts foreseeable but not many.
B3. Division of roles and responsibilities unclear	1	Green buildings are not very new; there is the need for an expert architect.
C1. Physical embeddedness	1	Induced changes similar to the one caused by a new, non-energy efficient building.
C2. Disturbs regular operation	1	
C3. Technology uncertainty	1	Known technologies, most of which are fully proven but there are always some new ones which have to be proven. Uncertainty score = 0-1
D1. Absence of knowledge of actor	1	Some people have high knowledge while some have none. People are not responsible for initiating the abatement option, but people who have low knowledge might have a negative attitude towards the final price and avoid the purchase
D2. Frequency of opportunity	1	Looking at a single building, the frequency is rare because of the long projecting time, but buildings are constructed every day in every city. Thus, a medium score is appropriate.
D3. Requires change in behavior	1	No changes for dwellers but in the construction process and in terms of regulation.
GENERAL / METHODOLOGICAL COMMENTS: In Germany energy efficient buildings follow the KFW (German national bank) standard (e.g.: KFW 40 = a consumption of 40 % of the standard, or 60 % savings).		

Barthel - [Household Changes]: Lighting switch incandescent to LED (residential)		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	A LED now costs about 10 €.
A2. Expected pay-back time	0	In less than 1-year current LEDs pay back their costs.
A3. Difficulty in financing investment	0	Accessible to most people.
B1. Dependence on other actors	0	Good market offering.
B2. Diversity of actors involved incl. conflicts	0	No interactions needed.
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	1	At first LEDs had blue light, now all desirable colors are available, and they have not start-up times (energy-saving lamps had). Proposed score = 0
C2. Disturbs regular operation	0	Installation times are very short.
C3. Technology uncertainty	0	
D1. Absence of knowledge of actor	1	People are used to Watts, and not to Lumen (600 Lm = 40 W). People need to know the brightness and colors they need. Medium between high knowledge of researches and industrial parties, and no knowledge of population.
D2. Frequency of opportunity	0	
D3. Requires change in behavior	0	Need to consider multiple new factors when purchasing an LED. Uncertainty score = 1-2

Barthel - [Household Changes]: Residential appliances		
Y-Factor	Preliminary Score	Argument
A1. Investment cost required	1	Large cost is the efficiency of the appliance (Refrigerator of energy class A++ can be 50% more expensive than one of class A+). The smart component might only increase the costs of 5%. Thus overall, there is a little investment needed.
A2. Expected pay-back time	1	Different field tests (especially in the UK) showing very different results: some record savings, some other do not. Savings are higher in the first year, then maintenance cost incur. Business case not clear yet.
A3. Difficulty in financing investment	1	Not many extra costs incurred. All appliances will have the smart component built-in. Uncertainty score = 0-1
B1. Dependence on other actors	2	Not much more interaction with other actors, as interactions will mostly happen automatically. Only new actors are the ones handling the data network. Proposed score = 1
B2. Diversity of actors involved incl. conflicts	2	Data privacy issues as in many other sectors (e.g.: internet), but it could become socially accepted, depending on individuals' values and preferences. Factor has a lower impact if a person trusts in the authorities and in the involved parties. Uncertainty score = 1-2
B3. Division of roles and responsibilities unclear	1	Experienced supply chain has to adapt to a very new concept of usage for residential appliances, thus having to clarify a few new responsibilities.
C1. Physical embeddedness	0	
C2. Disturbs regular operation	1	Both the installation and the interconnection with the network should not cause disruptions. Proposed score = 0
C3. Technology uncertainty	1	
D1. Absence of knowledge of actor	1	Medium between high knowledge of experts and low knowledge of population, responsible for purchasing and usage.
D2. Frequency of opportunity	1	Medium between nuclear energy (rare) and reduction of deforestation (often)
D3. Requires change in behavior	2	Changes related to active periods of appliances (not on demand if electricity costs want to be reduced). Behavioral changes are not currently required but will be in the near future.

GENERAL COMMENTS:
There are two main themes for Residential appliances: efficiency and smartness. Efficient appliances are already vastly available on the market, but smart appliances are currently only the very high-end ones. Smartness will be the key point in the very near future; thus, the discussion focused on smart appliances and the reported comments refer to it, unless specified otherwise.

Blok - [Energy]: Nuclear		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	
A2. Expected pay-back time	2	In Europe there is no pay-back time, while in China there are some examples of profitable nuclear projects.
A3. Difficulty in financing investment	2	A good business case, as in the UK with Feed-in tariffs specific for nuclear energy, makes the investment attractive for a consortium of actors. Proposed score = 1
B1. Dependence on other actors	2	There is a supply chain, which has proven to work. Thus, if a company is willing to initiate a nuclear plant, it can without having to solve many interdependencies. Proposed score = 1
B2. Diversity of actors involved incl. conflicts	2	Local population often feels threatened and protests, while large NGOs are always against.
B3. Division of roles and responsibilities unclear	0	Always a remaining risk: it is unclear the long-term responsibilities over waste disposal. Shall the government be responsible of possible issues? Insurances do not cover nuclear accidents. Proposed score = 1
C1. Physical embeddedness	2	Space is needed not only for the power plant (1,000 MW is still compact), but also for mining. Proposed score = 1
C2. Disturbs regular operation	1	Time needed for preparation of the land, but this and the construction are commonly not problematic. Proposed score = 0
C3. Technology uncertainty	2	Waste is the problem and, like it or not, waste can be underground. It is know how to do it; there are always hustles when treating radioactive waste, but it can be done. Proposed score = 1
D1. Absence of knowledge of actor	0	Both supporters and opposers are well aware of the technology.
D2. Frequency of opportunity	2	Long construction period
D3. Requires change in behavior	0	

Blok - [Energy]: Geothermal		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Trying to make it cheaper but probably will never become cheaper than gas heating.
A2. Expected pay-back time	2	
A3. Difficulty in financing investment	1	Always uncertainty whether the well will be productive, thus not all investments will bring returns.
B1. Dependence on other actors	2	Many hustles with municipalities, often preventing privates from investments in any geothermal project.
B2. Diversity of actors involved incl. conflicts	2	There is sensitivity, but not too strong. Proposed score = 1
B3. Division of roles and responsibilities unclear	0	Main hustles with municipalities caused by unclarity of responsibilities. Proposed score = 1
C1. Physical embeddedness	2	Some physical changes needed, especially for connecting the geothermal installation with surrounding infrastructure (e.g.: temperature of local heat net). Proposed score = 1
C2. Disturbs regular operation	1	Small construction, close to other buildings. And no changes after completion. Proposed score = 0
C3. Technology uncertainty	1	
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	Need quite some time for the development.
D3. Requires change in behavior	1	Mainly depending on size. Large geothermal plants for power generation are more invasive. Uncertainty score = 0-1

GENERAL / METHODOLOGICAL COMMENTS

Geothermal energy was discussed in the form of small size, shallow drilling plants for heating, and not the large (700 MW), deep drilling plants for electricity generation.

The value of factor C3 would be better described by Little rather than the available Medium.

Blok - [Forestry & Agriculture]: Grassland management		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	The implementation of the abatement option mostly relies on the actions of pool-farmers in developing countries. Thus, there is the need for tools, the price of which is to be covered by local farmers.
A2. Expected pay-back time	0	Good productivity allows for short pay-back times
A3. Difficulty in financing investment	0	Easy to finance because of the short pay-back times.
B1. Dependence on other actors	1	Dependence can likely be caused by the need for an irrigation system.
B2. Diversity of actors involved incl. conflicts	0	
B3. Division of roles and responsibilities unclear	1	Location dependent.
C1. Physical embeddedness	0	No evident physical changes, with possibly countries looking greener thanks to higher land productivity.
C2. Disturbs regular operation	0	
C3. Technology uncertainty	1	Dependent on climate, thus it is not proven in all situations.
D1. Absence of knowledge of actor	2	
D2. Frequency of opportunity	0	
D3. Requires change in behavior	2	Practices passed-on from generation to generation, thus difficult to modify habits.
GENERAL / METHODOLOGICAL COMMENTS Grassland consists also of those vast, free areas, with only some cattle. The key point of the discussion has already shifted from Nitrogen emissions to the carbon storage role of land. The exclusion of fertilization does not seem an essential part of Grassland management practices to the interviewee.		

Blok - [Forestry & Agriculture]: Reduced deforestation from timber harvesting		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Investment required to compensate for losses from timber sales.
A2. Expected pay-back time	2	Money is not coming back as it is not an investment; thus, the score should be the highest value.
A3. Difficulty in financing investment	1	Needs to be gathered from external sources, normally governments of developed country; thus, not low as it comes from the outside, but not high as it is an option with a high (public) appeal.
B1. Dependence on other actors	2	Local and national governments always involved, plus many timber companies.
B2. Diversity of actors involved incl. conflicts	2	Not trying to do something, but to prevent something from happening, which is already difficult: national regulation, local parties from supervision.
B3. Division of roles and responsibilities unclear	1	It is clear what everyone should do, but national governments need regulation in place and funding it needed.
C1. Physical embeddedness	2	Need for supervision as with cameras and fences, besides changes that lead to forest remaining in place.
C2. Disturbs regular operation	2	People want to cut trees, besides timber companies, as they have used timber for many private applications which allows them to survive.
C3. Technology uncertainty	0	No uncertainty.
D1. Absence of knowledge of actor	1	Small land owners are not aware but main driver of deforestation are large timber corporations which are aware of the consequences.
D2. Frequency of opportunity	0	Can be started anytime.
D3. Requires change in behavior	2	Same argument as for C2. Timber companies need to move away from “cut and leave it” model toward sustainable forestry, like the Swedish and Canadian model.

GENERAL/ METHODOLOGICAL COMMENTS:
Consider interdependencies between A factors: if A1 = 0, then A2 and A3 are also 0. Same argument used for factors C2 and D3, thus there is the need to define the factors better.

Blok - [Forestry & Agriculture]: Reduced intensive agriculture conversion		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Modest investment, in the form of annual payments to protect areas from being run-over (monitoring costs). Interesting to look at difficulty of implementation (different means). Uncertainty score = 0-1
A2. Expected pay-back time	2	Money is not coming back as it is not an investment; thus, the score should be the highest value.
A3. Difficulty in financing investment	1	Needs to be gathered from external sources, normally governments of developed country; thus, not low as it comes from the outside, but not high as it is an options with a high (public) appeal.
B1. Dependence on other actors	2	Local and national governments always involved, plus local landowners.
B2. Diversity of actors involved incl. conflicts	2	Not trying to do something, but to prevent something from happening, which is already difficult: national regulation, local parties from supervision.
B3. Division of roles and responsibilities unclear	1	It is clear what everyone should do, but national governments need regulation in place and funding it needed.
C1. Physical embeddedness	2	Need for supervision as with cameras and fences, besides changes that lead to forest remaining in place.
C2. Disturbs regular operation	2	People live close to the lands which are often first deforested and once no more trees are left, the land is converted to cropland, which provides income to local communities.
C3. Technology uncertainty	0	No uncertainty.
D1. Absence of knowledge of actor	1	Small land owners and local communities are not aware of the consequences of deforestation. Proposed score = 2
D2. Frequency of opportunity	0	Can be started anytime.
D3. Requires change in behavior	2	Same argument as C2. Local farmers have to change entirely their modus operandi.
GENERAL/ METHODOLOGICAL COMMENTS: Consider interdependencies between A factors: if A1 = 0, then A2 and A3 are also 0. Same argument used for factors C2 and D3, thus there is the need to define the factors better. The value of factor A1 would be better described by Little rather than the available Medium.		

Blok - [Fuel]: Bioethanol lignocellulosic		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Different if considering investment for users or for production, which is the more relevant perspective, thus considered. Second generation biofuels can also be produced on a small scale. Proposed score = 1
A2. Expected pay-back time	1	Production cost of diesel is below 0.6 $/L, with primary and secondary ethanol expected to cost more than diesel if oil prices remain in the common 60-70$/barrel price range. Thus, no pay-back is to be expected (structural problem). Proposed score = 2
A3. Difficulty in financing investment	1	Market is very uncertain (especially in EU), with much policy pressure to decrease the use of primary biofuels. Thus, while second generation biofuels are different, the industry and market suffer from many bad past experiences (policy problem). Proposed score = 2
B1. Dependence on other actors	2	The whole industry is involved, but a single producer can start dropping it on the market. Now diesel can have 10-20% of ethanol, but if percentage increases, changes are required leading to dependence on other parties (car fleet, distribution tanks as in Brazil). Uncertainty score = 1-2
B2. Diversity of actors involved incl. conflicts	1	Less involved in the eternal conflicts for land than primary biofuels, but still some competition exists, as waste usage might not be sufficient for large scale diffusion of secondary biofuels. Uncertainty score = 0-1
B3. Division of roles and responsibilities unclear	1	Clear unless the percentage of biofuels in regular diesel really increases from the current 10-20%. Proposed score = 0
C1. Physical embeddedness	1	
C2. Disturbs regular operation	2	Users can continue their usage, but there are some changes and interruptions for those involved in the biofuels production processes. Proposed score = 1
C3. Technology uncertainty	1	Not proven on full scale, size of the introduction and percentage in regular diesels matter. Uncertainty score = 1-2
D1. Absence of knowledge of actor	1	
D2. Frequency of opportunity	2	Possible to start dropping them more and more, no need to wait for new cars. Proposed score = 1
D3. Requires change in behavior	1	

Blok - [Industrial Processes]: Clicker substitution by fly ash		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	Depends on project size. Uncertainty score = 0-1
A2. Expected pay-back time	0	
A3. Difficulty in financing investment	0	Also considering the little investment required and the short pay-back time
B1. Dependence on other actors	2	Need for parties able to supply fly ash, with which to establish long term contracts.
B2. Diversity of actors involved incl. conflicts	1	Country dependent: in some countries cement with additives might be considered as not qualitative (e.g.: in India, ads celebrating the purity of "real Portland cement, without waste products").
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	1	Need for transportation system for cement substitutes, or at times cement companies are built next to steel plant from which to obtain the substitutes (e.g.: blast furnace of steel companies has slag as by-product).
C2. Disturbs regular operation	1	
C3. Technology uncertainty	1	The technology for substituting clicker with slag is clear, but there is uncertainty with procedures involving for other substitutes. Proposed score = 0
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	0	Can be started at any time
D3. Requires change in behavior	1	Completely different use of products for the cement mix.

Blok - [Industrial Processes]: Energy efficiency 1 Iron & steel		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Individual projects have large investments, but medium in terms of €/ton CO2 avoided.
A2. Expected pay-back time	0	See comment for A3 factor.
A3. Difficulty in financing investment	2	Because of the difficulty of financing investments in the IS industry, all projects must have short investment payback times.
B1. Dependence on other actors	0	Each IS company is able to decide for investment independently
B2. Diversity of actors involved incl. conflicts	1	Is companies are international with a very complex decision making, thus it is common to have internal conflicts.
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	0	
C2. Disturbs regular operation	1	Iron and steel plants work 24/7 thus processes need to be paused to implement changes.
C3. Technology uncertainty	1	The technology is maybe fully proven but there is often a perceived risk.
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	Every 3 to 4 years the Iron & Steel plants are closed down and revisited, allowing for substantial process modifications.
D3. Requires change in behavior	0	

Blok - [Vehicles]: Air transport		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	*Operational Efficiency:* Uncertainty score = 0-1 *Alternative Fuel:* No investment required but price of alternative fuel (production cost and market price) are much higher than for conventional fuels. Proposed score = 0
A2. Expected pay-back time	2	*Operational Efficiency:* Proposed score = 0 *Alternative Fuel:* Proposed score = 0
A3. Difficulty in financing investment	2	*Operational Efficiency:* Proposed score = 0 *Alternative Fuel:* Proposed score = 0
B1. Dependence on other actors	2	*Operational Efficiency:* Need cooperation with air traffic control, airports, etc. for operation efficiency. Proposed score = 1 *Alternative Fuel:* Need for fuel suppliers. Proposed score = 1
B2. Diversity of actors involved incl. conflicts	2	*Operational Efficiency:* Low diversity, no conflicts. Proposed score = 0 *Alternative Fuel:* Proposed score = 0
B3. Division of roles and responsibilities unclear	2	*Operational Efficiency:* Proposed score = 0 *Alternative Fuel:* Proposed score = 0
C1. Physical embeddedness	0	*Operational Efficiency:* No material changes. *Alternative Fuel:* Changes necessary for having an alternative fuels infrastructure. Proposed score = 1
C2. Disturbs regular operation	1	*Operational Efficiency:* System operations must be changed, thus disrupting previous ones. *Alternative Fuel:* Proposed score = 0
C3. Technology uncertainty	2	*Operational Efficiency:* Yes, especially for maintaining safety with new operational model Proposed score = 1 *Alternative Fuel:* Biofuels are not completed accepted yet, perceived as slightly uncertain. Proposed score = 0
D1. Absence of knowledge of actor	1	*Operational Efficiency:* Proposed score = 0 *Alternative Fuel:* All air lines know. Proposed score = 0
D2. Frequency of opportunity	1	*Operational Efficiency:* Proposed score = 0 *Alternative Fuel:* Proposed score = 0
D3. Requires change in behavior	0	*Operational Efficiency:* Proposed score = 1 *Alternative Fuel:*

		Proposed score = 0

GENERAL / METHODOLOGICAL COMMENTS
1) The definition of the option "Air transport" actually contains different abatement options: "Operational efficiency" (cheap) and "Alternative fuels" (expensive), which are thus separated in the scoring. 2) Consider adding a factor for lifecycle cost: "Alternative fuels" require no investment, but are expensive to produce, similarly forest management options, which are nevertheless cheap to sustain. 3) If A1 = 0, then A2 and A3 likely to be also 0.

Blok - [Vehicles]: Battery electric vehicles		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Currently very expensive but expected to reach a Medium value in the next 5-10 years. Key is large scale production (NL: ban fossil fuel vehicles after 2030).
A2. Expected pay-back time	1	Savings from reduced fuel costs are not sufficient to reduce the pay-back time given the large investment. Proposed score = 2
A3. Difficulty in financing investment	1	Depends on the target considered: many people are not able to afford extra cost of BEVs, which is not a problem for richer people, thus 1 is an average score.
B1. Dependence on other actors	1	Infrastructure is problematic, thus there is large dependence on the parties providing the infrastructure, not just nationally but also across border for holidays. Proposed score = 2
B2. Diversity of actors involved incl. conflicts	1	If there is one topic most people agree upon, it is the necessity of developing BEVs. Unclear if there conflicts between BEVs and non BEVs' owners might arise due to competition for parking slots. Proposed score = 0
B3. Division of roles and responsibilities unclear	1	While people agree on the what to do, there is unclarity on which party is responsible for the development (especially of the charging infrastructure).
C1. Physical embeddedness	1	Charging station and some parking spots which become reserved to BEVs.
C2. Disturbs regular operation	0	In a city like Delft, it would take a year to install sufficient charging infrastructure for a dominant presence of BEVs on the streets, but each station is installed quickly.
C3. Technology uncertainty	2	Some hiccups with charging stations which might not work, but minor problems, battery do not break down. Range is not considered as a technology uncertainty, as it is known in advance. Proposed score = 0
D1. Absence of knowledge of actor	1	Little rather than Low. Average amongst stakeholders (High) and many people's (Low). Garages workers are trained but still lack clear knowledge (e.g.: battery of cars on sales left discharged).
D2. Frequency of opportunity	1	A car is purchased on average every 4-5 years.
D3. Requires change in behavior	1	Need to be much more aware of route and consumption. Range anxiety is more of an issue than for ICE vehicles.

Blok - [Vehicles]: Cars full hybrid		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	
A2. Expected pay-back time	1	
A3. Difficulty in financing investment	0	Overall costs are modest.
B1. Dependence on other actors	0	From users' perspective, as they can easily buy HEVs.
B2. Diversity of actors involved incl. conflicts	0	
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	0	
C2. Disturbs regular operation	0	
C3. Technology uncertainty	0	After 20 year of experience, technology is fully proven.
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	On average, a person purchases a car every 5-10 years.
D3. Requires change in behavior	0	

Blok - [Vehicles]: Cars plug-in hybrid		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	
A2. Expected pay-back time	1	
A3. Difficulty in financing investment	0	Overall costs are modest, comparable to costs for full-hybrid vehicles.
B1. Dependence on other actors	1	Dependent on the infrastructure system, especially considering the long term perspective, with the infrastructure is being built-up
B2. Diversity of actors involved incl. conflicts	1	
B3. Division of roles and responsibilities unclear	1	It is unclear which party is responsible of developing the (charging) infrastructure, but still possible to continue driving PHEVs with limited charging infrastructure.
C1. Physical embeddedness	1	
C2. Disturbs regular operation	0	A score of 0 can be assigned assuming there are enough charging stations.
C3. Technology uncertainty	1	Some development still required to make the technology more effective.
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	On average, a person purchases a car every 5-10 years.
D3. Requires change in behavior	1	

Blok - [Waste]: Composting new waste		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	
A2. Expected pay-back time	1	Compost can be sold to recover the investment.
A3. Difficulty in financing investment	1	Rather common procedures, with limited investment required Proposed score = 0
B1. Dependence on other actors	1	Need for municipalities having adequate recycling systems in place, and to sell the produced compost. Moreover, a qualitative collection of waste relies on the actions of the population. Proposed score = 2
B2. Diversity of actors involved incl. conflicts	0	Some conflicts can arise given the many actors involved. Proposed score = 1
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	1	
C2. Disturbs regular operation	0	Waste separation process of individuals needs to change, which is nevertheless not a drastic change. Proposed score = 1
C3. Technology uncertainty	0	
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	Policy decision on this topic can be taken on any given moment. Proposed score = 0
D3. Requires change in behavior	1	

General Comments:
The interviewee specified the differences between and aerobic (composting) and an anaerobic digestion: Aerobic digestion does not produced gas, only producing CO_2 used to form compost, while anaerobic digestions produce both CO_2 and Methane, and both can be burned.

Blok - [Waste]: Electricity from landfill gas		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	The generators are not extraordinary expensive, but the pipes needed to recover the gas are expensive.
A2. Expected pay-back time	2	Differently from what expected by the interviewee, the cost displayed by McKinsey's MAC is negative. Thus, instead of assigning a score of 2 if the prediction was verified, the interviewee suggested a score of 1. Proposed score = 1
A3. Difficulty in financing investment	1	Relatively small-scale investment. It is always easier to finance a 600MW wind farm than a small-scale landfill project, as the former is more impactful.
B1. Dependence on other actors	2	Operator of the power plant at the landfill site and owner of the landfill site do not necessarily coincide.
B2. Diversity of actors involved incl. conflicts	1	
B3. Division of roles and responsibilities unclear	1	
C1. Physical embeddedness	1	
C2. Disturbs regular operation	0	Depending on the dimension of the landfill, part of the landfill might be emptied to install the needed infrastructure, but no regular process needs to be discontinued.
C3. Technology uncertainty	1	The burned landfill gas still contains a bit of CO2 and Methane, but it is less than 1% of the original amount. Moreover, landfill gas is biogenic (produced by organic organisms), and thus its emissions "do not count". Proposed score = 0
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	1	Can be retrofitted, but infrastructure needs to be installed swiftly once landfill begins operations to maximally exploit the produced gas, as gas production decays over time.
D3. Requires change in behavior	0	

GENERAL COMMENTS:
1) The interviewee predicted a slightly positive cost in McKinsey's MACC, and thus expected a long payback time.
2) The interviewee highlighted how the technology is not so popular anymore, as it is normally preferred to collect and upgrade the collected landfill gas to use it as regular gas.

Dejonghe – Sprengers - [Energy]: High penetration wind		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Investment for onshore wind turbines is around 800-1,000 €/KW, and higher for offshore wind turbines.
A2. Expected pay-back time	1	Lifespan of wind turbines is over 20 years, with a pay-back time between 5-12 years.
A3. Difficulty in financing investment	1	Key point is how much a project is de-risked, rather than financing. Thus, it is more difficult to find a good project (clear operation and maintenance agreements, electricity off-taker, etc.) than to find financing. Proposed score = 0
B1. Dependence on other actors	2	Significant amount of stakeholders to manage, also beyond the technical installation and operations of the turbines.
B2. Diversity of actors involved incl. conflicts	2	Main conflicts are not of technical nature but related to interfaces with population annoyed by the noise of rotating blazes and birds protection associations.
B3. Division of roles and responsibilities unclear	1	Much experience with onshore turbines. Most offshore projects are close to coast line (10-30 km) thus in national waters, with main issues being the interaction with ship routes and fisheries. There is much innovation for wind offshore technology (e.g.: storage of generated power as hydrogen), which is not relatable to the clarity of responsibility. There are clear parties responsible for the grid, for spatial planning and for constructing according to permits. Proposed score = 0
C1. Physical embeddedness	2	Location dependent. Environment is affected, question is how many people these changes impact (e.g.: in NL many, but there are some regions in Norway where no-one is living.)
C2. Disturbs regular operation	2	Location dependent. Onshore turbines might be close to population (not if on top of the mountain), offshore turbines might disrupt ships routes. Proposed score =1
C3. Technology uncertainty	1	For their magnitude, such projects would not be performed if there were doubts on the functioning and environmental effectiveness. Only issue is the life expectancy for offshore wind farms: they only exist for a few years and are expected to last 20 years. Given the large scale of implementation, the technology is perceived as stable and not risky. Uncertainty score = 0-1
D1. Absence of knowledge of actor	2	Most people have an intuitive but not-accurate understanding of the technology, but isn't it all people need to know? Awareness of problems caused by NIMB behaviors is more relevant than the level of technical knowledge. Key is knowledge on environmental impact rather than of technology. People do not want to know but to be involved. Proposed score = 1
D2. Frequency of opportunity	1	The key variable is the scalability of a project, which is much more than for a nuclear plant but still limited.
D3. Requires change in behavior	0	People have to get used to a different view, but it is a generational change: children who grow up with the windmill view do not notice them anymore.
GENERAL/ METHODOLOGICAL COMMENTS: Consider: 1) changing factor D1 in "Absence Information sharing / Communication with actors"; 2) adding the word "scalable" to the definition of factor D2.		

Dejonghe – [Energy]: PV panels homes		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	
A2. Expected pay-back time	1	Depends per country, around 7 years.
A3. Difficulty in financing investment	1	Many cheap loans, offering leasing contracts, paying back the lease with electricity savings. Now even been considered to be included in mortgages. In apartment blocks, there is a shared ownership of roof and which also included PV panels. Proposed score = 0
B1. Dependence on other actors	0	Not many permissions needed, thus no dependence on other stakeholders.
B2. Diversity of actors involved incl. conflicts	1	Uncertainty score = 0-1
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	1	Visible on flat and tilted roof. Sometimes roofs have to be strengthened to support the structure and weight of PVs.
C2. Disturbs regular operation	0	
C3. Technology uncertainty	0	
D1. Absence of knowledge of actor	1	People are aware of PVs but not of their implications.
D2. Frequency of opportunity	0	
D3. Requires change in behavior	0	As a consequence of the current subsidy regime (volume based), many PVs are being installed. This will lead to changes in the electricity tariffs, opening to the diffusion of smart grid systems, thus forcing severe behavioral changes. Proposed score = 2

Dejonghe – Sprengers - [Energy]: Small hydro		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Dependent on location. The most expensive part of hydro power projects is the mountaineering activities, which are absent for the construction of small hydro power plants. Proposed score = 1
A2. Expected pay-back time	2	Pay-back time similar to wind power, thus expected to be in the 5-12 years span. Proposed score = 1
A3. Difficulty in financing investment	2	Financing the investment is not about the technology but about the Power Purchase Agreements (PPA), that is how to sell the power. Once the project is de-risked, it is easy to finance the investment. Proposed score = 0
B1. Dependence on other actors	2	A lot of stakeholders involved in the projecting.
B2. Diversity of actors involved incl. conflicts	2	There are no issues with relocation & remuneration of communities as with large hydro power plants but closing/deviating a river to construct a small hydro power impacts the environment, with many environmental organizations getting involved. Proposed score = 1
B3. Division of roles and responsibilities unclear	0	Division of responsibilities is very clear, as there is much experience which has clarified the role of every party.
C1. Physical embeddedness	2	Environmental impact could be high but not necessarily. There is a difference between run-of-river projects, which are most of small hydro projects and are less invasive, and more impactful dam-projects. Major impacts are for local flora and fauna. Uncertainty score = 1-2
C2. Disturbs regular operation	1	Small hydro projects do not cause major disruptions, but there can be some disruptions for boats which cannot travel upstream.
C3. Technology uncertainty	0	
D1. Absence of knowledge of actor	0	All actors and the population have more knowledge about hydro power than about wind power.
D2. Frequency of opportunity	0	There is quite a number of projects, which are developed more frequent than nuclear plants. In fact, Statkraft has a separate company only focusing on small hydro projects. There are more projects than visible ones, as small hydro projects are often hidden and do not make noises. Proposed score = 1
D3. Requires change in behavior	1	Some behavioral changes might be needed for fishermen, who might have to change their fishing locations.

GENERAL/ METHODOLOGICAL COMMENTS:
The Clean development Mechanism (CDM) of the Kyoto Protocol (emission credits earned for any CO2-reducing projects installed in developing countries) defines “small hydro power plants” as having a capacity below 20 MW. In the UK, small hydro power plants are defined as having less than 15 MW. Thus, the main natural-need is a river with a decent stream.

Elizondo - [Energy]: Nuclear		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Large investment required.
A2. Expected pay-back time	2	
A3. Difficulty in financing investment	2	Difficult to finance, because of the magnitude of the investment and nuclear being a debated technology. Moreover, governments often maintain some sort of control over nuclear investments (e.g.: Mexico), as they regard a national security domain. Thus, private actors have limited freedom for initiatives, but can contribute to the investment.
B1. Dependence on other actors	2	Many actors are willing to get involved to obstacle nuclear projects and, after the nuclear accidents, the civil society has to be involved in multiple forms before a project is approved, so it can actually obstacle its realization of the project.
B2. Diversity of actors involved incl. conflicts	2	There is much controversy about the technology, even if it is continuously advancing, as people remember past nuclear accidents.
B3. Division of roles and responsibilities unclear	0	There is much experience with nuclear projects, but these have always been periodically performed, also depending on alternating political view. For instance, Mexico has quite much nuclear capacity but has not constructed any plants recently; thus, roles have to be refined now that the country is getting ready to expand its nuclear capacity. Proposed score = 1
C1. Physical embeddedness	2	Modern technology has reduced the size of the plants and waste deposits, which can be placed close to the plant locations. Uncertainty score = 1-2
C2. Disturbs regular operation	1	Plants are normally constructed in scarcely populated areas. Uncertainty score = 0-1
C3. Technology uncertainty	2	Extensive research has been performed on nuclear technology worldwide, so best practices are available for every project. Uncertainty score = 0-1
D1. Absence of knowledge of actor	0	Many actors who have the authority for expressing an opinion on the feasibility of nuclear projects (e.g.: some governmental agencies) are not highly knowledgeable on the topic. Uncertainty score = 0-1
D2. Frequency of opportunity	2	Nuclear energy is often present is long-term sustainable energy plans. Referring only to Mexico, the score would be a 1 considering its expansion plans.
D3. Requires change in behavior	0	

Elizondo - [Fuels]: Bioethanol lignocelullosic		
Y-Factor	Preliminary Score	Argument
A1. Investment cost required	2	
A2. Expected pay-back time	1	A whole supply chain needs to adapt.
A3. Difficulty in financing investment	1	In Mexico investments in second generation biofuels are particularly difficult because primary biofuels are very popular and governmentally supported as a means to empower farmers and rural populations. Proposed score = 0-1
B1. Dependence on other actors	2	The percentage of bioethanol which can be added to benzine without influencing the performance needs to be controlled, thus while producers can start adding second generation biofuels to benzine and diesel, coordination across the value chain is needed, even thou it might not be very difficult to achieved. Proposed score = 1-2
B2. Diversity of actors involved incl. conflicts	1	There is a rather common acceptance towards second generation biofuels for their higher sustainability compared to primary biofuels, with some tensions arising between the environmental and the transport sectors. In Mexico there are more conflicts than in the rest of the world because of the national politics. Proposed score = 1-2
B3. Division of roles and responsibilities unclear	1	Second generation biofuels are not being extensively discussed, thus responsibilities are much less clear than for innovations in other sectors (e.g.: EVs in the transport sector).
C1. Physical embeddedness	1	The production of second generation biofuels requires new technologies, and needs some planning for implementing the needed physical changes (e.g.: plantation of algae); these should nevertheless be minor, thanks to the high efficiency of the materials.
C2. Disturbs regular operation	2	The production of bioethanol requires new processes, thus disrupting the production processes of primary biofuels.
C3. Technology uncertainty	1	Most production technologies are still being researched and are not yet ready for market introduction. Proposed score = 2
D1. Absence of knowledge of actor	1	Some of the production technologies are known, while others are new. There is thus a lack of experience with both the technologies and the final products.
D2. Frequency of opportunity	2	Research on bioethanol has been ongoing for a while, but has not reached major commercial applications yet. Proposed score = 1
D3. Requires change in behavior	1	

Jasper - [CCS]: Coal CCS new built		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	The investment for a new power plant is always large and CCS technology is almost as expensive as the coal plant itself.
A2. Expected pay-back time	2	Definitely longer than 12 years. Current carbon price is 16 €/t, necessary 40-70 €/t (factor of 3 or 4) for CCS technology to have a positive business case over the entire lifetime of a coal plant, much longer than 12 years.
A3. Difficulty in financing investment	2	Lack of stable carbon price and possible market competition with other coal plants without CCS make the investment unattractive.
B1. Dependence on other actors	2	Beside the regulator of the power grid, a government approval is needed for realizing the CCS system, dependent on the availability of an adequate geological formation to store CO2. There often is no structural procedure for assigning a CO2 storage location, with thus different environmental agencies getting involved.
B2. Diversity of actors involved incl. conflicts	2	Major conflict points are finding a suitable CO2 storage location and public acceptance. A company willing to build a coal plant equipped with CCS is dependent on parties (governmental agencies) often not able and/or willing to find a site geologically fitting.
B3. Division of roles and responsibilities unclear	1	Context dependent: there is some experience with the construction of CO2 pipelines, but there is a lack of clarity on the allocation of CO2 storage sites: do governments register available locations, or shall investors make proposals?
C1. Physical embeddedness	2	A power plant is a large construction, which almost doubles in size if constructed incorporating a CCS system. Although the space can be optimized from the projecting phase, the environment is highly impacted.
C2. Disturbs regular operation	0	Only disruptions if the CCS system is not ready once the coal plant is finished and thus starts operations. Uncertainty score = 0-1
C3. Technology uncertainty	2	The carbon-capturing technology is well known but its effectiveness on a large scale is very much unproven. Thus, the size of the project is also a problematic topic.
D1. Absence of knowledge of actor	1	Varies across the population, but actors in the energy industry do have at least some knowledge over CCS technologies.
D2. Frequency of opportunity	2	It is nowadays even doubt if new coal plants will be constructed ever again.
D3. Requires change in behavior	0	None, unless CCS is finished after the plant is operational.

Jasper - [CCS]: Coal CCS retrofit		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Retrofitting CCS technology to an existing coal plant is more expensive than constructing a new coal plant with CCS, especially because of space and lower CO2-capture process efficiency.
A2. Expected pay-back time	2	Definitely longer than 12 years. Same reasoning as for CCS new built, but with a more difficult business case because of the higher cost and shorter lifetime available.
A3. Difficulty in financing investment	2	Lack of stable carbon price and possible market competition with other coal plants without CCS make the investment unattractive
B1. Dependence on other actors	2	Beside the regulator of the power grid, a government approval is needed for realizing the CCS system, dependent on the availability of an adequate geological formation to store CO2. There often is no structural procedure for assigning a CO2 storage location, with thus different environmental agencies getting involved.
B2. Diversity of actors involved incl. conflicts	2	Major conflict points are finding a suitable CO2 storage location and public acceptance. A company willing to retrofit a coal plant with CCS is dependent on parties (governmental agencies) often not able and/or willing to find a site geologically fitting.
B3. Division of roles and responsibilities unclear	1	Context dependent: there is some experience with construction of CO2 pipelines, but there is a lack of clarity on the allocation of CO2 storage sites: do governments register available locations, or shall investors make proposals?
C1. Physical embeddedness	2	Retrofitting a CCS system to an existing coal plant is not space efficient, an occupies much more space than building a CCS system while constructing the coal plant.
C2. Disturbs regular operation	2	Long installation times.
C3. Technology uncertainty	2	The carbon-capturing technology is well known but its effectiveness on a large scale is very much unproven. Thus, the size of the project is also a problematic topic.
D1. Absence of knowledge of actor	1	Varies across the population, but actors in the energy industry do have at least some knowledge over CCS technologies.
D2. Frequency of opportunity	2	Besides investment and technology, there are large compatibility issues.
D3. Requires change in behavior	2	Operations have to be largely modified

Jasper - [Energy]: High penetration wind		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Onshore costs are dropping, and are already below 1,000 €/KW, while investment costs are increasing for offshore, because turbines are increasing in size (13 MW offshore). Uncertainty score = 1-2
A2. Expected pay-back time	1	Subsidies are normally guaranteed for 20 years, thus pay-back times are longer than 12 years. Proposed score = 2
A3. Difficulty in financing investment	1	Depends on the subsidy scheme in place. Uncertainty score = 0-1
B1. Dependence on other actors	2	Many different parties involved, as the regulatory authorities of the energy market.
B2. Diversity of actors involved incl. conflicts	2	Many environment protection issues both onshore and offshore which, while different, cause conflicts.
B3. Division of roles and responsibilities unclear	1	Context dependent: In countries with mature wind markets, the roles and responsibilities are very clear. E.g.: Germany and the UK very clear regulations, while in Japan regulation is still very fuzzy. Assigned score is a medium of global average.
C1. Physical embeddedness	2	Evident environmental impact, increasing in the future with a larger diffusion of turbines and their increasing sizes.
C2. Disturbs regular operation	2	Depends on the definition of regular operation: looking outside the window and seeing turbines is not considered a disruption. An exception is constituted by grid operators, who might have to change congestion management practices. Having inaccessible areas because of the presence of turbines can also cause disruptions for the population. Uncertainty score = 0-1
C3. Technology uncertainty	1	Size of turbines will continue to rise until reaching an optimum size, but main uncertainties regard the interconnection of floating offshore farms which will be constructed in the future.
D1. Absence of knowledge of actor	2	The concept of wind generation is well known to the public as it is simple, the issue is the acceptance of the concept. Proposed score = 0
D2. Frequency of opportunity	1	Medium score for offshore turbines as there are issues with interconnections to the power grid, forcing to combine construction of wind farms, while for onshore turbines there are frequent opportunities. E.g.: Germany has currently 68 GW of onshore wind capacity, and at least 2,9 GW should be added every year. Uncertainty score = 0-1
D3. Requires change in behavior	0	People might start avoiding certain location as they are perceived as spoiled by turbines (as it is happening in norther Germany); a large penetration in the energy mix of volatile, wind power will require smart grids systems. Proposed score = 1
GENERAL / METHODOLOGICAL COMMENTS: It is important to consider the Levelized Cost Of Electricity (LCOE) besides the investment costs. Onshore turbines have normally a capacity of 3-3.5 MW.		

Morelli - [Building]: Building efficiency new build		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	The construction of a new building is expensive and there is an additional mark-up cost for the specific efficient design and components.
A2. Expected pay-back time	1	Dependent on the location, as for instance in Norway, which has a severe climate, energy efficient buildings allow large price-savings, leading to pay-back times of 3-4 years. On average, the pay-back time is medium.
A3. Difficulty in financing investment	1	Varies per country, as both the climate and the financial incentives are very different. For instance, considering Norway the score could be 0, considering Italy the score could be 2. Uncertainty score = 0-2
B1. Dependence on other actors	2	As for every building, different actors have to collaborate, but constructing an energy-efficient building does not require the interaction of more actors than usual. There might be the need for more contractors with a more specific expertise. Uncertainty score = 0-1
B2. Diversity of actors involved incl. conflicts	1	Diverse actors have to cooperate, and all have to ensure their own revenue, but there are no conflicts related to the realization of the building and its technology. Uncertainty score = 0-1
B3. Division of roles and responsibilities unclear	1	Architects and engineers should be aware of all the details of the relevant frameworks, independently of how difficult these might be to implement. Proposed score = 0
C1. Physical embeddedness	1	
C2. Disturbs regular operation	1	Constructing a new building hampers regular operations in the construction areas, but the construction of an energy-efficient building does not augment the disturbances, which are nevertheless minor. Uncertainty score = 0-1
C3. Technology uncertainty	1	Civil engineering practices for energy-efficiency have been known for 40 years, and the technology is thus fully-proven. The existence of different frameworks is justified by the different energy efficiency and construction needs. Proposed score = 0
D1. Absence of knowledge of actor	1	Thanks to their daily experiences, all people are instinctively aware of many of the energy efficiency practices and their consequences, as the higher thermal isolation enabled by a double glass window compared to a single glass one. What actors might not know are the specifics of different frameworks, and buyers have the emotional difficulty of spending more money in the present for future savings. Proposed score = 0
D2. Frequency of opportunity	1	Long works, even in the case of retrofitting installations, and especially considering the individual building. Uncertainty score = 1-2
D3. Requires change in behavior	1	Constructors have to perform some slight procedural adjustments.

Morelli - [Household Changes]: Lighting switch incandescent to LED (residential)		
Y-Factor	Preliminary Score	Argument
A1. Investment cost required	1	
A2. Expected pay-back time	0	
A3. Difficulty in financing investment	0	
B1. Dependence on other actors	0	
B2. Diversity of actors involved incl. conflicts	0	
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	1	There were some problems with light colors but should have been solved already. Uncertainty score = 0-1
C2. Disturbs regular operation	0	
C3. Technology uncertainty	0	
D1. Absence of knowledge of actor	1	LED technology is mainstream, people know it and are aware of its lower energy consumption. Proposed score = 0
D2. Frequency of opportunity	0	
D3. Requires change in behavior	0	

GENERAL / METHODOLOGICAL COMMENTS

Main barrier hampering the implementation of LEDs is the difficulty of people to accept higher costs at the moment of purchase in the name of future savings which are not tangible at present.

Morelli - [Household changes]: Residential appliances		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Implementing new appliances might require modifications to the physical structure of a household (e.g.: walls and electricity network). The investment needed is substantially lower than for the construction of a power plant, but it can be high relative to the income of a person. Uncertainty score = 1-2
A2. Expected pay-back time	1	Undoubtedly lower than 12 years; depending on the appliances considered, pay-back time could also be lower than 5 years. Uncertainty score = 0-1
A3. Difficulty in financing investment	1	Location dependent, considering the different subsidies offered in each country. In some countries the financing might be very easy, and in others difficult, also depending on the necessary bureaucratic procedure.
B1. Dependence on other actors	2	Depends on the appliances, which often have high costs because of the high level of automation. Once automated, the appliances often operate entirely autonomously (e.g.: air conditioning or lights turning on and off via sensors), and thus there is no dependence on other actors for those who install them. If they were not autonomous, they would not be called “smart”. Proposed score = 1
B2. Diversity of actors involved incl. conflicts	2	Conflicts are related to the background system enabling the functioning of appliances, but people installing appliances in their households do not notice the supporting system, which is managed by e.g.: aggregators and vendors. Thus, there is a huge barrier of data analytics, but people have no visibility on the supporting networks. Uncertainty score = 0-2
B3. Division of roles and responsibilities unclear	1	Final utilizers only have to buy and install appliances, which automatically reduce their energy consumptions. Instead, the necessary supporting networks face complex technical and responsibilities challenges. Uncertainty score = 0-2
C1. Physical embeddedness	0	Dependent on the considered appliance: an oven causes very limited physical modifications to the household, while a autonomous heating system might require more evident physical changes (e.g.: walls and electricity network). Uncertainty score = 0-1
C2. Disturbs regular operation	1	Connections with the supporting networks are not immediate.
C3. Technology uncertainty	1	Huge technological improvements have been made, and the functioning of efficient and smart appliances is now fully proven. Technological uncertainties are related to macro-systems, like smart-grid. Uncertainty score = 0-1
D1. Absence of knowledge of actor	1	Experts are clearly aware of the availability of the functioning and implications of smart appliances, while the people who can purchase and use them have little knowledge. Uncertainty score = 0-1
D2. Frequency of opportunity	1	Some planning for the investment and installation is necessary.
D3. Requires change in behavior	2	Dependent on the definition of behavioral changes: having the washing machine running at 8 am or 8 pm is not philosophically considered a severe behavioral change. An automatic heating system does not require behavioral changes. If too severe behavioral changes were needed, people would not purchase the appliances, which would have not been developed. Uncertainty score 0-1

GENERAL/ METHODOLOGICAL COMMENTS:

The interviewee mentioned how a high energy efficiency (certified in energy-class) is the current standard for appliances, and the innovative feature is the introduction of a smart component on top of energy-efficient appliances.

The interviewee also stressed the importance of establishing the perspective with which to analyze the barriers: if it is a barrier to implementation, the interviewee suggested to consider the perspective of the final utilizer; this leads to the resolution of all uncertainty scores.

Morelli - [Vehicles]: Battery electric vehicles		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	The new Nissan LEAF was launched as the first BEV to have a market price competitive with the ones of ICE vehicles. Tesla is the Lamborghini of BEVs. Proposed score = 1
A2. Expected pay-back time	1	Dependent on oil price and vehicle-usage. With oil price above 2 €/L, pay-back time can be less than 5 years. Otherwise, it should not be longer than 7-8 years. Uncertainty score = 0-1
A3. Difficulty in financing investment	1	There are often incentives for sustainable cars (as for HEVs like the Toyota Prius a few years ago), which are country-specific. Uncertainty score = 0-1
B1. Dependence on other actors	1	Large dependence of drivers on charging infrastructure, which is metaphorically comparable to the chicken-egg problem: should the BEVs or the charging infrastructure be introduced first? Proposed score = 2
B2. Diversity of actors involved incl. conflicts	1	Conflicts are not experienced by BEV owners, but exist amongst different industrial lobbies. Uncertainty score = 0-2
B3. Division of roles and responsibilities unclear	1	Conflicts are not experienced by BEV owners, but are background conflicts related to the management of the charging infrastructure. Being full-electric vehicles a new technology, the roles of all parties need some clarification achieved with experience.
C1. Physical embeddedness	1	City landscapes will have to be modified to support BEVs, for instance with regards to charging infrastructure and parking slots. Uncertainty score = 1-2
C2. Disturbs regular operation	0	
C3. Technology uncertainty	2	The technology is fully-proven, and those who drive BEVs are aware of the implications. Proposed score = 0
D1. Absence of knowledge of actor	1	Few people are aware of BEVs, with ICE vehicles clearly still being the mainstream transport technology.
D2. Frequency of opportunity	1	
D3. Requires change in behavior	1	Range anxiety is an important issue, requiring adequate planning. Proposed score = 2

Smith - [Forestry & Agriculture]: Agronomy practices		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	[Low rather than Absent]. Some seeds with longer roots are slightly more expensive than commonly used ones
A2. Expected pay-back time	0	No real investment incurred, and possible small one repaid quickly thanks to better land yields.
A3. Difficulty in financing investment	0	Little investment and better yields, thus attractive.
B1. Dependence on other actors	0	[Low rather than No]. Only dependent on the availability of advanced agricultural products on the market, such as seeds with deeper roots. Once there is a market for it, the technology is quickly developed.
B2. Diversity of actors involved incl. conflicts	0	No conflicts. Only exception is for Genetically Modified (GM) products, which are badly welcome on the EU market and on a few other markets around the world.
B3. Division of roles and responsibilities unclear	0	Sufficient experience has clarified the activities to perform.
C1. Physical embeddedness	0	Only a procedural change, no visible impacts besides improved land yields.
C2. Disturbs regular operation	0	
C3. Technology uncertainty	0	Some more biological R&D can further improve products' performance, but the available practices are fully proven.
D1. Absence of knowledge of actor	0	All farmers around the world are aware of practices like adjusting crops rotation to improve the land yield.
D2. Frequency of opportunity	0	Only require procedural changes, thus can be performed every day.
D3. Requires change in behavior	1	Some behavioral changes needed, not really related to the performance of new activities, but to a more regular performance of already know activities as crop rotation.

GENERAL & METHODOLOGICAL COMMENTS:
Agronomy practices are not implemented mainly because of non-financial incentives, as favorable regulation. The factor Regulation could be added to the matrix. Factors A1 and B1 would be better described with a Value 0 defined as Low.

Smith - [Forestry & Agriculture]: Cropland nutrient management		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	Slow-release fertilizers and nitrification inhibitors can cause slightly higher expenses than for common fertilizers. Uncertainty score = 0-1
A2. Expected pay-back time	0	The proposed nutrients have neutral or positive impacts on the land yield, thus extra costs are quickly paid back.
A3. Difficulty in financing investment	0	Small additional costs to be covered.
B1. Dependence on other actors	1	Farmers have direct oversight over the land they manage, either because they own it (most of cases) or because they live on it. Thus, they can adopt nutrient management practices without anyone stopping them. Land testing are often mandatory to establish the adequate fertilizer, as in Denmark, where external consultants paid by the government regularly perform the land testing). In the UK, fertilizers are established basing on the type of previous crops. Proposed score = 0
B2. Diversity of actors involved incl. conflicts	1	Some public complaints might arise from the use of certain fertilizers, as they might have leaches on dairy products. In New Zealand for instance, traces of nitrogen were found in milk.
B3. Division of roles and responsibilities unclear	1	Not common practices, thus some clarification on the procedures might be needed.
C1. Physical embeddedness	0	There are no physical constraints, as the amount of land used remains the same and so does its purpose and output type.
C2. Disturbs regular operation	0	Operations are no disrupted because of the neutral or positive impacts on land yield, and the new fertilizers can be applied without any preparation
C3. Technology uncertainty	1	Some slow-release fertilizers and nitrogen inhibitors have been used for enough time to be fully proven, while newer ones still require testing. Moreover, some more R&D is needed to eliminate small undesired leaches
D1. Absence of knowledge of actor	2	Context dependent: in developed countries farmers are well aware of the negative impacts of nitrogenous fertilizers and of alternatives to reduce them, while in developing countries there is lack or no knowledge on the issue. Uncertainty score = 0-2
D2. Frequency of opportunity	0	Slow-release fertilizers and nitrification inhibitors can be purchased and applied on any given day instead of standard fertilizers.
D3. Requires change in behavior	2	Some behavioral changes are needed as different fertilizers require different application timing, and nitrogen inhibitors need to be applied. Proposed score = 1

Smith - [Forestry & Agriculture]: Reduced deforestation from timber harvesting		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	An investment is initially needed to compensate large timber corporations and local lumbermen for already provided permits, plus some annual payment to limit forest exploitation.
A2. Expected pay-back time	2	The money is invested in the wellbeing of the planet and does not have a financial return.
A3. Difficulty in financing investment	1	While money is normally provided by national and international organization and thus not easy to gather, deforestation is a sensible topic to which is rather easy (publicly accepted) to destine money.
B1. Dependence on other actors	2	Many local and national governments and organizations involved for the organization and money provision, besides large timber corporations.
B2. Diversity of actors involved incl. conflicts	2	Large conflicts with timber corporations which loose, at least partially, a source of income or a profitable business model.
B3. Division of roles and responsibilities unclear	1	Project specific, but there are always many different parties having to interact
C1. Physical embeddedness	2	Forest is preserved, thus avoiding degraded land
C2. Disturbs regular operation	2	For decades forests have been heavily exploited for timber production, thus controlling it causes disruptions.
C3. Technology uncertainty	0	There are no doubts on the carbon capture role of forests.
D1. Absence of knowledge of actor	1	Context dependent, with local people usually not knowing about the impact of deforestation on GHG emissions and timber corporations being entirely aware of the consequences of deforestation. Uncertainty score = 0-2
D2. Frequency of opportunity	0	
D3. Requires change in behavior	2	Timber has been produced for the mass market for decades, heavily exploiting forest. A less-intensive timber production not only forces timber corporations to adapt business models but might require a modification of timber demand on the market.

GENERAL/ METHODOLOGICAL COMMENTS:
A factor capturing Governance could be added to the matrix, for instance using a government corruption index.

Smith - [Forestry & Agriculture]: Reduced intensive agriculture conversion		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	While not upfront, an investment is needed, which is an opportunity cost: the population needs to be compensated for the money they would earn selling the crops. Uncertainty score: 1-2
A2. Expected pay-back time	2	The money is invested in the wellbeing of the planet and does not have a financial return.
A3. Difficulty in financing investment	1	While money is normally provided by national and international organization and thus not easy to gather, deforestation is a sensible topic to which is rather easy (publicly accepted) to destine money.
B1. Dependence on other actors	2	Many local and national governments and organizations involved, especially for the distribution of the money to local populations.
B2. Diversity of actors involved incl. conflicts	2	Local populations are the ones impacted by the options not the organizations providing the funding. Thus, conflicts arise as the population needs to give up a reliable source of income, possibly not trusting the governments responsible for the payment.
B3. Division of roles and responsibilities unclear	1	Project specific, but there are always many different parties having to interact.
C1. Physical embeddedness	2	The usage of the land drastically changes, and so does it outlook: instead of being converted to cropland, the forest is conserved.
C2. Disturbs regular operation	2	Conversion of forest to cropland is a practice which has been performed for generation, thus preventing it causes disruptions.
C3. Technology uncertainty	0	There are no doubts on the carbon capture role of forests.
D1. Absence of knowledge of actor	1	Local populations have little knowledge about the CO2 capture role of forests, but programs for forest protection such as RED have been successfully implemented in the last decades and most people have heard about or have gotten paid by them.
D2. Frequency of opportunity	0	
D3. Requires change in behavior	2	Local populations have been living from farming for generations and stopping land conversion to agriculture not only disrupts operations but requires severe behavioral changes (e.g.: new occupation).
GENERAL/ METHODOLOGICAL COMMENTS: A factor capturing Governance could be added to the matrix, for instance using a government corruption index.		

Smith - [Forestry & Agriculture]: Grassland Management		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	No investment needed, as the key is to manage differently the grassland, coordinating actives already performed (e.g.: fires to burn woody roots are already initiated by local population and farmers).
A2. Expected pay-back time	0	No investment incurred and better yield, leading to visible improvements in a short time span
A3. Difficulty in financing investment	0	No investment needed.
B1. Dependence on other actors	1	Much of the grassland is exploited by multiple users, either by farmers belonging to the same consortium or by the general public. Thus, changing management practices requires the collaboration with a few stakeholders.
B2. Diversity of actors involved incl. conflicts	0	Conflicts are likely to arise over crucial zones as shed areas and areas of common grazing. Proposed score = 1
B3. Division of roles and responsibilities unclear	1	While for grassland with a single owner there is a clear initiator, it is often unclear whom should care for the grassland used for common grazing.
C1. Physical embeddedness	0	Practices such as fire management might affect the surrounding environment beyond intentions. Proposed score = 1
C2. Disturbs regular operation	0	
C3. Technology uncertainty	1	Uncertainty score = 0-1
D1. Absence of knowledge of actor	2	Context dependent. Uncertainty score = 0-2
D2. Frequency of opportunity	0	Can be initiated at any time.
D3. Requires change in behavior	2	Some behavioral changes needed to better take care of the grassland, but people are always spontaneously taking care of the land they exploit and need. Proposed score = 1
GENERAL & METHODOLOGICAL COMMENTS: Grassland refers to farmland intensively exploited for (e.g.) cattle, vast, to sparsely managed farmland, and to (public) land collectively exploited as the African savannah. This abatement option is mainly relevant for developing countries.		

Vaessen - [Energy]: High penetration wind		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Investment is needed: onshore for purchasing the land and constructing the turbines, but offshore turbines are more expensive. Onshore is at break-even cost. Uncertainty score = 1-2
A2. Expected pay-back time	1	Pay-back time for onshore turbine is rather short (several years), while for offshore turbines the pay-back time is much longer, and probably increasing given that the market prices of wind energy are decreasing. Uncertainty score = 1-2
A3. Difficulty in financing investment	1	Average score: onshore projects are small, and there is much more demand than construction; thus, investments are rather easy to finance, with struggles being mainly related to finding suitable locations. Offshore turbines are constructed in parks, thus investments are larger and more difficult to finance.
B1. Dependence on other actors	2	Onshore: Land owners, community, investors, licensing authorities, etc. Offshore: Military, shipping lanes controls, etc. Much dependence both on and offshore, but very different actors.
B2. Diversity of actors involved incl. conflicts	2	Many different interests clashing, as animal welfare and nature protection NGOS (e.g.: birds protection onshore and fish protection offshore). E.g.: in NL, to reduce conflicts people can buy a share of the turbines, and are awarded part of the revenues.
B3. Division of roles and responsibilities unclear	1	Onshore, construction of turbine is fast, with clear responsibilities thanks to long experience. Offshore construction is longer, as many more risks are to be tackled to protect the investment. Technology offshore is also evolving, fact which helps reducing complexity and construction times. Uncertainty score = 0-1
C1. Physical embeddedness	2	Land can still be used, for agriculture but not for housing; thus, onshore the view is mainly impacted. Offshore is difficult to find a suitable location. Thus, equally difficult but very different impact. Main challenge: Interconnections.
C2. Disturbs regular operation	2	Onshore locations are normally somewhat remote and easily accessible, thus very little disturbances to daily business occur. Offshore, regular business Is not interrupted at the location, but material transport is challenging. Uncertainty score = 0-1
C3. Technology uncertainty	1	Technology for onshore turbines is fully proven, while offshore turbines are increasing in size. Larger sizes introduce uncertainty for both on and offshore installations. Uncertainty score = 0-1
D1. Absence of knowledge of actor	2	Many actors talk about wind energy but do not know what the possibilities and challenges are. People know about turbines, but they do not directly link them to climate change. Uncertainty score = 1-2
D2. Frequency of opportunity	1	Lifetime is about 15 years for onshore and somewhat longer (about 20 years) for offshore turbines. Opportunity needs to be created, with special planning for connections. Onshore, permitting is much easier and frequent. Uncertainty score = 1-2
D3. Requires change in behavior	0	No limitations to day-to-day behaviors.

GENERAL/ METHODOLOGICAL COMMENTS:
Important to distinguish between On- and Offshore wind, as they have different problematics. The uncertainty intervals have the lower bounds referring to onshore wind turbine and the upper bound if offshore turbines are considered.

Vaessen - [Energy]: PV panels homes		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Many companies offer to lease or install PVs for free, sharing revenues. But PV systems can also be purchased. Uncertainty score = 0-1
A2. Expected pay-back time	1	With subsidies, pay-back time is about 7 years; costs are decreasing with increasing installations, but subsidies are also decreasing. Common to have pay-back time of around 12 years. Uncertainty score = 1-2
A3. Difficulty in financing investment	1	Only reasonably wealthy people can afford the investment, even if most would like it.
B1. Dependence on other actors	0	PVs can be installed independently.
B2. Diversity of actors involved incl. conflicts	1	There are discussions with neighbors, mainly for how PVs affect the view. Most people accept PVs, the acceptance of which is higher than for wind turbines. Uncertainty score = 0-1
B3. Division of roles and responsibilities unclear	0	Roles are clear.
C1. Physical embeddedness	1	Just the view is affected, but there are the functionality of land and roofs does not change. Uncertainty score = 0-1
C2. Disturbs regular operation	0	There were no operations on the rooftops before the PVs installation, thus there is no disturbance. An operation which might be impacted is the roof cleaning and maintenance, but it is a minor impact.
C3. Technology uncertainty	0	The technology of just PVs is fully proven, but there are still large issues with the impact PVs have on grid balancing. Proposed score = 1
D1. Absence of knowledge of actor	1	
D2. Frequency of opportunity	0	Can be purchased and installed at any moment; there is a correlation of number of installations and subsidies availability.
D3. Requires change in behavior	0	Currently the grid can simply absorb PVs' production, but it will change in the future with decreasing subsidies and increasing PV, moving towards smart grid. Uncertainty score = 0-1

Vaessen - [Vehicles]: Cars full hybrid		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Full hybrid are maybe only slightly more expensive than normal ICE vehicles, and have slightly lower costs than plug-In hybrid vehicles. Uncertainty score = 0-1
A2. Expected pay-back time	1	Cars do not really have a pay-back time but having a return on the investment is not a big issue for HEVs
A3. Difficulty in financing investment	0	HEVs just like ICEs are being leased more frequently, thus financing is not an issue.
B1. Dependence on other actors	0	They can drive without and electric charge
B2. Diversity of actors involved incl. conflicts	0	Few interfaces with the “outside world”.
B3. Division of roles and responsibilities unclear	0	Vehicle functioning is not reliant on an electric engine, thus responsibilities are more clear thanks to the similarities with ICEs
C1. Physical embeddedness	0	No changes, as they function just like ICE vehicles.
C2. Disturbs regular operation	0	Normal operations continued.
C3. Technology uncertainty	0	Proven technology.
D1. Absence of knowledge of actor	0	People do not know what HEVs are and how they work (minor differences from ICE vehicles) and do not care. Proposed score = 2
D2. Frequency of opportunity	1	Can be purchased as often as ICE vehicles because of the similar price.
D3. Requires change in behavior	0	

GENERAL COMMENTS

This option was discussed in comparison to [Vehicles]: Cars plug-in hybrid.
Toyota Prius was mentioned as model reference of Cars full hybrid. As a reference figure, 10,000 vehicles are sold in NL/year, in the world there are 1-2 bil. cars, of which 0.1% are electric.

Vaessen - [Vehicles]: Cars plug-in hybrid		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	1	Plug-in hybrid vehicles are maybe only slightly more expensive than normal ICE vehicles, and have slightly higher costs than full hybrid vehicles. Uncertainty score = 0-1
A2. Expected pay-back time	1	Cars do not really have a pay-back time but having a return on the investment is not a big issue for those who can afford to purchase a PHEVs.
A3. Difficulty in financing investment	1	PHEVs just like ICEs are being leased more frequently, thus financing is not an issue. But because of slightly higher prices, less people can afford them.
B1. Dependence on other actors	1	Dependence on charging infrastructure.
B2. Diversity of actors involved incl. conflicts	1	Many interfaces between the electric core and other system. There are many different technical standards, especially for charging technology, with different parties having different approaches to the infrastructure
B3. Division of roles and responsibilities unclear	1	Many new interfaces because of electric core, thus roles and responsibilities are much less clear. Proposed score = 2
C1. Physical embeddedness	1	There is the need for plugs.
C2. Disturbs regular operation	0	Charging is time consuming, which prevents to perform other operations by cars in the time span needed for charging. Proposed score = 1
C3. Technology uncertainty	1	Proven technology Proposed score = 0
D1. Absence of knowledge of actor	0	Those who have the money know about it and find the way to finance, while poor population segments have no opportunity to purchase PHEVs. Uncertainty score = 1-2
D2. Frequency of opportunity	1	Can be purchased as often as ICE vehicles as there are often subsidies.
D3. Requires change in behavior	1	Range anxiety rises, plug unplug continuously. Proposed score = 2
GENERAL COMMENTS This option was discussed in comparison to [Vehicles]: Cars full hybrid. Opel Ampera was mentioned as reference-model for Plug-in hybrid. As a reference figure, 10,000 vehicles are sold in NL/year, in the world there are 1-2 bil. cars, of which 0.1% are electric.		

Verhagen - [Forestry & Agriculture]: Agronomy practices		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	
A2. Expected pay-back time	0	Might work is some area with very favourable climates but such agronomy practices often lead to lower productivity in the long term (after 10 years), thus there actually is a negative. Uncertainty score = 1-2
A3. Difficulty in financing investment	0	
B1. Dependence on other actors	0	
B2. Diversity of actors involved incl. conflicts	0	There might be some conflicts with local laws as a result of certain practices (e.g.: if too much weed is produced as a consequence of low-till practices, chemical spray is needed, and this is problematic). Proposed score = 1
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	0	
C2. Disturbs regular operation	0	Lower output per hectare, thus needed more land to maintain the same output (similar to organic agriculture). Proposed score = 1
C3. Technology uncertainty	0	What to do is clear but the outcome is very location specific, and such practices might have an undesirable impact on land yield. Proposed score = 2
D1. Absence of knowledge of actor	0	
D2. Frequency of opportunity	0	Annually.
D3. Requires change in behavior	1	As most agricultural practices, behavioral changes are much influenced by the common practices of the local community.
GENERAL/ METHODOLOGICAL COMMENTS: Abatement option considered vaguely defined and is understood as low- and zero-till practices.		

Verhagen - [Forestry & Agriculture]: Cropland nutrient management		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	0	The investment depends on the crop and the cropland location. For instance, passing from a dry fertilization to a fertigation system is a relatively high investment, especially for the small farmers, which is nevertheless much lower compared to the investment for other abatement option. Every management strategy could be done with low-tech, cheaper means and high-tech more expensive means. Uncertainty score = 0-1
A2. Expected pay-back time	0	Investments is expected to have a return in terms of increased or more stable land yield, and benefits are visible in 1 year, especially in low-fertility areas (e.g.: Africa).
A3. Difficulty in financing investment	0	For decades there have often been subsidies from governments for the purchase and application of fertilizers, which take the burden of the costs.
B1. Dependence on other actors	1	Farmers are highly dependent on the fertilizers' supplier, who could be a middle-man or a third-party, respectively reliant on fertilizer producers. In Europe supply of fertilizer is reliable, but it is not so obvious in developing countries, where farmers are often dependent on price-taker and have no negotiating position. Uncertainty score = 1-2
B2. Diversity of actors involved incl. conflicts	1	Conflicts related to the application of fertilizers often arise, as neighbours complain about the smell, the nitrate leaching, ground water pollution, etc.
B3. Division of roles and responsibilities unclear	1	Roles are clear. Proposed score = 0
C1. Physical embeddedness	0	Some irrigation system and tractors might be added to the landscape, but these do not seem to be contemplated by the definition of the abatement option.
C2. Disturbs regular operation	0	With higher yields, agricultural land can expand, and it is sometimes the case that roads need to be enlarged, thus causing some minor disruptions in the long term. No disturbances are expected in a short-term time period.
C3. Technology uncertainty	1	Agricultural technology cannot ever be fully proven for its dependence on the location for factors like nitrate leaching and weather impact.
D1. Absence of knowledge of actor	2	All farmers are aware of the beneficial effects of nutrient application, even in developing countries. They do not know about the GHG emission caused by fertilizers, and all farmers around the world would not be interested in reducing the GHG emissions they caused unless these are taxed. Nevertheless, they are aware of the different nutrient management practice. Proposed score = 1
D2. Frequency of opportunity	0	Land management practices can be modified at least once per year, provided that the necessary equipment is available.
D3. Requires change in behavior	2	Agriculture is quite conservative. A farmer has only a maximum of 30 or 40 growing seasons in a lifetime (even less in developing countires), so experiments are not much welcomed. The reliable perspective of higher land yields can largely facilitate difficult behavioral changes. Proposed score = 1

GENERAL/ METHODOLOGICAL COMMENTS:

Definition is limited to dry fertilization techniques and the type of fertilizer, as it does not include all the irrigation techniques which are often combine with fertilization (pipeline nutrient management) as "fertigation", fertilization timing and "precision agriculture". The leaching of nitrogen to surrounding lands, depending on the location and terrain type, add uncertainty to the provided score. All scores could be a range dependent on location.

(Fertilizer quantities = 300 – 1,000 kg of fertilizer per acre.)

Viebhan - [CCS]: Coal CCS new built		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Construction of new plant is expensive.
A2. Expected pay-back time	2	Lifetime of a coal plant is 40 years, with pay-back estimated at 20 years. Thus, pay-back is larger than 12 years even without the upcoming renewables, reducing operating hours; there is a "lockin" effect which does not guarantee a pay-back at all.
A3. Difficulty in financing investment	2	More and more critical articles on the effectiveness of CCS technologies are appearing, mainly because of very weak business cases not able to attract investments
B1. Dependence on other actors	2	Many actors involved in decision making, as DSOs and TSO for electricity transport, but CO2 transport and storage are fundamental issues and require regulation, permitting and control.
B2. Diversity of actors involved incl. conflicts	2	Installation of the technology is not an issue, but operations are, especially for the transport and storage of CO2, as the ownership of storage location. E.g.: In Germany, a suitable storage location was found and private owners were force to sell the land to the government. Offshore location could decrease conflicts. Many conflicts also on responsibilities over waste.
B3. Division of roles and responsibilities unclear	1	No issues at power plant, but for transport and storage. Not clear which party is responsible for waste: up to 10 years, the coal plant ownership is responsible, then responsibility shifts to the government, but this is a highly debated topic. Even if clear by law, doubts in operations are expected. Uncertainty score = 1-2
C1. Physical embeddedness	2	While the CCS technology occupies less space with a newly built plant than in the case of retrofitting one, the CO2 transport and storage infrastructures cause substantial changes to the physical environment.
C2. Disturbs regular operation	0	There are no operations which are disrupted.
C3. Technology uncertainty	2	Capture seems to work technically, but almost no one implements it; transport of CO2 is not an issue (happening In the US); storage is technically not a problem but there are many policy uncertainties. Uncertainty score = 1-2
D1. Absence of knowledge of actor	1	Higher knowledge of operators and companies in the industry, but almost no knowledge of public, authorities, and even NGOs. Uncertainty score = 1-2
D2. Frequency of opportunity	2	China and India are building many new plants; thus, looking at potential chances, the frequency is medium. Looking at the reality of the projects, the frequency of opportunity is rare. Uncertainty score = 1-2
D3. Requires change in behavior	0	Everyone is aware of the new processes and procedures from the beginning.

GENERAL/ METHODOLOGICAL COMMENTS:
Clarity of factors (especially A and D factors) scores would benefit from a five-value scale:
No, little, medium, large, Yes.

Viebhan - [CCS]: Coal CCS retrofit		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Even larger than for a new coal plant with CCS, because it is technically more difficult. Thus, need to deconstruct, optimize process and equipment operations.
A2. Expected pay-back time	2	A McKinsey study from 10 years ago concluded that if a coal plant is older than 12 years, there is no business case in retrofitting it with CCS, because the 28 years of remaining lifetime are not sufficient for pay-back.
A3. Difficulty in financing investment	2	More and more critical articles on the effectiveness of CCS technologies are appearing, mainly because of very weak business cases not able to attract investments.
B1. Dependence on other actors	2	Many actors involved in decision making, as DSOs and TSO for electricity transport, but CO2 transport and storage are fundamental issues and require regulation, permitting and control.
B2. Diversity of actors involved incl. conflicts	2	Installation of the technology is not an issue, but operations are, especially the transport and storage of CO2, as the ownership of storage location. E.g.: In Germany, a suitable storage location was found and private owners were force to sell the land to the government. Offshore location could decrease conflicts. Many conflicts also on responsibilities over waste.
B3. Division of roles and responsibilities unclear	1	[1-2]. No issues at power plant, but for transport and storage. Not clear which party is responsible for waste: up to 10 years, the coal plant ownership is responsible, then responsibility shifts to the government, but this is a highly debated topic. Even if clear by law, doubts in operations are expected. Uncertainty score = 1-2
C1. Physical embeddedness	2	Retrofitting a coal plant with CCS requires a complete reorganization of spaces to allow the insertion of big, new components of the CCS mechanism. Besides these changes, there are the CO2 transport and storage equipment
C2. Disturbs regular operation	2	Plant operations need to be stopped for 1 year (McKinsey's study).
C3. Technology uncertainty	2	Capture seems to work technically, but almost no one implements it; transport of CO2 is not an issue (happening In the US); storage is technically not a problem but there are many policy uncertainties. Uncertainty score = 1-2
D1. Absence of knowledge of actor	1	Higher knowledge of operators and companies in the industry, but almost no knowledge of public, authorities, and even NGOs. Uncertainty score = 1-2
D2. Frequency of opportunity	2	China and India are building many new plants; thus, looking at potential chances, the frequency is medium. Looking at the reality of the projects, the frequency of opportunity is rare. Uncertainty score = 1-2
D3. Requires change in behavior	2	Totally new processes to get used to.
GENERAL/ METHODOLOGICAL COMMENTS: Clarity of factors (especially A and D factors) scores would benefit from a five-value scale: No, little, medium, large, Yes.		

Viebhan - [Energy]: Geothermal		
Y-Factor	**Preliminary Score**	**Argument**
A1. Investment cost required	2	Much larger than for small hydro and coal plants, especially for the need of performing exploration activities.
A2. Expected pay-back time	2	Lifecycle assessments, even with subsidies for renewables, estimate a 20 years span as pay-back.
A3. Difficulty in financing investment	1	Accidents and technical problems causing damages to households happened in the past, thus investors, as the government, are not very much in favor of the technology. Proposed score = 2
B1. Dependence on other actors	2	
B2. Diversity of actors involved incl. conflicts	2	Many issues with population who fears accidents.
B3. Division of roles and responsibilities unclear	0	Location dependent; in Germany there are only 2 or 3 large exploration sites, thus there is no much experience. Proposed score = 1
C1. Physical embeddedness	2	Besides a few pipes, most of the technology is installed underground thus not causing large physical changes. Proposed score = 1
C2. Disturbs regular operation	1	Geothermal plants for heating only disrupt operations for the construction (shallow drilling). More problems arise with large geothermal plants for the deep drilling.
C3. Technology uncertainty	1	Many technical problems which have caused the stopping of all researches, as induced earthquakes and damaged to households. Proposed score = 2
D1. Absence of knowledge of actor	0	High knowledge about geothermal plants for heating, low knowledge about deep geothermal technology for power generation. Uncertainty score = 0-1
D2. Frequency of opportunity	1	Deep geothermal has a rare frequency of opportunity, while geothermal for heating can be constructed more frequently. Uncertainty score = 1-2
D3. Requires change in behavior	1	Deep geothermal plants might require access restriction, while the installation of many small geothermal plants for heating might hamper the respective others' functioning.
GENERAL COMMENTS: The abatement option was discussed mostly referring to large scale, deep drilling (2,000 m) power generating plants.		

Viebhan - [Energy]: Small hydro		
Y-Factor	Preliminary Score	Argument
A1. Investment cost required	2	Investment is proportional to size. Whether building a new small hydro power plant or retrofitting a hydropower system on an existing building, the investment needed is substantial.
A2. Expected pay-back time	2	Lifecycle assessments, even with subsidies for renewables, estimate a 20 years span as pay-back
A3. Difficulty in financing investment	2	In Germany there are specific national subsidies for supporting the installation of small hydropower system in a retrofit fashion. Anyways, investment is definitely more attractive than for CCS. Proposed score = 1
B1. Dependence on other actors	2	
B2. Diversity of actors involved incl. conflicts	2	Main issues are related to the protection of the local flora and fauna. Proposed score = 1
B3. Division of roles and responsibilities unclear	0	
C1. Physical embeddedness	2	
C2. Disturbs regular operation	1	
C3. Technology uncertainty	0	Proven on projects of different scales.
D1. Absence of knowledge of actor	0	Long experience.
D2. Frequency of opportunity	2	
D3. Requires change in behavior	1	Depends on location, with some potential restrictions for fishermen.

GENERAL COMMENTS:
A hydro power plant on the Rhine was used as reference for discussing this abatement option, different from large power generating plants in South America and Africa. Small hydro power systems could also be retrofitted on existing buildings.