Exploring carbon futures in the EU power sector

Using Exploratory System Dynamics Modelling and Analysis
to explore policy regimes under deep uncertainty

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Abstract

The European Emissions Trading Scheme (ETS) in combination with other renewable electricity (RES-E) support schemes such as (premium) feed-in tariffs or tradable green certificates do not guarantee a carbon neutral power sector in 2050. This paper shows that many plausible futures of high carbon emissions exist when no substantial efficiency measures are taken in high growth futures. Using System Dynamics (SD) in combination with Exploratory Modelling and Analysis (EMA), it seems that the main European energy policies might result in high levels of carbon abatement but have very limited guarantees whatsoever. There are potential 'free lunches' for policy makers to reduce carbon emissions but these will probably not suffice when ambition levels remain high. This paper sheds new light on the path to find policy synergies for the European electricity sector with the aim to rule out lurking catastrophic futures of high carbon emissions combined with high costs for society.

Keywords: Carbon emissions*;* Deep uncertainty; Energy transition; EU power sector; ESDMA; Robust policy design

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1. Introduction

This section introduces the problem related to the design of policies that will result in a reduction of carbon emissions in the EU power sector.

1.1 Targets for a sustainable energy sector in the EU

With the studies on the potential environmental and economic impacts of greenhouse gas emissions due to combustion of fossil fuels [1-4], political support was created to combat climate change in the European Union (EU). Therefore, reducing greenhouse gas emissions is one of the 3 main objectives for EU energy policy design. The other two objectives are securing energy supply (decreasing the dependency on imported hydrocarbons) and increasing competitiveness (reducing price rises and creating growth and jobs) [5].

In an attempt to reduce carbon emissions and increase the share of renewables in the power mix the European Commission (EC) launched the European Emissions Trading Scheme (ETS) and Directive 2009/28/EC on the promotion of renewable energy sources (RES) [6, 7]. This directive aims to achieve 20% carbon emissions reduction (compared to 1990) and a share of 20% RES. The power sector needs to contribute substantially to achieve this target, aiming at 35% renewables in 2020.

Abbreviations: ABM, Agent Based Modelling; CCS, Carbon Capture and Storage; CP, Copper Plate (model); ETS, Emissions Trading Scheme; ECF, European Climate Fund; EC, European Commission; EU, European Union; EMA, Exploratory Modelling and Analysis; ESDMA, Exploratory System Dynamics Modelling and Analysis; FS, Feature Selection; FIT, Feed-in Tariff; GW(h), Giga Watt hour; IGCC, Integrated Gasification Combined Cycle; IPCC, Intergovernmental Panel on Climate Change; IEA, International Energy Agency; KDE, Kernel Density Estimation; LCOE, Levelised costs of electricity; MIC, Marginal Investment costs; MW(h), Mega Watt (hour); MS, Member State; NGCC, Natural gas combined cycle; PRIM, Patient Rule Induction Method; RB, Regional Blocks (model); RES-E, Renewable Energy Sources for Electricity Generation; SD, System Dynamics; TW(h), Terawatt (hour)

Longer term ambitions for carbon emissions reduction in the power sector are even higher. In 2009, the European heads of state signed a declaration to reduce carbon emissions by 80-95% in 2050 [8]. And the power sector itself has committed to become practically carbon neutral in 2050 [9].

Next to the just-mentioned directive on renewable energy supply, the European Commission (EC) launched the European Emissions Trading Scheme (ETS) in 2005 [7]. The ETS system is a market based instrument to cap-and-trade carbon emissions allowances amongst large polluters in Europe. In 2013 phase 3 of the ETS system commences. From then, power producers have to buy carbon allowances from the market to compensate for their emissions. The annual cap of carbon decreases linearly to trigger an increase in carbon abatement. When large emitters fail to comply with the ETS system, they have to pay a penalty which is currently EUR 100/ton CO_2. This system will be in operation until at least 2020 but probably longer [7, 10].

Looking at the overall achievements of the EU economy to reduce carbon emissions, we see that about 15% emissions reduction is achieved in 2010 compared to 1990. It is interesting to see that most reduction was achieved during the economic downturn in 2007-2009. However, the (short) economic recovery in 2010 and a relatively cold winter in caused a 2.4% increase in carbon emissions again [11]. On the other hand, renewable electricity investments are lagging further behind. Despite increasing efforts, the interim target of 21% electricity from renewable sources (RES-E) in 2010 was missed by 2%. So, a steep increase in EU wide investments in low carbon technologies would be needed to achieve these targets but is unlikely to happen in a short to medium term [12].

1.2 Characteristics of the EU power sector

Most of the electricity in the EU is generated in large centralized thermal power plants. This makes the power sector a potential interesting sector for large scale cuts in carbon emissions. As an interpretation of "Trias Energetica" [13], carbon emissions reduction in the power sector can either be achieved by fuel switching, demand reduction, fossil fuel efficiency gains and/or carbon storage and sequestration (CCS).

In order to study technological change and the performance on carbon emissions reduction in the EU power sector, a micro-economic perspective is needed [14]. Private investments mainly shape the power mix of different generation technologies in the current liberalized power market.

Dynamics in the power sector, such as the just mentioned investment dynamics, are characterized by long construction lead times, permit lead times and economic lifetimes of technologies. Furthermore, there are many interactions, delays and feedbacks in the system that can cause cyclic behaviour, lock-in effects and path dependency [15]. This implies that a long term modelling perspective is needed to study the effects of these dynamics.

When studying the EU power sector and its long term dynamics, many uncertainties can be identified that that influence the system and shape its future. Examples of uncertainties can be 'hard' parametric values like installed capacities and economic lifetimes but also 'soft' values, such as weight factors on strategic motives of private investors. Besides these parametric uncertainties, also structural uncertainties exist, such as the effect of low capacity reserve margins on strategic market bidding and the effect of demand growth on investment forecasting [16]. The level of uncertainty dealt with in this study is called "deep uncertainty". According to Lempert *et al.* [17]: "Deep uncertainty exists when analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate models to describe the interactions, among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes".

1.3 Implications for policy analysis and design

In order to effectively design policies that contribute to the objectives of a safe, secure and sustainable electricity supply in the EU, the earlier mentioned characteristics of the power sector imply that policy makers should focus on long term dynamics and influencing private investments. Therefore, this study uses a timeframe of the next 40 years and a uses micro-economic approach for modelling investment dynamics.

Given the many uncertainties that will shape the future EU power sector, policies are needed that will suffice in all 'plausible futures'. This is called robust decision making [17] and asks for a research method that is capable to incorporate both the complex dynamics as well as the uncertainties, as mentioned in 1.2. Exploratory System Dynamics and Analysis (ESDMA) is such a method. Section 2 provides a short explanation of ESDMA.

1.4 Previous research on policy design to decarbonize the power sector

A literature study was performed on carbon emissions reduction and policy design studies in the power sector. This included system dynamics modelling studies [15, 18-24], agent based modelling studies [25], cost-efficiency optimization studies [9, 26, 27], and ex-post policy assessment studies based on empirical and literature research [28-30].

What all these studies have in common (although some more than others) is that they fail to incorporate the effects of deep uncertainty in their analyses. Therefore the aim of this study is to incorporate deep uncertainty in the analysis of a transition towards a low carbon EU power sector, and suggest directions for policy design that provide satisfying outcomes in all plausible futures, as suggested by [17].

1.5 Research question

The just mentioned aim of this study leads to a desire to explore the impact of uncertainties on plausible carbon emissions futures in the power sector. The following research question fits this aim:

What are the effects of parametric and structural uncertainties on plausible carbon emissions futures in the EU power sector under different policy regimes to provide directions for robust policy design?

The study on the EU power sector presented here aims to (1) explore and not predict a wide array of plausible futures for carbon emissions reduction, (2) identify most risky and promising futures for decarbonisation, (3) assess the robustness of different policy regimes under different uncertainties and their plausible ranges, and (4) provide directions for policy making to enhance the robustness of policy regimes under review.

The next section indicates the policy regimes under review.

1. 6 Policy regimes under review

Given the dynamic and evolving character of the EU power sector's policy landscape, different policy regimes will be explored. A selection is made of 4 different regimes. Besides the current ETS system, one reference regime without the ETS system is also explored (i.e. No ETS). Furthermore, to two regimes are explored where the ETS system co-exists with a renewable electricity support scheme, these are a premium Feed-In Tariff (FIT) system and a Tradable Green Certificates (TGC) system.

- ***No ETS*** – A free and competitive market without the ETS system or support policies.
- ***ETS Only*** – The ETS system is introduced with different potential carbon cap pathways from 2020.
- ***FIT*** – On top of the ETS system, a premium feed-in tariff (FIT) is introduced that covers the gap between the electricity market price and the lowest levelised costs of electricity (LCOE) of some RES-E technologies[1]. An additional profit mark-up of 100% of is added and the tariff is limited to a maximum of EUR 150/MWh.
- ***TGC*** – On top of the ETS system, an EU wide suppliers' obligation to buy Tradable Green Certificates (TGC) is introduced. The obligation increases towards 80% fraction RES-E in 2050 and non-discriminatory for all RES-E technologies.

All policy regimes act in an energy-only market. Energy-only markets rely on the electricity market to provide investment incentives for power generation capacity [32]. This means that no fees are paid for installed capacity or other types of capacity mechanisms are in place. Loonen [16] provides a more detailed elaboration of the policy regimes explored in this study.

It has to be noted that this study does not aim to assess the effectiveness of the policy regimes for comparison. Tools and probabilities are lacking in this study to make such a comparison useful. The mere aim is exploration only.

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[1] RES-E technologies that fall under the premium FIT policy regime are wind power, biomass and PV solar power. Large scale hydro power is not included for two reasons: (1) Most FIT systems currently applied in the EU Member States mostly only account for wind, biomass and/or PV solar power [12], and (2) generating costs of large scale hydro power is generally substantially lower than the other RES-E technologies [31] so including large scale hydro power undermines the effectiveness of this policy support regime. The feed-in tariffs are regional specific in the Regional Blocks model.

1.7 Organization

The structure of this paper is as follows: Section 2 discusses Exploratory System Dynamics Modelling and Analysis as the research method for this study; in section 3, the results from the analysis on the base policy regimes are presented and interpreted; section 4 shows the results of an assessment of 4 policy directions on their robustness; in section 5, conclusions of this study are stated; and in section 6, a discussion on the validity of the outcomes and ex-post criticism is presented.

2. Modelling policy issues for exploratory purposes

After the introduction of the problem and aim of this study, the steps taken in modelling for exploratory purposes are listed. This section elaborates on Exploratory Modelling and Analysis (EMA) in combination with System Dynamics (SD) models as main research methodology.

2.1 Methodology

In order to explore the behaviour of the EU power sector in a wide array of plausible futures, Exploratory Modelling and Analysis (EMA) can be used [17, 33, 34]. EMA involves the design of plausible models and identification of most important uncertainties and their plausible ranges in order to generate plausible futures. These uncertainties and ranges are used as input for the simulation models.

An approach that builds forward on EMA, focussing on policy design under deep uncertainty is the Adaptive Robust Design (ARD) approach [35]. The steps of the ARD approach are used in this study.

Steps in ARD are:

1. Conceptualize the policy problem
2. Specify the uncertainties relevant for policy analysis
3. Develop an ensemble of models for exploring uncertainties
4. Run the computer models without any policies in order to generate the ensemble of futures
5. Explore and analyse the results from step 4 in order to identify the troublesome and promising regions across the outcomes of interest, as well as the main causes underlying these regions
6. Design candidate policies for addressing vulnerabilities and seizing opportunities
7. Implement and test the candidate policies across the ensemble of futures
8. Iterate through steps 5-7 until satisfying policies emerges

2.2 ESDMA and incorporating uncertainty

EMA asks for simulation models as the experimental setup to generate and explore plausible futures of a system under research. Although many different simulation models could be used, in this study EMA is combined with System Dynamics (SD) models. System dynamics models are particularly able to incorporate the characteristics of the power sector as mentioned in section 1.2. Combining EMA with SD modelling is called ESDMA [36, 37].

The second step in ARD is to identify uncertainties that are relevant for the problem under research. In this study, all uncertainties are divided in parametric and structural uncertainties.

Parametric uncertainties are values of parameters concerning relationships in the system [33] and are defined by a single value. These uncertain values are constant in during a whole simulation run. Examples of parametric uncertainties are initial values (e.g. generation capacities), constants (e.g. economic lifetimes of technologies), delays (e.g. information delays to forecast expected future electricity demand), and switches (e.g. to turn on/off a part of the model structure).

Structural uncertainties indicate specific structures of the model that can be turned on/off. By incorporating structural uncertainties in the model, the ability exist to use different assumptions about factors and relationships in the model [33]. Examples of structural uncertainties are: The effect of economic growth and electrification on electricity demand, the availability of battery storage to cope with intermittent electricity supply and the effect of different investor's perspectives on capacity investments for future electricity supply.

A wide range of literature sources is used for identifying most important uncertainties and their plausible ranges [31, 38-53]. Furthermore, a workshop and interviews were held with scholars and experts from the power sector to draw potential evolutions of some of the main structural uncertainties like economic growth, electrification rates and battery storage in electric vehicles. Moreover, the most important strategic motives that influence investment decisions were also verified during this workshop. However, when no real world data could be obtained, guestimates were made. All uncertainties and the way they affect the simulation models in the study can be found in [16]. The uncertainties and their ranges are listed in a Python [54] shell that is connected to the simulation models in order to provide the input values for the models.

2.3 Tools for exploration

Thousands of scenarios can be generated by connecting the SD models to a Python shell that ranges the input values for each run. When a dataset is generated of all runs, each ensemble of runs needs to be explored. Different tools exist to explore the large amount of scenarios. Tool used here are:

- Explorative visualization by means of envelopes that show the upper and lower limits of the scenario ensemble over time. These envelops are complemented with a kernel density estimation (KDE) on the end-state of each run [55, 56].
- The Feature Selection (FS) algorithm to identify uncertainties that have the largest influence on a specific performance indicator (PI) [57].
- Patient Rule Induction Method (PRIM) to identify *combinations* of uncertainties that are highly predictive for a specific model output [58].

2.4 Simulation models

As mentioned before, ESDMA needs plausible simulation models for exploration. In this study, 2 different simulation models of the EU power sector are designed. Most important distinction between both models is the modelling aggregation level. These 2 models are called the Copper Plate model (highly aggregated) and the Regional Blocks model (more detailed model, see figure 2). However, the basic structure of both models is largely the same. In total 9 different technologies are included that compete for investments (i.e. coal, gas, biomass, PV solar, hydro, nuclear, wind, gas with CCS and coal with CCS). The specific technological characteristics and the total uncertainty space is found in [16].

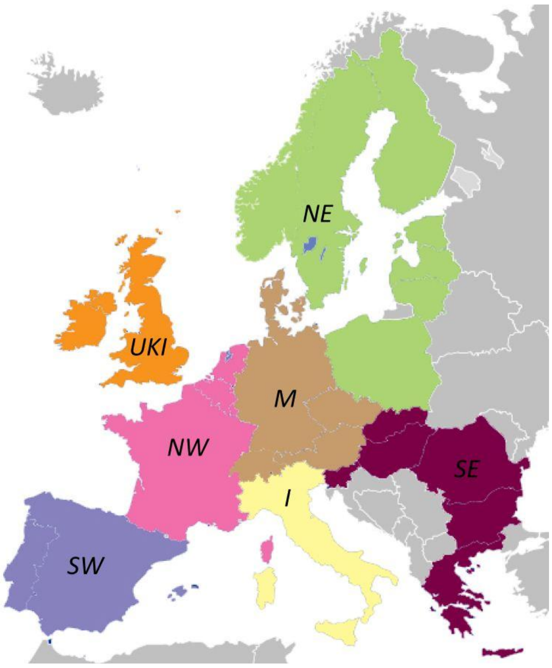

Figure 1: Schematic representation of the EU Regional Blocks model. This model includes regional characteristics for renewable electricity supply and interconnection capacity limitations for power trade and supply.

In a liberalized power market commercial parties determine the type and capacity amount of generation technologies. A micro-economic perspective is needed in order to research investor's behaviour in a liberalized power sector, such as the EU [14].

Figure 1 shows the main dynamics that underlie the simulation models used in this study. At a high aggregation level, basically 2 important factors drive new capacity investments. These are profitability and electricity demand. Investors assess the profitability of each technology, in order to determine the amount of new capacity investments. These dynamics and model structures are further elaborated in [16]. The levelised costs of electricity (LCOE) indicate the total costs during the whole economic lifetime of a technology, divided by the total (expected) power generation during its lifetime. The definition and formula of LCOE used in this thesis study is stated in [16].

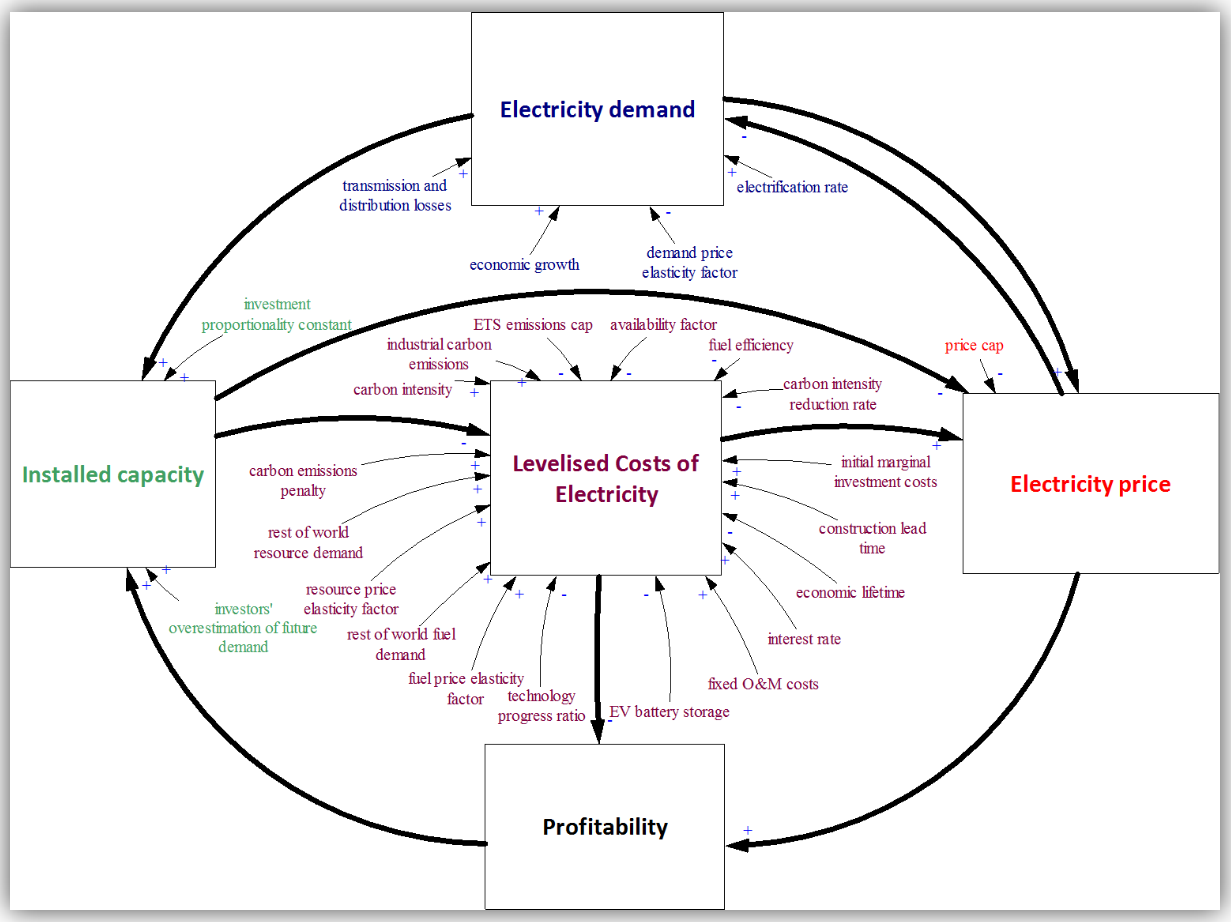

Figure 2: Highly aggregated causal loop diagram of investment dynamics in power generation capacity with main uncertainties, from a micro-economic perspective [14, 48].

3. Exploring base policy regimes

3.1 Visual inspection of envelopes with kernel density estimations (KDEs)

Although the primary focus of this study is on carbon emissions, other performance indicators are used to put the performance into context. These performance indicators are related to production, policy and investment costs, as well as renewable electricity supply. Outcomes on all these performance indicators are presented in [16] but only most relevant outcomes are presented in this paper.

3.2 Carbon emissions in base ensembles – Risks and opportunities for a low carbon power sector

Looking at the envelopes on carbon emissions (figures 3-5), a wide distribution of plausible end-states in 2050 is seen. It is not surprising to see that most risk prone high carbon futures are seen in the No ETS policy regime. In the Looking at the other policy regimes, worst high carbon futures are less severe but still rather bad.

From these envelopes, it seems as if introducing the ETS system, with or without a RES-E support scheme, is a push in the right direction to reduce carbon emissions but is not enough to effectively rule out all worst case futures.

Besides these catastrophic futures, also very low carbon promising futures are observed in all base policy regimes. However, most promising futures that lead to an almost carbon neutral power sector in 2050 are observed in the policy regimes where the ETS system co-exists with a renewable electricity support scheme (i.e. the FIT or TGC regime). From these observations, it seems possible to decarbonize the EU power sector to a large extent when opportunities are seized but there is no base policy regime that guarantees large emissions reductions.

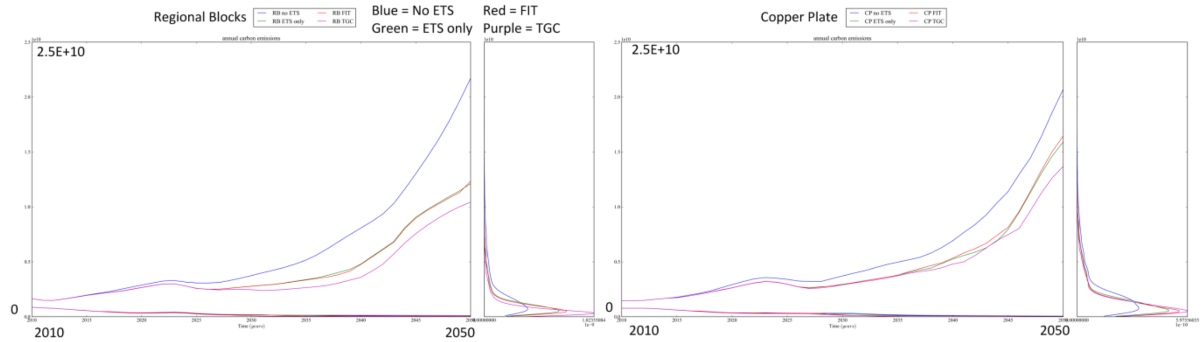

Figure 3: Annual carbon emissions envelopes base policy regimes [ton/year], 10.000 runs. High carbon futures are plausible in all policy regimes.

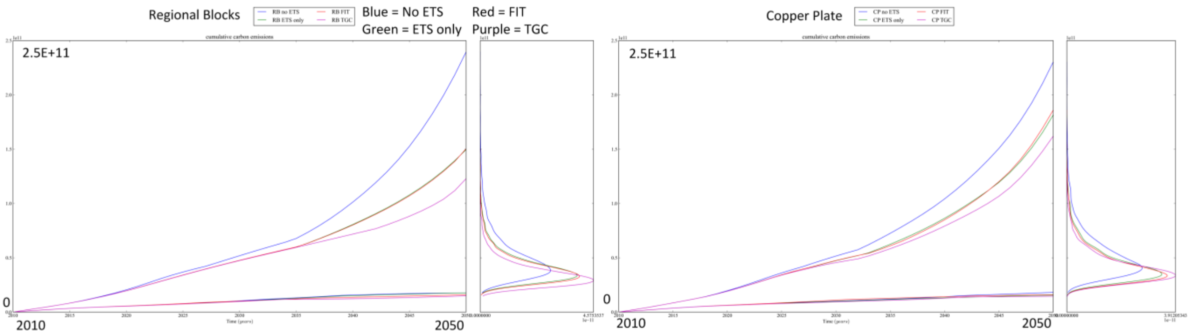

Figure 4: Cumulative carbon emissions envelopes base policy regimes [ton], 10.000 runs. A wide range of plausible carbon futures are observed in all policy regimes

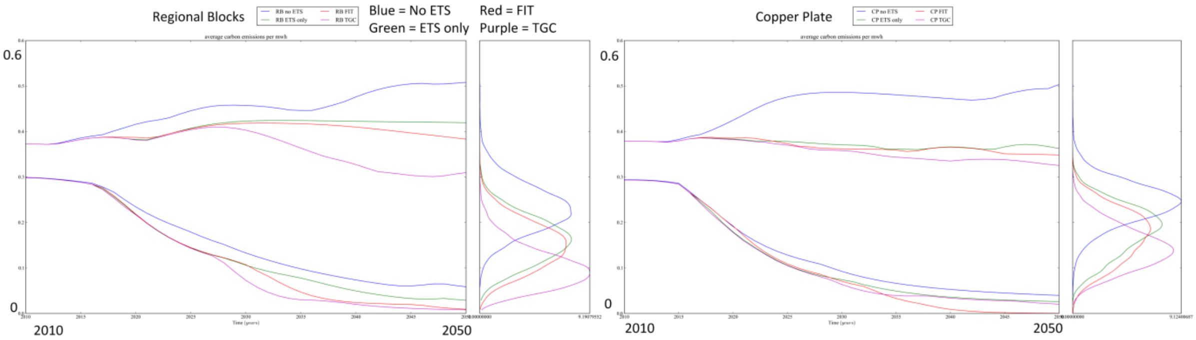

Figure 5: Average carbon emissions envelopes base policy regimes [ton/MWh], 10.000 runs. A trend towards lower average carbon emissions is observed in most policy regimes.

When looking at the financial implications of each policy regime (figures 6-8), it seems that for most of the promising low carbon futures the implications can be significant for society (in case of FIT), end-consumer (in case of TGC) and producers (in case of FIT and TGC).

Although we do not exactly know the correlation between the high costs futures and the high carbon reduction futures in the TGC and FIT policy regimes, the envelopes of the No ETS and ETS policy regimes show that there may be some opportunities for 'free lunch policies' available. 'Free lunch' policies are policies "that improve some or most measures of performance without degrading others" [59]. In this study it means that carbon emission can be reduced without increasing costs for society or producers. Reason is that in the No ETS and ETS only policy regimes some futures are observed where carbon emissions are reduced significantly, while the total costs do not necessarily increase significant.

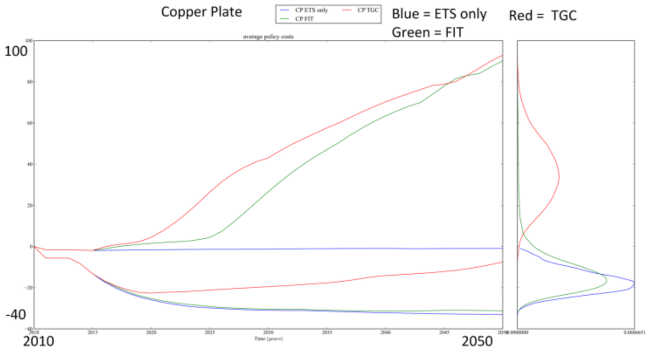

Figure 6: Average costs[2] of policies borne by society and/or end-consumer due to the ETS system and RES-E support schemes, Copper Plate model 10.000 runs.

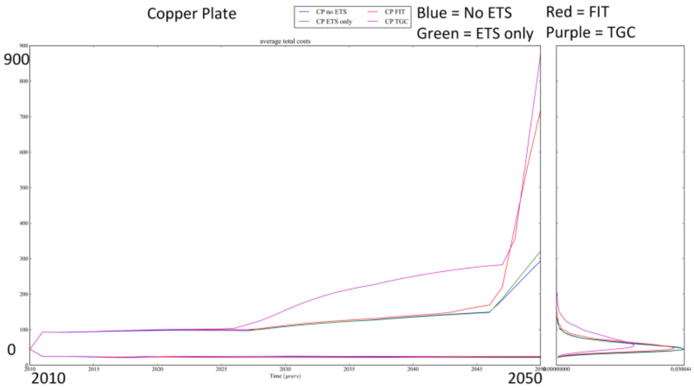

Figure 7: Envelopes of average costs for producers base policy regimes [EUR/MWh], Copper Plate model 10.000 runs.

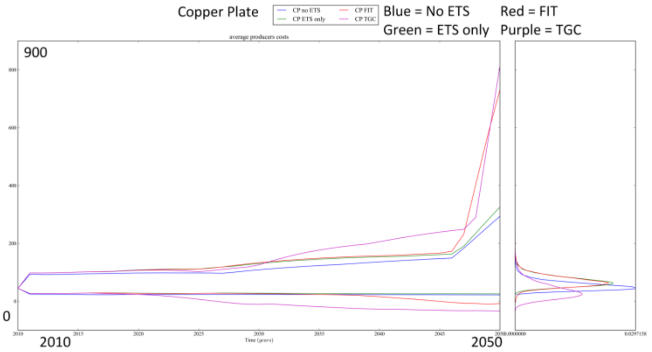

Figure 8: Average total costs envelopes base policy regimes [EUR/MWh], Copper Plate model 10.000 runs. Total costs consists of policy costs added with costs for producers

3.2 Identifying influential uncertainties on carbon emissions and costs

To identify the main causes and uncertainties underlying high and low carbon futures, two methods are used as introduced in section 2.3. These are a Feature Selection (FS) algorithm and the Patient Rule Induction Method (PRIM).

Tables 1 and 2 show the relative scores of individual uncertainties by means of the FS algorithm on annual carbon emissions. This is based on an underlying classification scheme; higher the annual carbon emissions reduction yields higher scores. These scores should merely be interpreted in a relative way and not in an absolute way.

It is not very surprising that economic growth and the rate of electrification of the economy turn out to have a high influence on annual carbon emissions in all policy regimes. The reason is that these uncertainties drive electricity demand and subsequently supply. In a power sector that largely consists of conventional high carbon emitting power plants, it seems obvious that these uncertainties are most influential. On the other hand, the extent of the influence of these uncertainties may be surprising, compared to the other uncertainties. Furthermore, it seems that the relative influence of economic growth and electrification decrease with introducing the ETS system and a RES-E support scheme (FIT or TGC). This also makes sense because these policy schemes intent to make a transition in the power mix from conventional high carbon emitting technologies to low carbon and renewable technologies. This is caused by the underlying mechanism of profitability that drives new investments. The ETS and RES-E support schemes intent to reduce the profitability of high carbon technologies while increasing the profitability of renewable and low carbon technologies. This increases the relative attractiveness of low carbon renewable technologies for investors.

Moreover, facilitating higher penetration levels of wind and PV solar power (intermittent RES-E technologies) seems to be a condition to further reduce carbon emissions. This could be done by using batteries in electric vehicles (or other storage possibilities) to temporarily store electricity in order to deal with the variability of supply.

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[2] These costs are averaged out over the total run-time. Negative costs indicate a revenue stream for policy makers/society, due to ETS allowances auctioning.

Table 1: Relative feature selection scores on carbon reduction Regional Blocks model base policy regimes. Economic growth and electrification of the economy yield highest scores.

Condition: ≥0.03 on ≥1 policies	**Regional Blocks**			
Feature	***No ETS***	***ETS Only***	***FIT***	***TGC***
Economic growth	0.207	0.158	0.142	0.157
Electrification rate	0.254	0.178	0.162	0.111
ETS price determination	0.015	0.005	0.031	0.058
Interconnection capacity expansion	0.030			
Storage for intermittent supply	0.002	0.028	0.030	0.035
Investors' overinvestment factor			0.001	0.042

Table 2: Relative feature selection scores on carbon reduction Copper Plate model base policy regimes. Economic growth and electrification of the economy yield highest scores.

Condition: ≥0.04 on ≥1 policies	**Copper Plate**			
Feature	***No ETS***	***ETS Only***	***FIT***	***TGC***
Economic growth	0.315	0.249	0.236	0.147
Electrification rate	0.248	0.192	0.183	0.186
Availability factor	0.043	0.010	0.001	
Physical limitations large scale hydro	0.042	0.021	0.042	0.035
Storage for intermittent supply	0.041			

The FS algorithm is also performed on the average total costs for electricity (this is the total costs of policies added to the total costs for producers and averaged out over the electricity generated during the period 2010-2050). The FS algorithm returned again economic growth and electrification rate for all policy regimes as important drivers for high costs, but their relative influence is less compared to the FS analysis on carbon emissions [16].. However, it seems that both from a carbon emissions perspective and costs perspective, the main drivers of increasing electricity demand should be targeted with policy measures.

Some uncertainties are only highly influential in combination with others. Together, these can create risks or opportunities. PRIM is a method to identify these combinations. This method is performed on all performance indicators, shown in [16], but only a brief summary of the most interesting outcomes is presented here.

Comparable to the outcomes of the FS analysis, the PRIM analysis on annual carbon emission returned economic growth and electrification rate as most influential. However, the analysis on *average* carbon emissions per MWh showed some other interesting outcomes. When choosing a No ETS policy regime, worst cases can be ruled out by reducing the carbon intensity rate of fossil fuel generation technologies, and by exploiting the full growth potential of large scale hydro power[3].

When a TGC system is chosen, some additional interesting results are seen in the PRIM analysis. At first, fuel price elasticity factors counteract a transition towards a renewable electricity supply. This means that when demand for fossil fuels decrease, prices decrease proportionally which make fossil fuels more attractive again. So in case of a large transition towards renewables,

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[3] Different estimates exist on the potential of large scale hydro power in Europe [60, 61]. This is amongst others dependent on what is perceived as acceptable potential for society and environment. This study does not elaborate on potential consequences for society and environment to increase the potential for large scale hydro power.

policy makers could counteract this effect by assuring structurally high fossil fuel prices (e.g. by increasing taxes or levies).

Furthermore, too optimistic estimations of future demand growth by investors also decrease average carbon emissions. Reason is that most renewables (except biomass) benefit from their low variable costs which give them priority position in the merit order for supplying electricity. So, even when investments are uniformly distributed over all technologies, excess investments could lead to lower carbon emissions. However, an overestimation of future demand growth amongst investors will also lead to higher average costs for producers. There are two reasons for this effect. The first reason is that overinvestments lead to lower average capacity factors of existing generation capacities, making their use less efficient. And secondly, overinvestments could lead to increased resource scarcity which drives marginal investment costs of new generation capacity.

Last note worth mentioning from the PRIM analysis is that ambitious short term targets for the ETS and TGC regimes (i.e. logistic growth or decrease) could have a beneficial effect on decreasing carbon emissions in the long run. However, these ambitious targets most likely also increase the total costs of electricity that needs to be paid by the end consumer and/or society. So here it seems that a trade-off needs to be made between reducing carbon emissions and increasing costs of electricity.

3.3 Conclusions on base policy regimes

The base policy regimes all show a wide distribution in plausible carbon futures for the EU power sector. Otherwise than might be expected, the ETS and RES-E policy schemes assessed here do not guarantee substantial carbon emissions reductions without additional policy measures.

There seem to be 'free lunch' policies available in reducing carbon emissions without increasing the total costs of electricity. These free lunch policies should be searched in limiting electricity demand growth.

Besides the potential 'free lunch' policies, sometimes trade-offs between costs and carbon emissions reductions need to be made. These trade-offs could be related to allowing or stimulating (over)investments in low carbon technologies. Increasing (over)investments in renewables could reduce carbon emissions due to the priority position of most renewables in the merit order. RES-E subsidy schemes could amplify this effect further. The same accounts for ambitious short term targets for the ETS and TGC schemes. When targets are set ambitious in early phases, higher carbon emissions reduction are seen that last for the longer term, but this would most probably also involve higher costs that need to be borne by consumers and/or society.

Last two observations made for further carbon emissions reductions, are to allow for higher penetration levels of hydro power by exploiting its full growth potential. And secondly, to facilitate (battery) storage of intermittent electricity supply.

4. Robust policy testing

From the analysis on the base policy regimes and the analysis on high versus low growth scenarios (see [16]) a set of new policy measures is suggested and tested here. These are really suggestions for policy directions and should not be interpreted as real world policy measures.

4.1 Directions for new policy design

From the previous analyses, we saw that limiting the main effects on demand increase (economic growth and electrification rate) seems to be beneficial to reduce absolute carbon emissions (direction 1). Furthermore, a condition to allow for large scale penetration of wind and PV solar power is to make (battery) storage available (direction 2). Moreover, carbon emissions are most likely to decrease further with exploiting the full potential of large scale hydro power (direction 3). And last, in order to prevent large costs increases for producers (i.e. finally transferred to the end-consumer), the maximum amount of overinvestments is limited (direction 4). .

The four directions for new policy design suggested and tested in this study are:

1. Limit demand growth to max. 1.5% per year.
2. Increase available (battery) storage for intermittent power supply towards 1.3TW in 2050.
3. Allow for higher penetration levels of large scale hydro power. See [16] for more details.
4. Limit overinvestments to a maximum of 50% of the expected future demand gap.

4.2 Exploring new policy ensembles

The directions for policy design in 4.1 effectively rule out most catastrophic high carbon and high cost futures for all policy regimes (see figures 9 and 10). Interestingly the FIT and TGC policy regimes show their best low carbon future in the original base policy ensembles. This is caused by policy direction 4 that limits overinvestments. On the other hand, the sacrifice that is made is relatively insignificant compared to the progress that is made to rule out worst high costs futures. Although the total costs (costs for producers and society summed) are reduced in most futures, so are the revenues from the ETS system. Some policy makers could find this undesirable because this system can be a real cash cow as seen in the base policy ensembles.

In order to further improve the performance on carbon emissions, a PRIM analysis was performed again to see what the most influential uncertainties on carbon emissions are for the new policy regimes (see [16]). This analysis indicated that still economic growth and the electrification rate are most influential in all policy regimes. This outcome is quite remarkable, given the policy measure that limits these effects on demand growth to a maximum of 1.5% growth per year. Apparently, demand growth remains the most important bottleneck for further reducing carbon emissions in the power sector. However, when the EU has the ambition to become (almost) carbon neutral by 2050, residual emissions need to be cut as well by fuel switching or carbon capture and sequestration. To push such a technological transition, the results from the PRIM analysis suggest that further increases in demand reduction should be combined with a steeply decreasing carbon cap early in phase 4 of the ETS system (logistic decline) and steeply increasing the obligation for green certificates short after introduction (logistic growth). However, following from the results of the base ensembles, this means that this would presumably lead to higher average total costs for electricity.

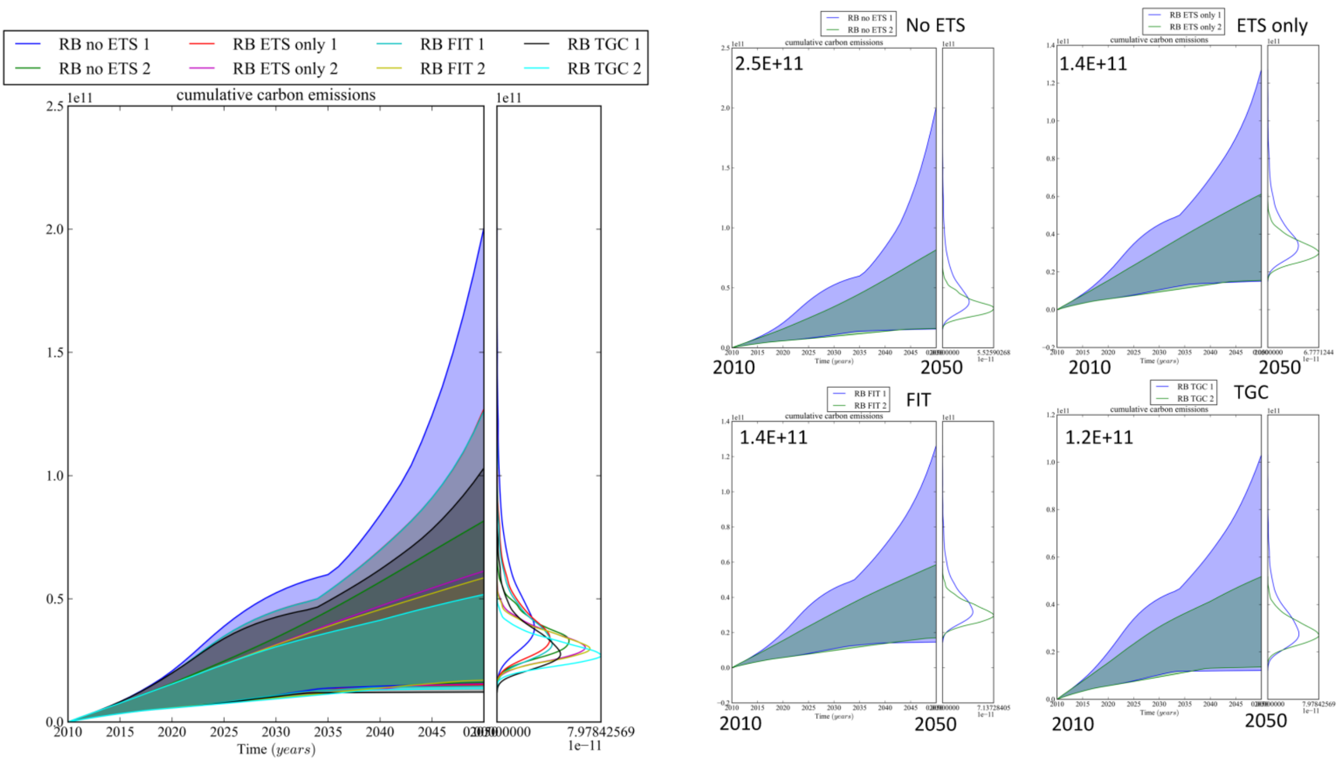

Figure 9: Cumulative carbon emissions, base (1 in blue) and new (2 in green) policy ensembles [ton], 6000 runs. Worst case futures are effectively ruled out with a small sacrifice for best case futures in FIT and TGC.

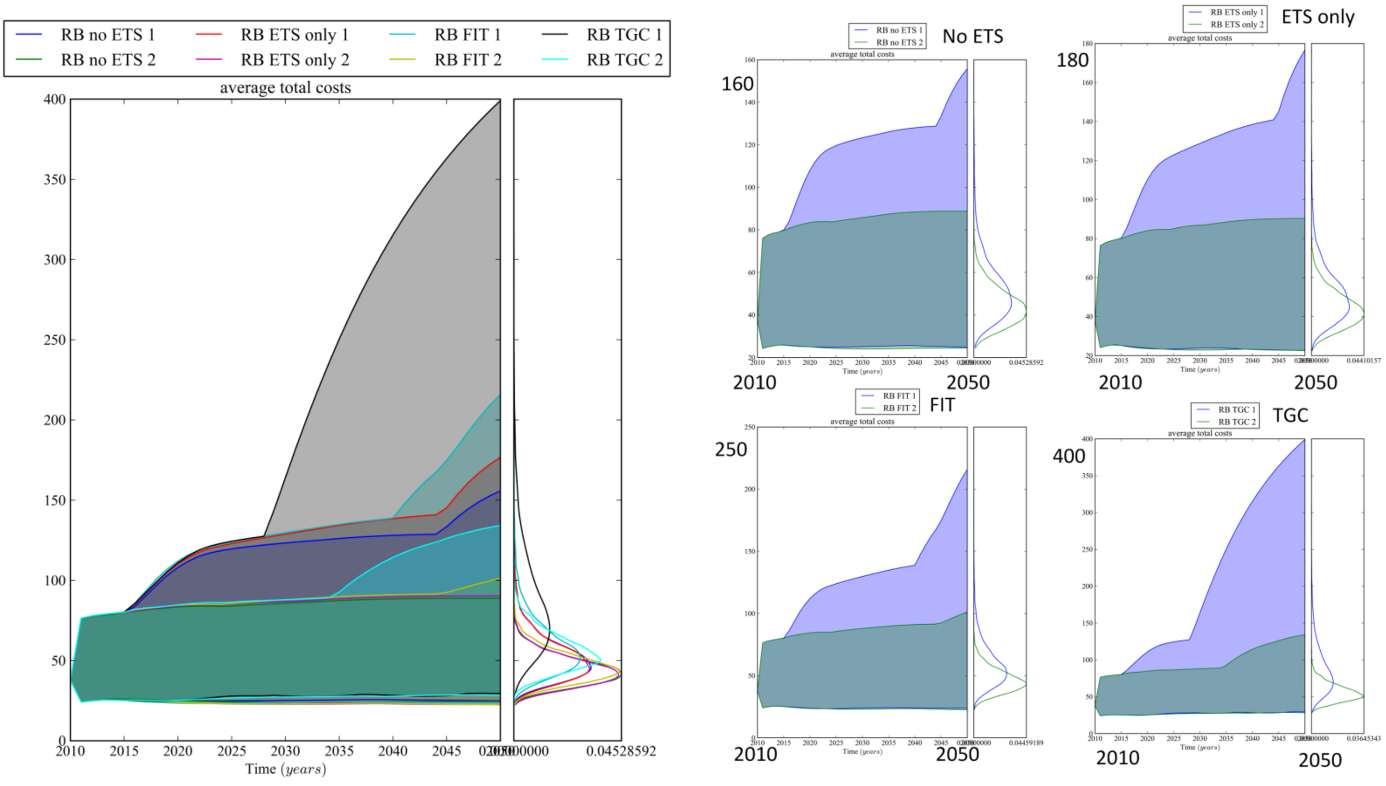

Figure 10: Average total costs of electricity, base (1 in blue) and new (2 in green) policy ensembles [EUR/MWh], 6000 runs. Total costs for society and producers largely decreased in worst case futures but so are revenues from the ETS system.

5. Final conclusions

5.1 General conclusions

The European Emissions Trading Scheme (ETS) in combination with other renewable electricity (RES-E) support schemes such as a premium feed-in tariff (FIT) or tradable green certificates system (TGC) certainly do not guarantee a carbon neutral power sector in 2050 in all futures. When these systems are implemented in isolation, there is a great risk of ending up in a high carbon future. However, the policy directions assessed here seem to be robust in ruling out most catastrophic future for all policy regimes.

There are potential 'free lunches' policies available to reduce carbon emissions while not hampering the performance on other crucial performance indicators. The 'free lunch' policies should be directed towards demand reduction. However, these 'free lunch' policies will probably not suffice when long term ambition levels for carbon reduction very high as stated by the European Commission and the power sector itself [8, 9].

Most promising futures are seen when synergies between the ETS system and RES-E support schemes are yielded. However, one of the critical success factors is to allow for high penetration levels of renewables like wind, PV and hydro power. Wind and PV solar penetration rates could increase by allowing (temporary) storage of electricity (e.g. battery storage in electric vehicles).

Furthermore, the balancing effect of lower fossil fuel prices in a transition towards non-fossil fuel generation technologies should be counterattacked. One of the options to might be to introduce taxes (or other levies) that increase proportional to the decreases in fossil fuel prices assure structurally high fossil fuel prices. However, the drawback is that this may interfere with the EC's objectives on competitiveness of the EU economy [5] . On this short term this will cause higher prices for producers that are transferred to consumers.

The other side of the coin is that there is a risk for high societal costs when the ETS system coexists with RES-E support schemes. Limiting risks of substantial demand growth is again one of the most important measures that should be taken to limit substantial societal costs, next to limiting overinvestments.

5.2 Conclusions on policy regimes

No ETS – Energy only market without policies

The No ETS policy regime showed the widest range in plausible carbon emissions futures. Although some promising futures are identified, a significant risk to end up in a high carbon future is taken when choosing this regime without additional policy measures. The additional directions for policy design improved the performance significant, but an increase (even a doubling) in carbon emissions in this regime remains plausible.

ETS only – Implementing the Emissions Trading Scheme

With the introduction of the ETS system, the worst case scenario is far less severe than without the ETS system. On the other hand, substantial emissions increases are still very plausible (up to 5 times current emissions) without additional policy measures. With the given directions for policy measures tested in this study, risks of high carbon futures are significantly decreased. However, in worst cases carbon emissions might still increase up to 50%. These measures also reduce revenues from carbon allowance auctioning from a policy maker perspective. However, electricity consumers will generally benefit if these lower costs for producers are carried forward in the electricity price.

(Dynamic) premium feed-in with the ETS system

Like the other policy regimes, the premium feed-in tariff on top of the ETS system without additional policy measures does not guarantee high carbon emissions reduction. However, when the additional measures as suggested in this study are implemented, the risk of carbon emissions increase in 2050 is (almost) completely ruled out. Furthermore, from a policy costs perspective these additional policy measures are also effective to prevent the risk of enormous costs for society to finance this system. The premium feed-in system tested here is dynamic and not fixed. This can cause the gap between the electricity market price and LCOE of renewables to increase, which drives the reinforcing loop that lead to higher policy costs in order to bridge the gap (until the maximum feed-in tariff). So, especially demand reduction and preventing overinvestments are important conditions to keep costs in hand for society.

Tradable Green Certificates with the ETS system

Comparable to the other policy regimes, a co-introduction of a TGC system and ETS system as tested here do not assure carbon emissions reductions towards 2050 without additional policy measures. However, when the additional policy measures are implemented, all plausible futures generated in this study show a guaranteed carbon emissions reduction towards 2050. And besides that, also an (almost) carbon neutral power sector seems plausible. Next to carbon emissions reduction the additional measures tested in this study are also beneficial from a societal and consumer's costs perspective. Without these measures, high prices for certificates in combination with a substantial increasing demand could result in unacceptable high costs.

The analysis on the TGC policy regime with new policy measures indicated that in order to further reduce carbon emissions, limiting demand growth (economic growth and electrification rate) remains the most important bottlenecks. And last, ambitious short term targets for reducing the carbon cap in phase 4 (after 2020) and increasing green certificates obligations could further drive carbon emissions reduction. The drawback is however, that most probably we need to accept higher costs for our electricity supply in that case.

6. Discussion, criticism and further research

6.1 Plausibility of futures

Plausibility of futures is one of the important conditions for exploring futures in an EMA study [17]. It is questionable if whether the demand scenarios sketched in this thesis study are plausible. A maximum threshold used in the thesis study of Loonen [16] for plausible power demand futures is 3TW full load capacity in 2050. It turned out that a fraction of 7.6-10.3% of all scenarios in the base ensembles exceeded this threshold. The main risk of including implausible scenarios in the dataset is that specific policies are designed to deal with these scenarios. This risk can be offset by designing adaptive policy measures rather than static policy measures. Adaptive policy measures are only activated when a certain situation occurs that indicates a risk or opportunity to predefined policy targets. According to Bankes *et al.* [62], designing adaptive policies is a very important type of solution complexity to achieve robustness in an uncertain future. So, next steps in this research would be related realistic and adaptive policy design to decarbonize the power sector, while keeping costs acceptable.

6.2 Ex-post criticism

Sterman [63] stated that "… systems thinking requires understanding that all models are wrong and humility about the limitations of our knowledge". The reality can never be fully incorporated in simulation models, which is also true for the study presented here. Some aspects are intentionally or unintentionally left outside the scope of research. The aim of this research was to explore the plausible uncertainty space of future carbon emissions in the EU power sector. However, some humility is required here.

Possible improvements on modelling and policy design to decarbonize the EU power sector are:

- Extension of the amount of (promising) generation technologies (e.g. geothermal, concentrated solar power, small scale hydro, (decentralized) biogas, combined heat and power, etc.)
- More and particularly real world (adaptive) policy testing. This study included only 1 specific carbon policy (ETS system) and 2 RES-E support schemes (FIT and TGC), but there are many more potential effective policies. Next, only some directions for policy design are suggested (demand growth limitation, limiting overinvestments, etc.) but these lack a sense of real world policy implementation.
- Towards a holistic (carbon emissions in the total economy) and hybrid (agent based and system dynamics) modelling approach. Using a holistic modelling approach allows to explore the potential effects of shifting carbon emissions from one sector to another, for example by electrification. And a hybrid modelling approach would allow for including the aspects of bounded rational and discrete event decision making of agents with the continuous information flows that influence these decisions [64].

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