Future Prospects of the Dutch Energy Transition: Analysis of Agents’ Behavior through Energy System Modelling

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in Management of Technology

Faculty of Technology, Policy and Management

by

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To be defended in public on July 13\textsuperscript{th} 2018

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Executive summary

The present research takes place at the Environmental Assessment Agency, in the Department of Climate, Air and Energy. The core objective is to improve the investment module of a national energy system simulation model (Ensysi) that wants to represent actors’ technology-investments in the energy transition context.

An initial literature review has revealed the importance of the agents’ rational and non rational behavior in determining the future stock evolution, given the high level of uncertainty of some key variables such as future energy carriers prices and ETS prices. With regard to this, Ensysi presents the shortcoming that investment decisions are not forward looking but just consider the costs and revenues of the year in which the decision takes place. The model expansion performed in this research is therefore aimed at re-formulating the investment concept through a discounting calculation so that some exploratory scenarios in terms of actors’ behavior and expectations can be designed and analysed.

The literature review has covered firstly an overview of energy modeling techniques and categories in order to introduce Ensysi and categorize it within the existing energy modelling scenario. Secondly, the core object of the research was investigated: how investment decisions happen in reality for the actor group of consumers and companies. Since Ensysi is not yet provided with a solid theoretical formulation, the main theories for technology-investment decisions were reviewed in order to find the one appropriate for the theoretical underpinnings of Ensysi. Based on that a conceptual model was formulated, clarifying the nature of the relationships among different variables and providing a first guide for the subsequent research steps. The formulated conceptual model is based on Diffusion of Innovation theory from Rogers (2003) and some notions from environmental psychology.

After the literature review and theoretical validation, a careful analysis of the current module formulation has been done to reformulate a part of the investment simulation module. More specifically a new parameter connected to a net present value calculation was created to introduce in the model the actors’ perceived time dimension of money flows so as to include expectations about future costs.

The outputs from the new version were then compared to the ones from the original version to observe which new potentialities arise from the model expansion. Two case analysis for different energy subsystems (transport passenger cars for consumers and electricity generation for companies) were considered to draw research insights valuable for energy policy from the new potentiality of the model. The results of these simulations confirm the added value of defining actor scenarios based on different expectations and long term financial evaluations rather than highly uncertain behavioral parameters: more modelling transparency and validation possibilities, as well as richness of decision-making simulation scope.
Acknowledgements

Working at the Environmental Assessment Agency has been my first real job and I can honestly say that I could have not asked for a better environment and better colleagues. The project I have worked on for the last five months has been very intense, but this research challenge has made me conclude in a very satisfying way my studies. I want to first thank my supervisor, Laurens de Vries, for giving me this opportunity and for always supporting with enthusiasm this project since the very beginning. We had a lot of hours of discussion in the studio about the scope, methodology and objective of the research, that at the beginning have been very hard to define, but even without having ever looked at the model, he had always come up with some interesting research hints. Many thanks also to my supervisor at PBL, Robert Koelemeijer, for his kindness and patience, and for always welcoming me with a smile when I had to drop by to his room for help despite his very busy schedule. Same for the other intern student Manuel Sanchez, I could have not found a nicest and smartest colleague to share with my internship experience. Last but not least, I want to thank my second supervisor, Servaas Storm. I have attended all the possible courses where he was the teacher, so to have him in my thesis committee is really the icing on the cake.

This research work is dedicated to all the people that have supported me during these two years of master studies abroad. Time runs so fast that it seems like yesterday when I arrived to the Netherlands for the first time. If I look back at two years ago I can really see how much I have grown during this period and how being a student at TU Delft has enriched my personal life-background, even more than my academic knowledge. If I am the woman I am now, after this incredible experience, it is also because of all the amazing people that have shared with me this fundamental stage of my life, the new friends as well as all the ones that have always supported me.

In firs place I want to thank my family, in particular my mom, my father, my brother and my grandma. You are really the first and everlasting source of joy of my life, and you made me feel that every single day even if I was far from home. However, I have been that lucky that I could share this whole experience of studying abroad with a small piece of family, my cousin Raffaello. Eventually, we had to share this adventure for real, as we used to do when we were just playing as children. Thank you for always making me laugh of all my drama with your improvised singing live sessions and for accepting patiently my (sometimes a bit fluctuating) mood.

A special thank goes also to Barbara and André for being my “Dutch” family during my very first year abroad. Your kindness and support really helped a lot in the most difficult moments. Finally I want to thank the “mandatory crew”, you guys are the nicest group of people I have ever met and with you I have always felt like I was at home again.

Elisa Baldisseri - July 2018
Chapter 1

Introduction

The greatest threat to our planet is the belief that someone else will save it.

ROBERT SWAN

According to an alarming announcement stated by the International Energy Agency (2008) what has been done so far in terms of energy policy is not enough to accomplish the challenging mission of drastically reduce CO₂ levels in the atmosphere. An example of a compelling policy target that EU nations are currently committed to is the one commonly designated as 20-20-20: a 20% reduction of greenhouse gas emissions from 1990 levels, a 20% share of total energy consumption from renewable energy, and a 20% improvement in energy efficiency has to be achieved by 2020 (Ellerman et al., 2014). The 80% of the world’s energy supply still depends on fossil fuels (Wüstenhagen & Menichetti, 2012) but the existing power plant set has been deteriorating and will need to be replaced in 10-20 years to face future demand and energy security issues (International Energy Agency, 2006). Moreover, the fact that the economy’s level is growing, together with the world’s population, makes the climate change issue even more urgent, requiring to take action now.

A revolutionary change in the global energy mix consisting of a growing share of renewable energy and carbon dioxide removal technologies is then a necessary condition to mitigate the current environmental damage. To do this, policy and institutional interventions alone are not sufficient: the whole society has to commit to the energy technology revolution and both private and public actors play a fundamental role in this demanding process. Therefore, in order to understand which policy measures are effective to attract capital commitment it is essential to scrutinize what drives investors’ choice of new power generating plants and energy-consumers purchasing decisions (Masini & Menichetti, 2012). This is the core issue the present proposal wants to focus on, by providing a specific contribution on the future energy sector’s assessment of the Netherlands.

1.1 The need for energy system modelling

Given the importance of predicting potential energy system’s developments, the creation and implementation of simulation models has increased during the second half of the twentieth century. As argued by Hamming (2012), the main reason behind the spread of this kind of systems is the need for insights about development of scenarios to provide a background for long-term energy policy strategic decisions. Following the oil crisis of the seventies, the urgent need for scenario planning has led several institutions to the development of energy system models. The first pioneer of the “future-now-thinking” approach was the RAND Corporation in 1940 (Chermack et al., 2001),
realizing the importance of analysing a part of the economy that was getting more and more complex, in an attempt to figure out in advance its possible future evolution.

Moreover, as stated by (Pfenninger et al., 2014) energy models do not just lead to scenario development but also to the formalization of dispersed knowledge concerning the complicated and multiple interactions in the energy sector, as well as a “structured way of thinking about the implications of changes to parts of the system” (p. 75).

In fact, the complexity of the energy transition issue, having several dynamic elements that continuously interact with each other, has led to the diffusion of multi-criteria decision analysis approaches (Wang et al., 2009). If the final energy policy aim is sustainable development, intended as the equilibrium between the environment and economic and social activities (Hofman & Li, 2009), the traditional single criteria for energy investment choices, whose aim is to arrive at the most efficient technological portfolio at a moderate cost, can be no longer valid. Other determinant factors enter the debate, such as environmental and social criteria. As identified by Wang et al. (2009), environmental criteria mostly concern emissions of greenhouse gases, with a particular importance given to \( \text{CO}_2 \) because it leads to increasing global warming. However, other pollutant elements might be considered as well, for instance mono-nitrogen oxides (\( \text{NO} \) and \( \text{NO}_2 \)), that particularly contribute to local air pollution and can have a direct effect on the health of the surrounding community. Social criteria cover instead public acceptance and the consumer point of view on a certain energy project realization, based for example on the impact on social life or job creation.

Indeed the introduction of additional elements to be considered when evaluating an energy project from the sustainability point of view, has led to additional complexity and contrasting targets, interests and perspectives. The operationalization of such complex relations among different variables within the framework of an energy system simulation model can represent a strong analysis tool and decision support. As it will be explained in the following chapter, the aforementioned multi-criteria approach has been adopted by the energy model considered in this research. The next section introduces more in details the context of the research at stake as a part of the general challenge introduced here.

### 1.2 Research context

The project takes place at the Netherlands Environmental Assessment Agency (PBL). A research group in the Department of Climate, Air and Energy has recently developed a national model, Ensysi, which calculates in quantitative terms future developments of the Dutch energy system for the period 2010-2050 in time steps of one year. More specifically, the model calculates the evolution of energy demand and production for different sectors, greenhouse gas emissions and energy system costs.

The evolution of technological stock in Ensysi is determined by agents’ simulated decision-making. The peculiar approach taken by Ensysi for that is characterized by a set of motivation factor aspects that wants to cover both financial and non financial elements (such as climate concern of the actor and other technological characteristics). As introduced above, this reflects an important trend that has been recently experienced in energy policy decision-making: the need to extend the evaluation process with the integration of the social dimension and public perception of the technologies at stake (Ribeiro et al., 2011).

In fact, nowadays the main energy policy issues are dealing not only with the technical component, but also with the social aspect (Ottens et al., 2006). Together with the new tendency of the multi-criteria decision analysis mentioned above, this calls for an extension of the scope of traditional energy models so as to include agents’ subjective reactions to policy directives or technology market evolution. In other words, the model has to be comprehensive enough to be able to represent most of the elements of the socio-technical system it wants to represent (Chappin et al., 2012). However, this is a challenging step further as well, because of the intrinsic unpredictable and uncertain nature of social behavior.

The difficult task of modelling actors investment considerations within such a complex context represents one of the main challenges that the modelers of Ensysi had to face. As every model that wants to represent reality it has some
shortcomings and limitations. Given the broad scope covered by Ensysi and the several research possibilities it can provide, a more specific point of improvement and research approach needs to be chosen. A preliminary literature review has provided the research hints that enabled a more specific problem definition. Those are illustrated in the following section.

1.3 Problem statement

The National Energy Outlook (NEO) that has been recently published by PBL in collaboration with other research institutes defines 2017 as a “gap year” in terms of policy making because of the elections that have occurred in the Netherlands, the United Kingdom, France, and Germany (NEO, 2017). The Dutch energy policy debate has recently paid a special attention to the long-term directives needed for the energy transition, following the agreements of the Energy Agenda released in 2016.

As generally acknowledged by the literature concerning the power sector and data from real energy markets, the prices of energy carriers are characterized by a high level of volatility, and they are mostly determined by global development. According to the price predictions of the NEO and the International Energy Agency (IEA), the prices of coal, oil, gas and CO\textsubscript{2} registered in the markets have been lower in 2016 compared to 2015 and will stay on such a low trend until 2020. The long-term predictions are expecting a price increase but indeed there is a lot of uncertainty concerning such expectations.

The future developments of energy carriers prices is a matter of concern not only for policy makers in their establishment of long-term energy directives that can enable the energy transition but also for consumers and company investors, whose activity and welfare is largely dependent on energy costs and utilities. For instance, with the new passenger car offer including sustainable and innovative vehicles consumers are facing an additional factor that has to be taken into account in their purchasing decision: the relative advantage derived from a more energy efficient car (Morrow et al., 2010). In fact, if oil and fuel prices are expected to rise in the future compared to current levels it is likely that they will be more inclined towards the adoption of vehicles with higher efficiency and lower emissions. The same holds true for company investors who have to cope with the difficult trade-off between profitability and sustainability, a choice that is made even more burdensome by the surrounding policy uncertainty.

Such considerations, that have been found in the literature concerning the energy transition challenge, represent the research hints that have shaped the problem statement presented below. In fact, as Ensysi has been formulated, actors’ investment choices are based on elements that only refer to the current year (the one in which the actor’s choice occurs), i.e. current costs and benefits of the technologies. In reality this is not the case, given the fact that all the agents involved in technological investments have certain expectations about the future, and these expectations contribute to the overall decision-making process and trade-off.

Actually, the whole objective of current energy policies is to steer someway agents’ behavior (Franke, 2006). The kind of incentives enacted by policy institutes are indeed based on future expectations, just let us think about the CO\textsubscript{2} trading scheme aimed at increasing the adoption of cleaner technologies when the emission costs are predicted to grow. Considering that one of the main objectives of Ensysi is to explore long-term possible future scenarios depending on actor investment choices and policy instruments, in light of the considerations illustrated in this section it can be concluded that an energy system simulation model as Ensysi cannot give a complete perspective on the future system’s evolution and consequences of energy policies if it does not take into account future prospects and expectations of the agents involved. The following section takes this shortcoming as the triggering element of the research, and derives from that the research objective and research question(s).

1.4 Research objective and research question(s)

The previous three sections have gradually introduced some important elements of the considered research topic. Firstly, the arising complexity of the decision-making processes aimed at creating a balance between economic
growth and sustainability. The set of energy projects evaluation factors has been recently extended taking into account social and environmental criteria in addition to the traditional technical and economic criteria (Wang et al. 2009). The need for structured frameworks that enable to capture multiple interactions in the energy system as well as exploring possible scenarios has led to the formulation of energy models such as Ensysi. Among the determinant elements of agents’ behavior the literature has pointed out the key role of expectations concerning future energy carrier prices and emission costs. Consumers and company investors might choose different technologies for the deployment of their activities according to their perception of future price developments. As it will be better illustrated with the literature review, to face future uncertainty actors make use of several financial instruments (the one that here will be referred to as rational behavior), but they are also influenced by their own subjective perceptions like expectations about the future (irrational behavior). A simulation model aimed at exploring long-term energy system’s development would miss some important dynamics if the simulated actors’ investments evaluations are not forward looking and missing these elements. Such shortcoming has been chosen as point of improvement for the model, determining the research process.

The main research objective of the present research is then:

To contribute to a systematic and consistent understanding of how different (rational and irrational) actors’ behaviors can influence the future development of the Dutch energy system through the simulation of different actors’ scenarios.

Since Ensysi does not come with a strong theoretical formulation at the basis of its assumptions, a first research step, which is fundamental for the subsequent model analysis and implementation, is to identify the theories in literature that might reflect its behavior so that the model can be theoretically validated.

The research objective can be divided into three sub-objectives:

1. To provide Ensysi with the appropriate theoretical framework to check its theoretical validity;
2. To improve the current model formulation through a technical intervention to the code at the basis of the model;
3. To derive future scenario predictions according to different variables of interest (actors expectations).

The main research question of the present proposal, which is based on the results of Ensysi, and that needs to be answered in order to achieve the research objective is: how are future developments of the Dutch energy system influenced by rational and non-rational behavior of the actors involved in the energy transition? As already mentioned the behavioral component at stake for this research is the investment evaluation, with a particular focus on future energy prices trends expectations. Starting from the general context of the big challenge considered here, the following set of research sub-questions will guide the whole workflow by narrowing down the main broad problem to the specific variables of interest:

1. How are investment decisions made in the context of the energy transition according to scientific literature and to what extent Ensysi reflects that?
2. How can the model be improved in order to fulfil the research objective?
3. How are investments in the model influenced by differently simulated actors' financial evaluations?
4. How the inclusion of subjective elements, such as expectations about the future, influence investment decisions by actors?
5. What can be concluded from the analysis’ results in terms of how energy analysts should deal with simulation modelling and what implications can be derived for energy policy makers and technology managers?

A more detailed explanation of how these questions will be answered through the research process is provided in the following section.
1.5 Research methodology

This section presents an overview of the subsequent steps needed to achieve the research objective, following the path established by the research questions ordering.

**Answering the first research sub-question: How are investment decisions made in the context of the energy transition according to scientific literature and to what extent Ensysi reflects that?** A literature review has to be carried out to acquire the basic knowledge on the focal problem of the research. The following topics will be covered:

- the energy transition process and the current modeling approaches to simulate it;
- investments in the energy sector and in particular renewable energy investments;
- the role of financial and non-financial factors in energy investments;
- consumer adoption theories of renewable energy technologies.

To answer the research question, a theoretical framework will be developed in the form of a conceptual model based on the theories explored with the literature review that can best reflect the actors’ decision-making approach of Ensysi. Some simulations will be then carried out to check whether the model behaves accordingly. In such a way a first theoretical validation of the model will be done, providing an appropriate basis for the subsequent analysis.

**Answering the second research sub-question: How can the Ensysi model be improved in order to fulfil the research objective?** An analysis of the investment decision module of Ensysi will be performed to understand how investment decisions are simulated. As it will be subsequently explained, those are based on the values of five motivation factor aspects that result from some calculations based on input data of the model, such as technology characteristics and costs. The programming language of the model is Fortran95, so a prerequisite of such an analysis is the study of this type of coding.

Given the research objective, improvement potentialities of the model performance will be identified and discussed within the involved research group at PBL to determine which ones can be implemented by changing the current model assessment. A first shortcoming of the model that has been already pointed out is the fact that the actors are not forward-looking, meaning that the costs evaluated by them are based on energy and CO$_2$ prices of the year in which the investment decision is taken, which indeed is not the case in real life decision-making processes. Moreover, their cost evaluation is just restricted to the levelized cost associated with each technology. An additional motivation factor based on discounting of future money transaction can then be formulated to include the complete financial case over the whole economic lifetime of the technology. The starting point for that will be the literature concerning real investment behavior and the approach of other models in the energy context. The resulting concept will be operationalized and introduced to the coding of Ensysi.

**Answering the third research sub-question: How are investments in the model influenced by differently simulated actors’ financial evaluations?** Once the appropriate modifications to Ensysi (mentioned in the previous paragraph) will be applied and verified, some simulation runs will be performed to compare the expanded version of the model with the previous one. As a first step, different financial evaluation elements, as motivation factors, are considered for actors investment decisions. More specifically this can be done first by considering investment outcomes based on levelized cost calculations and secondly future discounting calculations, to see whether they give different results. The resulting outcomes will be validated from both a qualitative perspective (comparing them with another acknowledged energy system simulation model) and quantitative perspective (based on predictions from the NEO).
1.6. Relevance of the research

For methodological clarity reasons, only variations of those motivation factors (levelized cost and future discounting) will be considered since the overall process this research wants to initiate is to incorporate the actor behavior-related parameters into a single comprehensive element, such as the NPV, that can include different predictions of future cash inflows as well as risk perception components.

Answering the fourth research sub-question: How the inclusion of subjective elements, such as expectations about the future, influence investment decisions by actors? The analysis conducted to answer this question will be based on the design of some possible future scenarios through the variation of the key variables considered in this research: actors’ expectations about future energy carriers or CO₂ prices. These variables concerning expectations will be new to the model together with the additional motivation factor based on discounting calculation. The aim at this point of the research will be then to compare the new scenario possibilities with different settings of the previous motivation factor parameters as they have been originally formulated in Ensysi, to analyse the results obtained from the different scenarios and evaluate the new model potentialities resulting from the model expansion. Two case analyses will be selected according to the first general model results obtained, in order to provide key insights for both categories of company-investors and consumers.

To make the whole analysis and scenario developing process handier, some functions of a graphic user interface created with Matlab will be expanded and used. In particular, the function generated for this research purposes is to display on the screen of the interface the scenarios input files (in the form of data tables) and to give the user the possibility to change the parameters directly in this environment without singularly opening the input datasets.

Answering the fifth research sub-question: What can be concluded from the analysis’ results in terms of how energy analysts should deal with simulation modelling and what implications can be derived for energy policy makers and technology managers? The final part of the research is aimed at deriving conclusions from the previous step analysis that are not only relevant in terms of the model’s overall assessment, but also from a policy and managerial perspective. In fact, at this point of the research process the model represents a tool to make predictions on different energy system developments based on actors’ behavior and their response to different policy scenarios.

1.6 Relevance of the research

There is a large amount of literature concerning studies on the agents’ commitment, intentions and actions within the energy transition context and several models have been designed to analyse them. Ensysi represents a particular example here because it embraces the challenge of representing both rational and non-rational actors’ behavior. This is not an easy issue because the approximation of subjective factors cannot closely follows reality. However, the present research wants to take up the challenge offered by Ensysi as a research tool, exactly in virtue of some agent-specific investment evaluation elements, such as future expectations, that might offer more insights and modelling possibilities if implemented as an expansion of the current model formulation.

The first step for such investigation is to base the considered model on a sound theoretical framework. The current documentation regarding Ensysi is still missing the theory’s underpinnings and the literature review from which the assumptions of the model have been drawn. Therefore, the first relevance that the research presents to the Environmental Assessment Agency is to collect the theories concerning the investment behavior of the agents playing a role in Ensysi, and to check whether the model reflects that. It is in fact important to theoretically validate the set of formulations behind every model used for policy purposes. Once this basic theoretical phase has been conducted, the subsequent analyses that see the model as research tool have more explanatory power.

Through energy system models policy makers can make clear the energy goals they want to achieve and the way to do that (Pfenninger et al., 2014). A crucial point for every model that aims at simulating the long-term system

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1 These concepts will be better investigated with the literature review in Chapter 3
1.7. Structure of the thesis

Evolution is the investment module. Therefore, an improvement of the investment concept behind it and the eventually derived scenario analyses and predictions, are determinant research steps that can help policy agencies such as PBL to find the answer to this kind of compelling questions: which policy instruments should be implemented to encourage a low-carbon society? What are the decisive elements that can be steered by policies in order to influence the long-term development of the energy system?

The importance of introducing dynamic projections in a model that aims to simulate the evolution of the national energy system is valid not only for policy institutes such as PBL, but also to provide insights to technology managers. In fact, as stated by Pinkse and Kolk (2010), the role that business can, and should, play in the energy transition is one of the key issues in the climate debate. However, what makes the corporate contribution even more challenging is the fact that technological innovation arising from climate change is mostly still characterized by a certain level of novelty and immaturity. This can explain the cautious approach that has been presented so far by many corporations. Widespread market adoption of low carbon technologies will be successful only when companies will be able to bring them to the end-users as complete products with the related services, and to expand to mainstream international markets rather than local niche (Wellington et al., 2007). Moreover, corporations have to move away from the safe traditional technologies that have been already taking benefits from technological learning and economy of scale dynamics. Indeed all this challenges and tradeoffs are made differently according to the managerial mindsets, rational financial calculations, but also subjective perceptions. This is the case for future energy input and output prices, that are core elements of the present analysis.

For instance, the introduction of emissions allowances with the EU ETS and the resulting opportunity cost for CO$_2$ emissions has created new incentives for companies to commit to cleaner technologies and fuel substitution (Frontier Economics, 2006). Fundamental elements that steer these incentives are the expectations about future CO$_2$ cap and allowance prices. Higher costs of energy products due to emissions costs are in turn conveyed to end-users who then face the same risks deriving from future uncertainties. An accurate analysis of different actor-behavior scenarios is indeed relevant for technology managers as well, since it can point out the technologies that will be more successful according to the applied policy scheme.

Those kind of issues are taken on by the present research, with an analytical approach that uses as main research tool a national simulation model for the Netherlands. The overall relevance of the present research is then to provide a systematic and consistent understanding of how some key factors related to investment decisions can influence long-term energy system’s developments. In fact, considering the uncertain behavior of the agents within that system (for instance the government when it has to provide energy-related directives or companies when they have to choose among several technology options) it is important to consistently think about the relationships of the variables of interest and to identify some scenario possibilities derived from the relevant literature. This will be the overall main result deriving from an appropriate technical intervention to the model.

1.7 Structure of the thesis

To conclude this Chapter, the structure of this manuscript is illustrated. Two main parts can be identified: a theoretical one (Chapter 2 and 3) and a practical one (Chapter 4,5,6). Finally, the thesis concludes with the conclusions and recommendations chapter where the results of the work are analysed and some reflections are discussed. Following the order of Figure 1.1:

- Chapter 2 provides an overview of energy system modelling typologies and introduces Ensysi in such context characterizing its main features and model potentialities;
- Chapter 3 resumes the literature review and gives the theoretical validation of the model according to a fit-for purpose theoretical framework, answering the first research question;
- Chapter 4 describes the focal investment module object of the research and the code expansion, answering the second research question;
1.7. Structure of the thesis

- Chapter 5 compares outputs from the previous and the new versions, together with the model extension validation, answering the third research question;
- Chapter 6 presents two case analysis where different scenarios on the key parameters of interest were analysed, answering the fourth research question;
- Chapter 7 is dedicated to conclusions, recommendations and reflections, answering the fifth research question.

![Figure 1.1: Structure of the thesis](image-url)
Chapter 2

Modelling the Energy Transition

This chapter is dedicated to an overview of energy system modeling in order to insert Ensysi in the appropriate research context. It is articulated as follows. Firstly, some basic concepts characterizing the research context are provided, followed by an historical overview of how the energy transition has been modeled through the years. Afterwards, a detailed description of Ensysi and the main model parts of interest are explored. Finally, in order to contextualize Ensysi among the most recent applications, an overview of the current categories of energy system models is given as well as the main tackled challenges and methods to solve them.

2.1 Introduction to energy modeling

2.1.1 Definition of main concepts

As stated by Pinkse and Kolk (2010), the technological change needed in order to realize the transition towards a less carbon-intensive society involves not only companies’ actions but a change in the broader socio-technical system. The concept of sociotechnical system refers to the set of rules steering technological design as well as to the rules that shape market development, such as user preferences and rules for regulating these markets (Schot and Geels, 2007). In other words, it recognizes the role of a technology in performing a certain societal function, for instance energy supply, and the set of actors that can influence how that technology accomplish that role.

Given the fact that a change in the sociotechnical system is then the result of the interaction of different actors, i.e. companies, consumers and governments, focusing only on companies’ unilateral change is not enough for a complete analysis of the energy transition simulation. This means that a technology has to accommodate consumers preferences and policy makers have to adapt their rules in such a way that that technology adoption is favoured, for example by providing subsidies and tax breaks. The regulatory context experienced so far seems to present too many uncertainties for companies to undertake a radical innovation process towards the decarbonization pattern because of the constantly changing climate policies and the lack of a global approach to enact the Kyoto Protocol (Pinkse & Kolk, 2010).

Following the definition adopted by Chappin (2011) the transition of energy infrastructures from a socio-technical system perspective can be referred to as a fundamental change emerging from the interactions of the main actors “that act upon or make use of elements in the physical world which also change during transition” (p. 13). A large portion of the literature generally assume that the final aim of a transition is sustainability, and, more specifically, sustainability of energy supply and demand. This can only result from a behavioral change by energy producers and consumers, as well as a transformation of institutional directives and the physical elements of energy infrastructures, such as power plants, electricity grids and households appliances.
Moreover, it is not possible to achieve such a transition for the action of a single actor but, instead, there is a “distributed control” (p. 13) emerging from the interaction of several agents acting at the same time. The fact that the current energy infrastructures are mostly huge and complex makes the issue even more challenging.

2.1.2 Overview of main paradigms

As stated in the previous chapter the need for simulating such complex mechanisms has called for a large amount of effort of several institutions. This section, which is based on a review from Chappin (2011), provides an historical background of the main modelling paradigms that have been implemented to simulate the energy transition, together with their advantages and shortcomings.

Econometrics and scenario analysis

Econometric models are based on statistical fitting and correlation. They investigate the links between variables to identify what are the key elements that can be steered by climate policy. Scenario analysis has a similar aim but it involves the definition and exploration of what-if cases. Several potential future scenarios are then predicted with the condition of being internally consistent. Afterwards, the considered policy interventions are simulated within each scenario to evaluate their effects. Both qualitative and quantitative scenario techniques are possible.

For instance, a quantitative approach is shown by the Energy Transition Model (Quintel Intelligence, 2010) created by a Dutch energy consulting firm in collaboration with the Dutch government and several other companies. It covers a large range of energy demand sectors (households, transport infrastructures, industries etc.), types of primary energy carriers (electricity, gas, heat, fuels), costs evolution (carbon prices, market prices, production costs), and policy targets (renewable share, emission reduction etc.). Despite the extensive scope of the model the dynamics of how the outputs are generated and which mechanisms are activated by the implemented energy policy are not simulated. Another model from the scenario analysis category is the Roadmap 2050 (European Climate Foundation, 2010), resulting from the work of several companies, institutions, and academic institutes. It calculates what are the conditions to achieve certain emission reduction targets in Europe, but again without providing insights of how to realise these conditions in terms of investment choices.

The main problem of this kind of models is that they are missing the dynamics of the system’s structure that are indeed important for the analysis of the energy transition: a change in the structure of a system is reflected in the change of its underlying dynamics (Chappin, 2011). To accomplish that there is the need for a simulation model which simulates also how a system changes over time.

Computational General Equilibrium

Computational General Equilibrium models (CGE) are mostly implemented for public policy analysis to study macro-economic notions such as labour, market prices, and demand for goods (de Melo, 1988). Based on balancing linear macroeconomic relations, they usually refer to a technology-matrix or dataset providing the attributes of the technologies implemented to meet the demand (Leontief, 1998). In more recent times CGE models estimate policy results in different possible system developments characterized by variations in some key parameters. At every time step a certain set of macro-economics equations are balanced so that data from real economy enable to calibrate the initial equilibrium state of the model (Kehoe et al., 2005). To reach the balance between demand and supply, the prices of energy inputs and outputs are adjusted until an equilibrium is reached at every time step. However, the main limitation arising with these models is that being so focused on the economic equilibrium they lack the simulation of some important mechanisms that are changing over time and that can affect long term policy outcomes. In fact, there are some key factors, such as the technology figure and decision-making by actors that are assumed constant within CGE models even if in real life it is not the case. For instance, a technology is represented as mere production mean and the decision-making of actors is made at an aggregate level (Chappin, 2011).

In addition to that, this typology of models can hardly capture the dynamics of the systems they intend to simulate. This occurs because it is assumed that from one time step to another the economic parameters can find a stable
2.1. Introduction to energy modeling

equilibrium. Dealing with time-dependent paths of economic variables they are still regarded as dynamic, but what they actually do is to lurch from an equilibrium state to another, missing a continuous evolution (Mitra-Kahn, 2008). For this reason CGE models cannot represent the dependence between subsequent time steps, meaning that the overall approach of the model is static. However, the assumption that an equilibrium in the economy can actually occur is not without questionings.

Despite the mentioned drawbacks, CGE models are often used in the energy policy context to analyse the development of economic parameters. For instance, the classic example of such kind of model implementation is the study of the influence of subsidies on trade (Taylor & Black, 1974). Actually, CGE has been spread all over many institutions, including the International Energy Agency (IEA), the World Bank (LINKAGE model, Van der Mensbrugghe, 2005), and in the Dutch context the Netherlands Bureau for Economic Policy Analysis (CPB) and the Energy Research Center (ECN). For this reason CGE modelling can be defined as the de facto technique to support energy policy worldwide (Chappin, 2011). Moreover, as it is a quantitative simulation method, it has been particularly favoured by the advancement in technical computing experienced in the past few years.

An international example of CGE is the World Energy Model used by IEA to predict future energy trends based on a reference scenario which is defined as the global energy market evolution if the underlying trends in demand and supply are maintaining over time (IEA, 2008). A Dutch example of CGE model usage is instead provided by the Netherlands Bureau for Economic Policy Analysis (CPB). The main activity of this institution is to give recommendations on the effects that political planning has on some macro-economic parameters such as economic growth and job creation. Those predictions are calculated in their World Scan model that includes consumer goods markets, producer markets, capital markets, and the labour market.

Given the high number of variables and equations that are calculated within those models an industry-standard software (GAMS) is commercially available that enables to solve this kind of large algebraic problems (GAMS Software, 2010).

Agent-Based modelling (ABM)  The main focal point of the ABM concerns the individual agents and their interactions. This means that the “lowest practical level” is analysed so to look for the emergence of strategies due to the relationships with the environment and the other agents (SAM Corporate Sustainability Assessment, 2010). Scientists use these models as a “playground” to “explore emergent outcomes of the interaction of a set of autonomous agents (Chappin, 2011, p. 57).

Right after their first implementation ABM models were mostly used for simulations in the social science field (Kohler and Gunnerman, 2000; Gilbert et al., 2007). However, in more recent times they have been applied for modelling energy markets as well as other technology- and industry-related contexts (North, 2001; Guerci et al. 2005). A further step in ABM modelling is represented by Agent-Based Computational Economics (ACE) that consist of a subclass of ABM models with additional elements from the economic theory, being “the computational study of economic processes modelled as dynamic systems of interacting agents” (Tesfatsion, 2006, p. 3). The main European example of these is the EURACE project that has been designed to model on a large scale the policy environment of the European economy.

System dynamics and dynamic systems  System Dinamics (SD) models have been developed to analyse the long term behavior of a system state when its evolution criteria are known (Robinson, 1998). Applied to the industrial sector SD wants to simulate the effect of the organizational framework, policy directives and time delays of decisions and actions on the industrial activity itself (Forrester, 1958). Dynamic Systems (DS) modelling is a subclass of System Dynamics which is applied to physical systems.

At the basis of an SD model there is a set of differential equations representing the flowing process of different goods, such as materials, energy, money, people etc. Those flows want to represent events at an aggregate level, for example the adoption of a certain technology from a group of agents. This change of the state of system’s elements is modelled through a flow of agents/people (Sterman, 2000). The DS modelling technique instead does not allow to simulate that because they are continuous models of a physical system and, having only continuous variables, the
2.2. Main outline of the model

aggregation of more elements is not possible. In the policy context those SD models are implemented to understand how some evolutions of a social system can occur. Some of them are used to model and analyse electricity markets (Olsina et al., 2006).

**Discrete Event Simulation** Discrete Event Simulation (DES) modelling is based on a chronological sequence of events occurring in a fixed manner (Gordon, 1978). Those events determine variations of the state of the system and of the other elements within the system so that other events are triggered. The formal basis of DES is the discrete event system specification developed by Zeigler (1987) describing several discrete-event formalisms that can be implemented in DES models. This is based on definitions of how the system state can variate according to a set of inputs and the resulting outputs.

The typical DES configuration consists of entities that move from one block to the other within a flowchart where they can either stay in queues or be processed creating a continuous flow of de-queueing events. Every event is the consequence of another and those consequences are reported through the update of the overall state of the simulated system or by calling for further events (Jones, 1986).

2.2 Main outline of the model

This section illustrates the general composition and functioning of Ensysi. In particular the core inputs and outputs are mentioned, together with the main modules and parameters of interest for the research. Afterwards, the lists of energy subsystems and energy carriers included in the model are provided. Finally, given their relevance for the research analysis, the main investment decision types are described. All the information are based on the draft of the Ensysi manual which has not been published yet.

2.2.1 Overview

Ensysi is a national model which calculates in quantitative terms future developments of the Dutch energy system for the period 2010-2050 in time steps of one year. More specifically, the model calculates the evolution of energy demand and production for different sectors, greenhouse gas emissions and energy system costs. The main inputs of the model are the developments of economic sectors (such as the number of houses and offices, transport kilometers, economic development of industry), prices of primary energy carriers (coal, oil, natural gas, biomass) and energetic and cost parameters of more than 250 technologies (such as off-shore wind, electric cars, types of houses) that can evolve over the simulated time period. Each time step, the demand and supply of energy carriers is matched. For all carriers except electricity, annual total demand and supply is balanced.

Energy system developments are simulated based on investment decisions of actors, such as large or small companies, house owners, farmers, etc. In the model, those investment decisions depend on different aspects referred to as motivation factor aspects, as they describe the motivation of actors to choose for certain technologies above other technologies. Moreover, policy instruments like CO₂-pricing and emission caps, or setting standards can be inserted as inputs in the model and influence actors’ investment decisions.

The amount of investment for each technology (stock) is determined by the magnitude of a motivation factor, which is a number between [-1; 1]. If the motivation factor is zero or below, no investments are made unless it is necessary to do so to not run out of the corresponding stock. Each motivation factor for a technology is calculated through the weighted average of five components, motivation factor aspects (listed below). This means that to each component is assigned a weight ranging from 0 to 1.

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1Those inputs are mainly based on policy predictions, literature and data used for the Edesign1 model (run by PBL in collaboration with ECN).
2.2. Main outline of the model

- **social attitude**: accounts for the importance that an investor attributes to *climate change* and the attitude toward a technology, for instance in terms of *public resistance*.

- **targets**: accounts for the extent to which a technology contribute to meet targets for emission reduction, renewable energy and production and energy efficiency improvements;

- **costs**: refers to the full cost of a technology (capital cost, fuel cost, O&M costs, etc.) and/or the payback time of the investment;

- **complexity**: accounts for the perceived complexity to introduce the technology in current production processes and the perceived supply risk in depending on imported fuel;

- **investment barrier**: refers to the resistance in committing to a large upfront investment.

Actors in the model are divided into eight groups and within each group there are four categories: as showed in Table 1 and 2 actors groups differ in terms of value-added tax and discount rate, whereas actor-types (following the traditional *Diffusion of Innovation Theory* (subsection 3.1.3) differ in terms of the weights given to the motivation factor aspects.

<table>
<thead>
<tr>
<th>Actor</th>
<th>Value added tax</th>
<th>Discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>National</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>Consumer</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td>Housing Association</td>
<td>0</td>
<td>0.06</td>
</tr>
<tr>
<td>Farmer</td>
<td>0</td>
<td>0.06</td>
</tr>
<tr>
<td>Government</td>
<td>0</td>
<td>0.06</td>
</tr>
<tr>
<td>Company (small)</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>Company (medium)</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>Company (large)</td>
<td>0</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 2.1: Actor-groups in Ensysi

<table>
<thead>
<tr>
<th>Actor type</th>
<th>Relative size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovators</td>
<td>0.05</td>
</tr>
<tr>
<td>Early Adopters</td>
<td>0.15</td>
</tr>
<tr>
<td>Majority</td>
<td>0.55</td>
</tr>
<tr>
<td>Laggards</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2.2: Actor-types in Ensysi

Table 2.3 shows the parameters determining the motivation factor aspects not related to technological cost and investment. The range of variation has been already established by the default design of Ensysi. The ranges of the weights for the motivation factor aspects are instead all: [0,1]. Apart from *SocAttClimateConcern* these parameters are specified in the *Technology Characteristics* input file of the model.

The model code is written in Fortran95 programming language, and has a modular structure. Input and output files are ASCII text files. The input text files have been generated in Excel, such that the input data can be documented in detail within these Excel-files. A Graphic User Interface has been also developed in Matlab to create and visualize scenarios from Ensysi and it can be enlarged according to the research needs. One simulation run, spanning the 2010-2050 period, takes a few minutes on a laptop PC.

\(^2\)The sum of the weights given to *climate concern* and *public resistance* has to be equal to 1.
Table 2.3: Non-financial motivation factors and parameters

<table>
<thead>
<tr>
<th>Motivation factor</th>
<th>Parameters</th>
<th>Description</th>
<th>Range of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Social Attitude</strong></td>
<td><code>SocAttClimateConcern</code></td>
<td>Level of climate-change concern</td>
<td>[1,3]</td>
</tr>
<tr>
<td></td>
<td><code>iPubRes</code></td>
<td>Public resistance against a technology (the more negative the value the higher is the resistance)</td>
<td>[-3,1]</td>
</tr>
<tr>
<td></td>
<td><code>iMitPot</code></td>
<td>Perceived mitigation potential</td>
<td>[0,10]</td>
</tr>
<tr>
<td><strong>Targets</strong></td>
<td><code>iCO2poor</code></td>
<td>Contribution to decarbonisation</td>
<td>[-1,1]</td>
</tr>
<tr>
<td></td>
<td><code>iEnEff</code></td>
<td>Contribution to energy efficiency improvements</td>
<td>[-1;1]</td>
</tr>
<tr>
<td></td>
<td><code>iRenew</code></td>
<td>Level of renewable energy production</td>
<td>[0, 10]</td>
</tr>
<tr>
<td><strong>Complexity</strong></td>
<td><code>iComple</code></td>
<td>Perceived complexity of introducing the technology</td>
<td>[-3, 0]</td>
</tr>
<tr>
<td></td>
<td><code>iResSupplyRisk</code></td>
<td>Dependency of the technology on import fuels with supply risks</td>
<td>[-3, 0]</td>
</tr>
</tbody>
</table>
2.2. Main outline of the model

2.2.2 Technologies and subsystems

The environment of the model represents the national energy system and it is divided into energy subsystems, provided in Table 2.4. Within each subsystem there are a number of technologies that are substitutes and compete for actors’ investment choices. These technologies are characterized by energy inputs and outputs, all the associated costs, the technology potential (which is the maximum possible increase of the stock of a technology in a year), technical and economic lifetime, the stock in the base year, and the age-distribution of the stock in the base year. Technological learning as well as the potential of a technology mostly follows an s-curve shape. Additional parameters describing possible energy efficiency improvements and cost developments can be specified based on technological learning curves.

Table 2.4 distinguishes among end-use subsystems, whose development is steered by the final demand of energy users, energy-conversion subsystems, where one form of energy is converted into another, and infrastructure subsystems, characterized by the demand of utilities dedicated to energy transport and management. The last two sub-systems types are steered by the demand for an energy carrier. The number of technologies competing in each subsystem is also indicated. For output layout purposes, subsystems can also be aggregated into sectors.

The nomenclature indicated in the table is roughly based on the one used by Eurostat and PRIMES (E3M-lab, n.d.).

According to the general definition an energy carrier can be defined as a substance containing energy that can be converted into other forms and used in physical or chemical processes.
### 2.2. Main outline of the model

<table>
<thead>
<tr>
<th>Sector</th>
<th>Subsystem</th>
<th>Description</th>
<th>Type</th>
<th>nTechs</th>
</tr>
</thead>
<tbody>
<tr>
<td>WasteHandling</td>
<td>WasteIncineration</td>
<td>waste combustion</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>WasteSewage</td>
<td>waste combustion</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>WasteLandfill</td>
<td>waste combustion</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td>TransportRoad</td>
<td>TranRoadCAR</td>
<td>energy demand from passenger cars</td>
<td>end-use</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>TranRoadLDV</td>
<td>energy demand light duty vehicles</td>
<td>end-use</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>TranRoadHDV</td>
<td>energy demand heavy duty vehicles</td>
<td>end-use</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>TranRoadOther</td>
<td>energy demand other road transport</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td>TransportMM</td>
<td>TranMobMachinery</td>
<td>energy demand mobile machinery</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>TranDefence</td>
<td>energy demand defense</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td>TransportRail</td>
<td>TranRail</td>
<td>energy demand rail</td>
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<td>energy demand airplanes (LTO)</td>
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<td>end-use</td>
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<td>ResidHeatDwellings</td>
<td>heat demand dwellings</td>
<td>end-use</td>
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<td>ResidHeatFlats</td>
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<td>ResidElec</td>
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<td>ProdHeatLT_OS_WI</td>
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<tr>
<td>Services</td>
<td>ServicesHeatCdr</td>
<td>heat demand car dealers and repairation</td>
<td>end-use</td>
<td>5</td>
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<tr>
<td></td>
<td>ServicesHeatEducation</td>
<td>heat demand education</td>
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</tr>
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<td></td>
<td>ServicesHeatHospitality</td>
<td>heat demand hospitality</td>
<td>end-use</td>
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</tr>
<tr>
<td></td>
<td>ServicesHeatNch</td>
<td>heat demand nursery and health care</td>
<td>end-use</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>ServicesHeatOffices</td>
<td>heat demand offices</td>
<td>end-use</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>ServicesHeatOther</td>
<td>heat demand other services</td>
<td>end-use</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>ServicesHeatStores</td>
<td>heat demand stores</td>
<td>end-use</td>
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<td></td>
<td>ServicesHeatWholesale</td>
<td>heat demand wholesale</td>
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<td>5</td>
</tr>
<tr>
<td></td>
<td>ServicesElec</td>
<td>regular electricity demand services</td>
<td>end-use</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>ProdHeatLTServices</td>
<td>production of heat for service-sector</td>
<td>energy conversion</td>
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<td>Agriculture</td>
<td>DemandHeatAgriHo</td>
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<td>end-use</td>
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</tr>
<tr>
<td></td>
<td>DemandHeatAgriOther</td>
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<td>end-use</td>
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</tr>
<tr>
<td></td>
<td>AgriElec</td>
<td>regular electricity demand agriculture</td>
<td>end-use</td>
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</tr>
<tr>
<td></td>
<td>ProdHeatAgriHo</td>
<td>heat production horticulture</td>
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<td></td>
<td>ProdHeatAgriOther</td>
<td>heat production other agriculture</td>
<td>energy conversion</td>
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<td>IndAmmonia</td>
<td>energy demand ammonia production</td>
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<td>ChemHVC</td>
<td>IndHVC</td>
<td>energy demand plastics production</td>
<td>end-use</td>
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</tr>
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<td>IndOtherChemETS</td>
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<td>NonFerro</td>
<td>IndNonFerro</td>
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<td>end-use</td>
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<td>energy demand iron and steel production</td>
<td>end-use</td>
<td>8</td>
</tr>
<tr>
<td>OthIndustry</td>
<td>IndOtherETS</td>
<td>energy demand other industry (ETS)</td>
<td>end-use</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>IndOtherNonETS</td>
<td>energy demand other industry (non-ETS)</td>
<td>end-use</td>
<td>3</td>
</tr>
<tr>
<td>ImExEn</td>
<td>ImExEn</td>
<td>import and export of energy</td>
<td>end-use</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.4: Energy sectors and subsystems in Ensysi (I)
### 2.2. Main outline of the model

<table>
<thead>
<tr>
<th>Sector</th>
<th>Subsystem</th>
<th>Description</th>
<th>Type</th>
<th>nTechs</th>
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</thead>
<tbody>
<tr>
<td>Losses</td>
<td>Losses</td>
<td>energy losses</td>
<td>end-use</td>
<td>1</td>
</tr>
<tr>
<td>ProdHeatInd</td>
<td>ProdHeatSHTInd</td>
<td>production super high temperature heat industry</td>
<td>energy conversion</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>ProdHeatHTInd</td>
<td>production high temperature heat industry</td>
<td>energy conversion</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>ProdHeatLTInd</td>
<td>production low temperature heat industry</td>
<td>energy conversion</td>
<td>5</td>
</tr>
<tr>
<td>ProdElec</td>
<td>ProdElec</td>
<td>production electricity</td>
<td>energy conversion</td>
<td>25</td>
</tr>
<tr>
<td>ProdTranFuel</td>
<td>ProdTranBiofuel</td>
<td>production biofuel</td>
<td>energy conversion</td>
<td>10</td>
</tr>
<tr>
<td>ProdTranFosfuel</td>
<td>ProdTranFosfuel</td>
<td>production fossil transport fuel</td>
<td>energy conversion</td>
<td>8</td>
</tr>
<tr>
<td>ProdFinGas</td>
<td>ProdFinGas</td>
<td>production methane</td>
<td>energy conversion</td>
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<tr>
<td>ProdHydrogen</td>
<td>ProdHydrogen</td>
<td>production hydrogen</td>
<td>energy conversion</td>
<td>6</td>
</tr>
<tr>
<td>ProdFinSolBio</td>
<td>ProdFinSolBio</td>
<td>mixing solid biomass streams</td>
<td>energy conversion</td>
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<tr>
<td>Infra</td>
<td>InfraElecOnshore</td>
<td>onshore electricity transmission</td>
<td>energy conversion</td>
<td>1</td>
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<tr>
<td></td>
<td>InfraElecOffshore</td>
<td>offshore electricity transmission</td>
<td>infrastructure</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>InfraEVCharging</td>
<td>infrastructure for charging EV-cars</td>
<td>infrastructure</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>InfraFinGas</td>
<td>gas infrastructure</td>
<td>infrastructure</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>InfraLTHeat</td>
<td>heat networks</td>
<td>infrastructure</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>InfraHydrogen</td>
<td>hydrogen infrastructure</td>
<td>infrastructure</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.5: Energy sectors and subsystems in Ensysi (II)

The activity level of end-use subsystems determines the demand for final energy, i.e. the final energy carriers that have to be produced by energy conversion subsystems. Also some end-use subsystems produce final energy carriers as a by-product, so that this is subtracted from the demand that must be produced by energy-conversion subsystems. The same holds for imported energy carriers (defined in the import/export scenario of the model), whereas exported energy carriers determine an additional amount of final energy that has to be produced by energy conversion subsystems.

The balancing demand and production of final energy carriers is described by a set of coupled equations. For instance, the demand for industrial heat generates demand for gas and electricity inputs, and the demand for electricity in turn generates additional demand for gas. Therefore, those equations are solved in an iterative way in each time step taking as a first value the one coming from the previous year or a first-guess value. On average, five or six iterations are needed for energy demand and production to converge within a time-step for all energy carriers with an accuracy of 1PJ. Within this cycle also the price of final energy carriers is determined as the weighted average of the levelized energy production costs of the individual technologies producing them. For all energy carriers demand and supply are balanced yearly, whereas for electricity this happens at an hourly time-step so that the effects of intermittent renewable generation, demand-side response, and electricity storage can be taken into account for the development of energy system costs and emission.

The demand for electricity that has to be provided by dispatchable generation is found by subtracting intermittent generation from wind and solar. This demand is then matched according to the merit-order of generation capacity resulting from the variable costs of electricity production. The variable cost of the marginal production option necessary to match the demand determines the price of electricity in the hour concerned. The annual average electricity price is then found through the average of the price per hour weighted by the electricity demand in that same hour.

---

4 A dispatchable power source can be turned on or off according to the demand.
2.2. Main outline of the model

2.2.3 Energy carriers

The energy carriers in Ensysi are provided in Table 2.6. They are distinguished in primary and final energy carriers: primary energy carriers are available directly, whereas final energy carriers all have a subsystem with different technologies producing them. The table also specifies whether the energy carrier is an energetic input that has to be combusted or used during the industrial process, or a process input used as feedstock for some plants and manufacturing processes. An emission factor is specified in the file of technological characteristics when the energy carrier is combusted during the technological process to calculate greenhouse gas emissions.

---

5 A feedstock can be referred to as a biological material that can be employed directly as a fuel, or converted to another form of fuel or energy product (Energy.gov offices, n.d.).
### 2.2. Main outline of the model

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Carrier type</th>
<th>Energetic</th>
<th>Process</th>
<th>Primary/Final</th>
</tr>
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<tbody>
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<td>Anthracite</td>
<td>Anthracite</td>
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<td>●</td>
<td>P</td>
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<tr>
<td>Uranium</td>
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<td></td>
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<tr>
<td>Waste</td>
<td>Waste</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Crop wood</td>
<td>Solid Biomass</td>
<td>●</td>
<td>●</td>
<td>P</td>
</tr>
<tr>
<td>Waste wood from forestry</td>
<td>Solid Biomass</td>
<td>●</td>
<td>●</td>
<td>P</td>
</tr>
<tr>
<td>Waste wood from industry</td>
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<td>●</td>
<td>●</td>
<td>P</td>
</tr>
<tr>
<td>Sugars</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Starch</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Grasscrops</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Other dry organic material</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Manure</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Other wet organic material</td>
<td>Solid Biomass</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Final solid biomass</td>
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<td></td>
<td>F</td>
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<tr>
<td>Crude oil</td>
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<td></td>
<td>P</td>
</tr>
<tr>
<td>Vegetable oil</td>
<td>Oil</td>
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<td></td>
<td>P</td>
</tr>
<tr>
<td>Waste oil</td>
<td>Oil</td>
<td>●</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Residual light oil products</td>
<td>Oil</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
<tr>
<td>Road transport fuel</td>
<td>Oil</td>
<td>●</td>
<td></td>
<td>F</td>
</tr>
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<td>Jet kerosine</td>
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<td>Heavy oil for shipping</td>
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<td>Residual heavy oil products</td>
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<td>F</td>
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<td>Final gas</td>
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<td>F</td>
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<td>P</td>
</tr>
<tr>
<td>Other extracted heat</td>
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<td>●</td>
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<td>Heat</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
<tr>
<td>Heat HT for industry</td>
<td>Heat</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
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<td>Heat LT for industry</td>
<td>Heat</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
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<td>Heat LT for OS with infra</td>
<td>Heat</td>
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<td>Heat air cooling</td>
<td>Heat</td>
<td>●</td>
<td></td>
<td>F</td>
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<td>Electricity</td>
<td>Electricity</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
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<td>Road transport fosfuel</td>
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<td>●</td>
<td>●</td>
<td>F</td>
</tr>
<tr>
<td>Road transport biofuel</td>
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<td>●</td>
<td>F</td>
</tr>
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<td>Heat production orticulture</td>
<td>Heat</td>
<td>●</td>
<td>●</td>
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<td>Heat production other agriculture</td>
<td>Heat</td>
<td>●</td>
<td>●</td>
<td>F</td>
</tr>
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</table>

Table 2.6: Energy carriers in Ensysi

The data given as input to the model concern primary energy carriers; for the final energy carriers produced by energy conversion subsystems according to the demand of end-use activities the input data are used only as a first guess value to start the iteration cycle that balances energy demand and supply.
2.2.4 Investment types in Ensysi

The stock of all the technologies present in Ensysi, i.e. the number of cars, houses, industrial installations, infrastructure etc., is initialized for the base year and updated for each following time-step. It has also an age distribution so that the part of the stock that exceeds the technical lifetime of a technology is scrapped at the end of each time step, while the other part is increased in age by one year. New stock is added in time through the following investment actions simulated in the model.

- **Development space investments**: if the demand for an activity exceeds the activity level provided by the actual stock of technologies within that subsystem, investments are triggered for that subsystem. The same happens when activity growth (specified in the scenario-input) occurs. Examples of this type of investments are replacement of end-of-life technologies or investments due to a transport volume growth.

- **Technology transfer investments**: they are retrofit investments consisting in the outfit of a system with newly developed or previously unavailable parts or equipment. The stock of one technology increases while the stock of another technology decreases at the same rate. Examples are the expansion of a power plant with a CCS-unit or with energy efficiency measures. Payback time is a key criteria for this kind of investments.

- **Unforced investments**: they occur when technologies grow in stock independently of the demand for activities. One example is households’ installations of solar-PV panels. Again payback time evaluations are important for this investments choices.

- **Forced investments for point sources**: point sources are fixed facilities from which pollutants are discharged. Those investments concern both investment and scrapping and they can be specified in the scenario-input. Examples are the close-down of a fire plant or construction of an offshore wind farm.

- **Subsidy driven investments**: an annual subsidy can be specified for renewable energy technologies so that the additional cost compared to the fossil fuel counterpart is subsidized. In the model it is assumed that this happens every year so that investments in RES are triggered also when the activity demand is already covered by the available stock.

- **Infrastructure investments**: they do not depend on agents’ investment choices but on the annual average demand of the concerned energy carrier.

- **Premature scrapping**: it consists mainly in disinvestments, occurring for instance when the load hours are lower than a certain percentage of the maximum load hours level or when a technology has a high variable cost compared to the other technologies in the same subsystem.

With regard to the motivation factor aspect *costs* in the case of unforced investments and technology transfer investments the score is based on the payback time of the investment. On the other hand, for development space or other investments the relative increase of the cost of a technology with respect to the cheapest technology within the subsystem determines the *costs* score.

2.3 Contextualization of Ensysi among energy models

To compare Ensysi with other approaches so that its main strong points and challenges are identified, there is the need to collocate the model in the current energy modeling scenario. For this purpose the classification of Pfenninger et al. (2014) is adopted, leading to the following list of main classes of energy models:

1. **Energy system optimization models**: based on optimization techniques applied to the whole energy system, they are mainly used to draw scenarios of system’s evolutions;
2.3. Contextualization of Ensysi among energy models

2. **Energy system simulation models**: they cover the whole energy system as well, and are aimed at determining forecasts of the system’s evolution;

3. **Power system and electricity market models**: they are models restricted to the electricity system, and they can be of both types optimization/scenario and simulation/prediction;

4. **Qualitative and mixed-methods scenarios**: they are mostly based on qualitative and mixed methods rather than exhaustive mathematical models.

Ensysi is an energy simulation model and therefore it belongs to the second class specified above. The following subsection is then dedicated to an overview of the current paradigms and challenges that characterize specifically energy system simulation models in order to provide the appropriate research background and steer the current analysis towards the most urgent issues that have been experienced so far by this class of models.

### 2.3.1 Energy system simulation models

Generally designed to cover the national or regional energy system, this group of models wants to predict possible developments of the system through its simulations. They can be built in a modular way with several submodules, rather than being based on strict optimization formulas. The most important examples currently implemented for energy policy are NEMS, which stands for U.S. Energy Information Administration’s National Energy Modeling System, and PRIMES (a similar model covering the EU). The former is run by the U.S. for the preparation of the Annual Energy Outlook and includes several submodules that make the system quite flexible (Gabriel et al., 2001). It provides a background for U.S. policy decision making. Used by the European commission to back policy choices, the PRIMES model covers the whole Europe and is made of different integrating modules representing independent agents. The main task of the module is to find the equilibrium solution between energy demand, supply, cross-border trade, and emissions from the European countries (EI3Mlab, 2008). Another example is the Long-range Energy Alternatives Planning System created by the Stockholm Environment Institute and implemented both in public and private sectors (SEI, 2012). Its main function is to deliver a year-based accounting system of the energy supply.

The main challenge that those models have to face is uncertainty. According to the differentiation of Der Kiureghian et al. (2009) there are two types of uncertainty in modelling. Firstly epistemic uncertainty, when the uncertainty can be reduced through more or better data; secondly aleatory uncertainty where uncertainty cannot be further reduced. Whether a model belongs to one category or another is a modeler’s choice. Contrarily to epistemic uncertainty there are some formal methods that a modeler can implement to cope with aleatory uncertainty. Those are deterministic and stochastic methods (Pfenninger et al., 2014). The first one seems to reflect the same approach that can be applied to Ensysi: being a deterministic model, because all the variables are deterministic, an uncertainty analysis can be conducted through the variation of the input to check the effects on the output, which is basically the Monte Carlo approach. Otherwise the uncertain variables could be already incorporated into the model by defining variables distribution functions instead of just inserting deterministic values. An example of such a stochastic approach is given by the MESSAGE model (Messner et al., 1996) which includes nonlinear risk functions.

As pointed out by Ravetz (1999), the fact that the final purpose of energy system models is not to represent an observable physical phenomena but to map out a potential storyline, makes those models neither certain nor value-free. In other words, the circumstances that an energy model wants to represent cannot be entirely monitored and measured. For this reason they cannot be fully validated and thus taken as a structural truth. The assumptions underlying the default parameter setting need then to be transparent especially when the uncertainty at stake is so high. In fact, the uncertainty issue can be easily linked to the one of intransparency, because of the hypothesized underpinnings that an energy modeler is likely to apply to her specific modelling approach. Representing methodologies to scrutinize the outcomes of assumptions made by the modelers (for example in terms of technology costs and performance, economic development, and energy policies), energy system models have been criticised when applied to policy decisions in some European countries and beyond (Helm et al., 2003).
However, the fact that Ensysi wants to cover also human behavior mainly in terms of risk perceptions and social attitude towards climate change issues and technologies, can lead to a classification in between simulation models and qualitative and mixed-methods scenarios (Chermack et al., 2001). A prominent example of a combination of quantitative and qualitative judgements is provided by Pacala and Socolow (2004) in their calculations about potential technological pathways for emissions reduction.

As illustrated by Pfenninger et al. (2014), to capture the human dimension is one of the main challenges of energy system models. In fact, even if a big portion of methodologies relies on technical and economic aspects what actually steer technology deployment is “political will, public acceptance, behavior and the difficulty of changing it” (p. 79). The difficulty of representing these elements and integrating them into a model has led to the tendency of focusing mostly on technological and economic factors. With regard to this, Ensysi has a great potential because it tries to capture human behavior and non-financial barriers to technology adoption as well. However, this can be seen both as a strong and weak point, given the fact that the social aspect are characterized by high uncertainty and they are not continuous in time and across variations of conditions not specified in the model.

Within this context it is worth mentioning that top-down approaches, i.e. the ones that consider first energy supply and regard energy demand users as sinks, have been challenged by more recent bottom-up approaches. The latter is in fact based on the appraisal of individual behavior and the resulting energy demand, which in turn can be used to extrapolate energy supply (Swan & Ugursal, 2009). To take actions on people’s behavior is then a new strategic element for climate change mitigation that does not imply the limitation imposed by technological evolution (Kramer & Haigh, 2009). Yet it seems quite difficult to capture definite energy behavior elements and integrate the diverse approaches implemented so far to analyse them into a single energy model (Pfenninger et al., 2014).

For instance, several empirical and quantitative work have been done to assess acceptance and rejection of renewable energy technologies such as wind farms (Firestone et al., 2012) (Wolsink, 2007). Nevertheless, there is still the need for a comprehensive and integrated methodology to translate those empirical researches into energy system modelling. Examples of how such challenges have been tackled are the Foresight SEMBE (Sustainable Energy Management and the Built Environment), where economic and technological factors are explored together with political and social aspects within the built environment sector (Rydin et al., 2008), and the socio-technical transition framework developed by Geels (2002) to explore energy transition routes for the UK electricity sector.

Conclusions

Based on the literature review conducted in this chapter we can conclude that Ensysi presents a quite innovative approach that has the potential to provide a comprehensive overview on the dynamics and functioning of the socio-technical system it wants to represent. The fact that it includes some actor-related subjective variables, such as perceived technological risk, it is indeed something that makes Ensysi stand out from the other computational and mostly optimization-based models. However, such a potentiality is also one of the main challenges presented by the model because as mentioned in the last section to integrate subjective elements with other technical components leads to uncertainty and validation issues.

The intrinsic uncertain nature of the variables mentioned above points out the importance of focusing the research analysis mostly on their application within Ensysi. Moreover, recalling the transparency issue mentioned above, assessing the impact of such parameters choices on the model final outcome is important to make the model’s assumptions as transparent as possible. Again, the practical relevance of the study is then to identify potential relationships between those elements and the whole energy system evolution in order to provide a scenario analysis for policy makers and technology managers.
Chapter 3

Theoretical Framework

The previous chapter has illustrated the various types of existing energy system models to contextualize Ensysi and compare it with other available tools. The following part aims now at exploring the mechanisms Ensysi wants to simulate in terms of agents’ investment behavior. To fulfill this purpose a literature review has to be conducted covering investment decision-making of both the main actors categories considered in the research: consumers and companies. The research question this part of the work is intended to answer is then: How are investment decisions made in the context of the energy transition according to scientific literature and to what extent Ensysi reflects that?

To answer the second part of the question there is the need to make a verification of the model or, as it will be called here, a theoretical check of the model. In fact, a model is built on a set of assumptions made by the involved modelers (Pfenninger et al., 2014) and since Ensysi has not yet an appropriate documentation specifying the theory used in terms of actors’ decision making, the main purpose here is to remedy this shortcoming by constructing a theoretical framework that can reflect the model behavior. This will be done by identifying among the whole bunch of theories collected during the literature review the one that seems to better reflect the approach of Ensysi. A conceptual model will then be constructed based on that theory. Afterwards, the model will be tested to check whether its behavior reflects the one expected from the conceptual model and thus the theory behind it.

The chapter is structured as follows: first a review on theories and empirical finding concerning how both consumers and companies make investment decisions in the concerned technologies is provided. Afterwards, the chosen theoretical framework is described, as well as the steps taken to conduct the theoretical model validation.

3.1 The energy transition from a consumer perspective

3.1.1 Introduction to the literature review

Among the main actors involved in the energy transition, consumers play indeed a key role for the diffusion of renewable energy technologies (Elmustapha et al., 2018). There is a huge body of scientific literature analysing both from a theoretical and empirical perspective the mechanisms underpinning consumers’ purchasing decisions and investments in technologies belonging to the energy sector. Given the massive amount of available information it has been necessary to make a choice based on the specific approach assumed by Ensysi.

In particular, the review wants to look at the one of transport and residential heating because those are the major subsystems in Ensysi where consumers are the main actors. To make the research approach more specific the choice of the literature sources has been then tailored to these two purchasing context. Before explaining that more in detail it is worth mentioning an important classification regarding consumers’ buying decisions, i.e. the distinction into high involvement and low involvement.
3.1. The energy transition from a consumer perspective

The concept of level of involvement refers to the perceived importance or interest of the individual in buying a product and the amount of information needed to make the decision (Open Textbook Library, 2015). The high involvement ones imply high price tags, product complexity and an overall higher risk for the consumer if they eventually fail. Some examples are cars, houses and policy insurances. The purchase of these products does not occur much often but they are important items for the buyers.

According to Lambert-Pandraud et al. (2005), not only the purchasing of cars has a high environmental impact, but also it can be considered as one of the most involvement-intensive buying choice from a consumer. On the other hand, households purchasing behavior in the residential sector is directly linked to their energy-related behavior. Following the definition of Frederiks et al. (2015), energy-related behavior refers to curtailment behavior (daily actions to reduce energy-consumption, such as limiting heating/cooling usage, switching off lights, etc.) and efficiency behavior (actions to save energy, including among the others investing in sustainable technologies and energy efficiency home-improvements). According to the distinction made before curtailment behavior can be mostly classified as low involvement kind of initiatives, whereas efficiency behavior can also include actions with a high level of involvement.

A first analysis of the literature review has revealed that for low involvement purchasing decisions a wide range of cognitive and rational theories have been developed. However, as will be better explained below, those approaches does not seem sufficient for a complete explanation of high involvement buying actions. Therefore, the following literature review, which provides the basis of the choice of the theoretical framework to be applied to Ensysi, will cover both. Starting with the classic two categories of rational and normative theories, other more comprehensive explanatory models, in particular the one of innovation diffusion theory, will be mentioned to overcome the limitations that the former still present. In such a way, a good theoretical basis can be provided also for higher level of involvement purchasing decisions. In fact, those are the ones Ensysi wants mainly to focus on, being an energy transition model. The final aim is then to build an integrated research framework to be applied to Ensysi. This will be explained below together with the main theories from which it has been drawn.

The main branches of theory from which the following cited studies have been taken are the ones of rational and normative theories, pro-environmental psychology, and innovation adoption theory. In particular the last two, taking a step further from the traditional rational models of decision-making based on information, regulation and economics (Caird et al., 2008), have as a common idea the fact that consumers choices are far from the precise financial calculations made by corporation members, and other less rational elements are rather playing a key role. This already can give a hint for the choice of the theoretical framework to be given to Ensysi that indeed gives a special room to such subjective factors.

3.1.2 Theories overview

A big portion of the literature concerning environmental attitude has formulated several cognitive and normative behavioral models trying to explain the determinants of pro-environmental behavior among consumers. This refers to the “behavior that consciously seeks to minimize the negative impact of one’s actions on the natural and built world (e.g. minimize resource and energy consumption, use of non-toxic substances, reduce waste production)” (Kollmuss & Agyeman, 2002, p. 240). Since this research wants to focus on behavior that significantly alter the quality of the environment, the definition of pro-environmental behavior will be scoped particularly to purchasing behavior which, as stated by Gardner and Stern (2002), has a greater impact compared to, for example, recycling actions.

In general, the main determinants of pro-environmental behavior considered by the following theories are motivations, i.e. psychological factors that drive behavior and explain what humans do (Nevid, 2012). Those can be divided into extrinsic and intrinsic motivations. Extrinsic motivations are the ones originating from the outside of the individual, such as social recognition and financial incentives. According to Frederiks et al. (2015), even if monetary rewards are often established to encourage pro-environmental behavior, they can only yield temporary and inconsistent effects. A voluntary behavioral change is then expected to last longer only if it is based on non-financial determinants, such as praise and public recognition. This means that people feel more motivated in doing something if they expect the approval of the surrounding friends, family members or neighbours.
3.1. The energy transition from a consumer perspective

Intrinsic motivations are instead arising within the individual himself. As it will be mentioned when analysing normative theories, pro-environmental values and attitudes are considered responsible for shaping most of the intrinsic motivations behind pro-environmental behavior (Kollmuss & Agyeman, 2002). The concept of values refers to a set of ideals that guide actions in one’s life, while attitudes indicate a more in particular positive or negative evaluations of an object, activity or person (Frederiks et al., 2015).

Theory of Planned Behavior (TPB) and Theory of Reasoned Action Among the first category of rational theories the main examples are Theory of Planned Behavior (TPB) and Theory of Reasoned Action (TRA) that explain how consumers’ beliefs translate into attitudes towards pro-environmental behavior and eventually into innovation adoption (Ajzen, 1991) (Ajzen & Fishbein, 1980). According to TPB individuals make decisions based on rational considerations and potential outcomes of those actions (Ajzen, 1991). Perceived feasibility and expectations from the purchase, compliance to social norms, knowledge and experience with the product are all examples of elements determining those decisions. The TRA, also called rational choice theory, additionally implies an underlying rational utility maximization approach of consumers purchasing decisions (Carley et al., 2013).

Normative Theories The second category is the one of normative theories, assuming that internal norms and values are the determinants of consumer actions. In the specific case of the adoption of sustainable products environmental values, beliefs and norms are considered to influence adoption behavior, as explained by the Value-Belief-Norm (VBN) Theory from Stern (2000). This means that the recognition of some core values, such as the importance of nature integrity or altruism, is followed by the acknowledgement of consequences and the implied responsibility of human actions, and eventually by the resulting personal moral norms formulation, leading to a chain of elements that shapes human behavior. Unlike the previous category of theories, those are based on motivations that are mostly driven by care for other people and the environment rather than self-interest motives. However, several studies have pointed out the existence of a “value-action gap” or attitude-action gap” that makes not immediate the positive relationship between pro-environmental values/attitudes and energy saving and efficiency investment (Blake, 1999). In fact, according to Becker et al. (1981), people actually tend to behave in ways that minimize costs and maximize benefits for them rather than acting in accordance to general values.

The theoretical approaches mentioned above, present a limited perspective for understanding actual adoption of diffusion considering that most of them have been focusing only on intentions as predictors of consumer behavior (Ozaki & Sevastyanova, 2011). An example of such shortcomings can be found in Jansson et al. (2010) study where the Values-Beliefs-Norms theory can explain only the 41% of variations in sustainable vehicles purchasing. The reason is that those theories mainly refer to non-consumption behavior or low involvement purchasing, such as energy conservation and recycling, which can be quite different in terms of motivations from high involvement purchases of products marketed as being environmentally responsible. In fact, as already mentioned before, high involvement purchases are mostly characterized by a large search for information and high expenditures (Asamoah, 2012). Therefore to gain a major focus on actual adoption of a technology rather than on the factors influencing adoption, other elements from pro-environmental psychology theories were analysed in the literature review as well as Diffusion of Innovation theory.

Among the additional factors that have been identified as important determinants of pro-environmental behavior, there are contextual factors (monetary and physical constraints), as well as social influence. In particular, financial incentives have been found to be critical elements of government policies aimed at inducing consumers to invest in renewable energy technologies. Such strategies aimed at varying contextual factors are considered more effective in promoting pro-environmental behavior than informational campaigns trying to raise environmental awareness (Elmustapha et al., 2018).

With regard to social influence, several researches in the energy domain have proven that energy-related behavior is socially embedded (Welsch & Kuhling, 2009). This means that an individual is not an isolated actor, but her actions and choices partially depend on others’ actions and expected behavior. More specifically, the literature review has pointed out the importance of the role of pro-environmental subjective norms. Pro-environmental subjective
norms refer to “individual perceptions of the extent to which important others would endorse a given behavior and individual motivations to comply with this social pressure” (Abrahamse & Steg, 2011, p. 31). In other words, households who think that their friends will approve of them using energy efficiently, and who give a large weight to their opinion on the issue at stake, are more likely to adopt, for example, electrical vehicles instead of the traditional one with gasoline.

Furthermore, some scholars assert that the symbolic meaning of a product together with the relationship between their purchase and the self-identity of the actors are important elements of psychological theories related to buyers behavior (Burgess et al., 2013). For example a car is a product that can not only satisfy the mobility need of its owner but it can also express concern for the environment in the case of a sustainable vehicle (electric vehicle) (Noppers et al., 2014). From this kind of studies a self-image congruence theory (Sirgy, 1986) has emerged arguing that the consistency of the symbolic image of a product with the buyer self-image can positively influence the intention to buy it. The same holds true for a pro-environmental lifestyle (Axsen et al., 2012).

A special focus is now given to Innovation Diffusion Theory because of the similarities with the approach taken by Ensysi. In fact, adoption and diffusion of innovations is described by Rogers (2003) as a social process taking a step further from cognitive assessment and rational choice theories. Considering the particular nature of renewable energy technologies, it is important to focus on product characteristics when analyzing consumers’ adoption. Various studies have proven that perceived attributes of products “are better predictors of consumer adoption than personal characteristics” (Elmustapha et al., 2018, p. 349). Moreover, Ensysi well reflects that because the motivation factors are mainly based on technology characteristics rather than actors’ features.

The main concepts of the Diffusion of Innovation theory are illustrated in the following subsection, having as main reference Rogers (2003).

### 3.1.3 Diffusion of Innovation theory

The Diffusion of Innovation theory mainly focuses on how an innovation enters and spreads into the market through communication channels and among individuals belonging to a social system. According to the main definition an innovation is an idea, practice or technology considered as new. The adoption of innovation process and, in particular, the speed at which adoption rates occur have been found to depend on five perceived features of a technology as well as the adopter’s propensity to accept an innovation. The five innovation attributes are provided in Table 3.1.

<table>
<thead>
<tr>
<th>Technology attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative advantage</td>
<td>Perception of the technology as better than the incumbent one from an economical or social perspective</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Consistency with existing values, behavior and needs</td>
</tr>
<tr>
<td>Complexity</td>
<td>Skills, capacity, and effort required to adopt an innovation</td>
</tr>
<tr>
<td>Trialability</td>
<td>Possibility of testing a technology on a limited scale</td>
</tr>
<tr>
<td>Observability</td>
<td>Degree to which an innovation is visible to others</td>
</tr>
</tbody>
</table>

Table 3.1: Perceived technology characteristics according to Diffusion of Innovation theory.

The innovation adoption process can be divided into five stages. The first one is characterized by knowledge of the product, i.e. the decision-making unit comes to know about the innovation existence and its attributes. Secondly, persuasion occurs when a positive or negative attitude towards the innovation is determined based on the information acquired during the first knowledge phase. The third stage is decision when the adopter engages in activities that lead her to actual adoption or rejection of the product. Fourth, implementation occurs when the innovation is de facto used by the adopter and, finally, confirmation takes place when information supporting the
### 3.1. The energy transition from a consumer perspective

Table 3.2: Examples of technology characteristics categorized according to Diffusion of Innovation Theory. Adopted from Faiers and Neame (2006).

<table>
<thead>
<tr>
<th>Positive characteristic</th>
<th>Negative characteristic</th>
<th>Innovation attribute: relative advantage</th>
<th>Innovation attribute: compatibility</th>
<th>Innovation attribute: complexity</th>
<th>Innovation attribute: observability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe form of power generation</td>
<td>Not a safe form of power generation</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Could develop in the future</td>
<td>Probably will not develop in the future</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compatible with modern living</td>
<td>Not compatible with modern living</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It will be more widespread in the future</td>
<td>Unlikely to become popular</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generate saving/profits</td>
<td>Does not generate savings/profits</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity improvement</td>
<td>Waste of money</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provides a visual statement of beliefs</td>
<td>Not highly visible</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It has a short payback</td>
<td>Long payback</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple to install</td>
<td>Difficult to install</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduces carbon emissions</td>
<td>Increases carbon emissions</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduces pollution</td>
<td>Increases pollution</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acts all of the time</td>
<td>Seasonal</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does not affect the visual landscape</td>
<td>Affects the visual landscape</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance free</td>
<td>Needs maintenance</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Adds value to a property</td>
<td>Does not add value to a property</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The systems are hidden away</td>
<td>The systems are intrusive</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Affordable technology</td>
<td>Unaffordable technology</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High level of grant available</td>
<td>Low level of grant available</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.1. The energy transition from a consumer perspective

decision to adopt or not to adopt is sought. This whole information-seeking and -processing process can eventually lead to adoption or rejection of the innovation, and those can also be reversed at a later stage.

Since not all the adopters engage in and conclude the innovation adoption process at the same time, five categories of adopters have been identified to reflect how the whole product diffusion process occurs in the market. This categorisation is based on adopters’ attitudes, values, behavior and characteristics.

3.1.3.1 Actor types categorization

Ensysi reflects the method of classifying adopters based on innovativeness, which is defined as the degree to which a consumer adopts an innovation earlier than others within her same social environment (Rogers, 2003 cited in Elmustapha et al., 2018). Vandecasteele and Geueens (2010) have identified three motivational reasons leading to consumer innovativeness: instrumental, hedonic, and symbolic motives. Generalizing from their specific application of those motives to the adoption of electric vehicles, the instrumental motives can be referred to the functionality of the product, hedonic motives to anticipated emotions, for instance the amusement deriving from the utilization of the product, and symbolic motives to the importance given to the product’s symbolic features.

Following a normal frequency distribution (Figure 3.2), five adopter categories can be identified together with the approximate percentage of individuals included in each category (Rogers, 2003):

- **Innovators** (first 2.5% of the individuals adopting an innovation): they are characterized by a risk-seeking attitude and eagerness in trying new ideas. This means that they can afford substantive financial resources to recoup possible financial losses due to an unprofitable purchase and the required knowledge about a new complex technology;

- **Early adopters** (13.5%): they are the ones with the greatest level of opinion leadership and they are seen by their peers as examples of successful and discrete use of new products, decreasing its uncertainty;

- **Early majority** (34%): they are characterized by a longer innovation decision period being adopters of an innovative products just before the average member of a social system;

- **Late majority** (34%): characterized by a sceptical and cautious approach towards innovations, they become adopters right after the average member of a social system because of an economic necessity or social pressures. To motivate their adoption they need to be sure that the uncertainty level of a new idea has almost disappeared and that many others have already become adopters;

- **Laggards** (16%): having resource-limits they are forced to be extremely cautious and suspicious towards innovation. They are the last ones in adopting an innovation in their social system, having as point of reference the past and traditional values.

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1See the previous subsection.
3.2. The energy transition from a company perspective

Figure 3.1: Rogers’ innovation adoption curve. Based on Rogers (2003).

An assumption made in Ensysi with regard to this, is that actor-types (Table 2.2) differ in terms of the weights given to the motivation factor aspects, so they can be assigned different values for each element according to their behavior, beliefs and values.

At this point it is important to specify that according to the perspective of Ensysi, as it is currently formulated, all the actor groups are assumed to give the same weights to the motivation factor aspects, i.e. irrespective of whether they are consumers, companies etc. The only elements differentiating them in this sense are the rate of return, taxes and other kind of financial benefits. Therefore, what results from the analysis of the investment module of Ensysi, is that at the moment of the investment decision all the agents act as technology adopters looking at technology attributes to make their investment choices. This is the reason why the chosen theoretical framework, that will be explained in section 3.4 is mainly based on a theory that refers to consumers. Even a company investor’s decision making is simulated in such a way that she will look at perceived attributes of the technology as well as cost factors.

However, as it will be illustrated with the second part of the literature review concerning companies investments, there are some important differences between the way a company investor makes decision compared to consumers. This issue will be reconsidered in the recommendations part.

3.2 The energy transition from a company perspective

3.2.1 Introduction to the literature review

As stated before, the scope of this research covers both household consumers and companies of small/medium/large size as the main actors in the energy transition path. This section is dedicated to the investment decision-making of financial investors from companies within the energy system that face energy/heat demand of different sub-sectors (such as Industry, Transport, Services etc.). As it will be outlined below, the decision-making process here is different from the one characterizing consumers.
3.2. The energy transition from a company perspective

The way investors choose among uncertain technological options has been studied so far mostly adopting the full rationality approach, meaning that the main focus is on economic features such as capital and maintenance costs (Jacobsson & Johnson, 2000). However, additional studies have been recently conducted to explain renewable technologies diffusion and adoption barriers, including behavioral and social aspects. Both categories of elements (financial and non) are considered in the following paragraphs.

The main reference for the review of financial evaluation techniques to cope with uncertainty and risk is the paper of Yang and Blyth (2007) for the International Energy Agency. A section dedicated to the weighted average cost of capital (WACC) presents some data about discount rates used in investment decisions in the power sector, derived from surveys gathered by Capros et al. (2016). Finally, the section concerning subjective elements is based on the literature review conducted by Masini and Menichetti (2013).

3.2.2 Financial elements of investment decisions

In real life decision-making processes are based on rational elements. The term rational refers to a decision process based on the knowledge of preferences and the utilities derived from every potential option (Weber, 1947). This means that precise financial evaluation tools are implemented to derive expected future outcomes. However, even if formal evaluation methods, such as the Net Present Value one, are commonly used in several investment processes, this kind of decisions can be considered rational only up to a certain extent. As it has been found by Groot’s literature review (2013), this is mainly due to limited quantity of time and resources to process information. To address these challenges technology investors have developed several evaluation tools, briefly explained below.

As stated by Brealey and Myers (2003) one of the main questions that arise for a company’s financial manager is which investment decision has to be undertaken to maximize their market value. This can be referred to as a capital investment decision. Formal evaluation tools are then required to accomplish such a crucial decision-making process. To construct and apply them there are some peculiar characteristics of the power sector that have to be taken into account. According to Yang and Blyth (2007) investments in the power sector are specifically characterized by three important elements that need to be included quantitatively in a good and comprehensive model or investment evaluation methodology:

- **irreversibility**: after the investment has been done, the capital cost becomes entirely or almost entirely sunk cost;
- **uncertainty**: as already mentioned above, it concerns future prices but also projected cash inflows and future returns on investment;
- **flexibility**: investments can be made at different times: according to their predictions of return on investments they can postpone their financial commitment until this is high enough to recover risks and costs or until they can access better information. They can also abandon, expand, and reduce the project operation once the investment is done.

Traditional evaluation methods, identified as payback period method and discounted cash flow (DCF) methods, can hardly cover all those three elements.

In the payback period methodology the number of years it takes to the future income to recoup the initial expenditures is calculated. There are two bias that can be found in this approach. Firstly, the bounded time horizon settled in terms of the investment’s consequences which might leave out some benefits arising later. Secondly, different timings of return to investment are overlooked, meaning that the time cost of money is not taken into account. Being a simplistic approach, it is commonly implemented for projects where transactions are not significant and the payback happens in short-term (Yang & Blyth, 2007).

The traditional evaluation tools that are mostly used are the discounted cash flow methodologies. Among these the most well known technique is the Net Present Value (NPV) method. It entails the calculation of the present value of projected cash inflows minus the present value of the incurred costs. The discounted value of a cost or benefit
can be calculated by multiplying that amount for the discount rate \( \left( \frac{1}{1+r} \right) \), which enables to take into account the time preference for money. The concept of time preference of money expresses the fact that people value more a dollar earned today, rather than a dollar earned tomorrow because the latter, at least in theory, can be invested and therefore provide returns. The \( r \) in the formula indicates the appropriate rate of return of the investment opportunity (Brealey & Myers, 2003). The longer the time at which future cash flows occur the higher is the discount rate to balance time value of money and risk issues. The result is then an exponential function in time. To evaluate the outcomes of different project options in terms of net present value the main decision rules are Internal Rate of Return, NPV and Hurdle Rate, that have been documented in detail by Berk and Demarzo (2011).

However also these methodologies present some shortcomings. Firstly, the future cash inflows are not certain because they are related to variable energy and \( CO_2 \) prices. Secondly, to establish the appropriate discount rate able to represent future uncertainty is quite challenging and still lacking a certain methodology. In fact, the main effect of the discount rate function’s shape on actual investment behavior is that is that long term effect are valued less to an exponential degree. This means that from a financial perspective the returns on investments arising within the first years of a power plant installation are prioritized compared to the ones occurring in a longer-term horizon (Yang & Blyth, 2007).

As mentioned above a crucial element of the discount rate is the rate of return or cost of equity. It can be defined as the return that shareholders demand to compensate for their share of ownership according to a perceived risk profile evolving in time. Many complications arise when determining a realistic and appropriate rate of return. A formal method that has been developed to face this issues is the Capital Asset Pricing Model (CAPM) which combines the value of a risk-free interest rate and an interest addition due to the “risk premium comparable to what they would earn taking the same market risk through an investment in the market portfolio” (Berk & DeMarzo, 2011, p. 378). However, the approximations made for the implementation of this method are still not realistic.

To face the limitations presented by those traditional methodologies investors have come up with stochastic methods and different scenarios analysis. For example, investors can calculate the DCF for each considered scenario as well as the probability of likelihood of each scenario, and then find the expected overall value from the weighted average of those DCFs. Regulatory uncertainties and variable electricity and \( CO_2 \) prices are often given a particular focus. In fact, they might limit investment choices to flexible power production technologies characterized by short term payback time, brief construction process, and possibility to easily switch among fuels. However, in order to capture the advantages of economy of scale, i.e. the reduced cost per unit due to an increase in quantity produced, there is the need to commit to large power production units so that costs of production can be minimized. To overcome this conflict investors have been implementing new financial assessment methodologies that take a step ahead from the traditional discounted cash flow method and that are actually guiding both corporate strategists and energy policy makers (Yang & Blyth, 2007).

While the main objective of the DCF methodology is to assess whether to undertake a project or not, an innovative method has been developed in order to provide indications also for the best timing of investment: the Real Option Analysis (ROA). The concept of real option, that has been firstly used in this sense by Myers (1967), refers to an opportunity (usually requiring capital investment) with different values at different time periods to launch some business projects. Combined with stochastic methods and multiple scenarios ROA enable to evaluate a project’s outcome at different points in time because it takes into account uncertainties and flexibility. Examples of real options in this research context are buying an emission permit, which enables to enlarge, scale down or quit a certain project, and investing in R&D that can lead to business development, and technological procurement or licensing. Such an approach enables the investor to flexibly administer and adjust his irreversible investments.

As found in the empirical analysis of Graham and Harvey (2001), large corporations mostly refer to discounted cash flow methods and the capital asset pricing model, whereas smaller companies tend to use the payback method because of its simplicity of utilization. This is also confirmed by the review of Groot (2013) who states that power companies evaluation methods are mostly based on discounted cash flows. The use of real option analysis is more rare because of its complexity, high expertise and information requirements. Moreover, the results of such analyses are more difficult to explain within the organization because not many are familiar with that yet.
3.2. The energy transition from a company perspective

3.2.2.1 Discount rates for investments in the power sector

A special focus is now given to the discount rate values adopted in the power generation sector. In general the discount rates are defined following the approach of the weighed average cost of capital (WACC). The WACC is defined as the firm’s unit cost of capital that depends on different sources of funding and each source is associated to a different interest rate (Capros et al., 2016). Usually the sources of funding are the equity capital (E), valued at a subjective discount rate \( r_e \), and borrowed capital (D) referred to a market-based lending rate \( r_d \). The general formula is:

\[
WACC = \frac{E}{E + D} r_e + \frac{D}{E + D} r_d
\]  

(3.1)

The first step to identify a realistic estimation of discount rates is to look at risk-free or low-risk rates. Relevant business surveys have evaluated this for industries as 4% or 5%. To such risk-free discount rate is usually added the equity risk premium of 6-9% and a country of project-specific risk factor. Considering that the general capitalization structure is based on 65% borrowed funds at 5.5% interest rate and 35% equity capital valued at 9% cost of equity rate the resulting minimum WACC is obtained:

\[
WACC = 65\% \times 5.5\% \text{(debt)} + 35\% \times (4\% + 2.5\% + 2.5\% + 2\%) \text{(equity)} = 7.5\%
\]  

(3.2)

where 4% is the risk-free rate, 2.5% the equity risk premium, 2.5% the industry risk premium and 2% the company-specific risk-premium. According to the approach of Capros et al. (2016) this is the minimum WACC used as rate of return a regulator would establish for regulated natural monopoly infrastructures. A 1-3% risk premium can then be added to specify the company size-related risk premium, as well as technological immaturity risk premium. This leads to a general discount rate of 8.5% for the power, gas, and coal market. The following table shows other discount rates variations due to different kinds of risk-premium factors.

<table>
<thead>
<tr>
<th>Type of investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulated monopolies and grids</td>
</tr>
<tr>
<td>Companies in competitive energy supply markets</td>
</tr>
<tr>
<td>RES investment under feed-in tariff</td>
</tr>
<tr>
<td>Investment under contract for differences</td>
</tr>
<tr>
<td>RES investment under feed-in premium, RES obligation and quota system with certificates</td>
</tr>
<tr>
<td>RES investment in competitive markets</td>
</tr>
<tr>
<td>Risk premium specific to immature or less accepted technologies</td>
</tr>
</tbody>
</table>

Table 3.3: Discount rates in energy supply sectors. Adopted from Capros et al. (2016).

3.2.3 Subjective elements of investment decisions

As identified by the review from Masini and Menichetti (2013), four non-financial elements derived from behavioral theories mainly influence renewable energy investment decision processes, explained below.

Firstly, \textit{a priori} beliefs play a role in individual decisions. It means that the personal history, social interactions, education background and previous experience all contribute in creating a cognitive framework that steers an individual decision-making process. Among these factors, the level of confidence in policy measures is particularly important, given the high level of uncertainty of renewable energy projects and the resulting importance of the effectiveness of policies supporting those. In fact, incentive mechanisms are fundamental when a technology is still at the beginning of its life-cycle and it is not yet market competitive.
A second group of factors affecting investment decisions concerns institutional isomorphism, which is the tendency to stick to the main rules and norms characterizing actors’ institutional environment. Regulations, implicit or explicit industry standards, influence from peers and recognized authorities can have a large impact on sustainability measures. The influence of such elements is even more for investment decisions in renewable energy technologies given the high level of uncertainty characterizing them and the lack of knowledge in their implementation and potential advantages. With regard to this, also the attitude towards radical technological innovations has a strong influence on technology adoption decisions. Being directly related to an actor’s risk attitude, it represents one of the main challenges that are currently studied in behavioral finance (Shleifer, 2000).

Finally, the level of knowledge of the operational context surrounding renewable energy projects is an important determinant within this kind of decisions. In fact, imperfect information about a new technology might hamper both risk-neutral and risk-seeking investors, and can eventually result in a priori biases (Teel et al., 2006).

The integration of cognitive and behavioral factors allows to take a more complete perspective on the mechanisms underlying investment decisions in the energy sector. The approach taken by Ensysi follows in fact this line of reasoning.

### 3.3 Choice of the theoretical framework

In the context of a research the theoretical framework consists of a theory, or a combination of theories, that the researcher has found in literature when looking for a theoretical underpinning that can match the research project (Verschuren & Doorewaard, 2010). The role of a research framework is therefore to guide the study of the research object (in this case is the actors’ investment simulation of Ensysi), so that the right insights can be drawn on the basis of acknowledged theories.

As stated before, the chosen theoretical framework has to be as comprehensive as possible so as to reflect the approach of Ensysi, which covers not only the financial elements of a technology but also other more subjective perceived attributes of a technology. The technology investment choice framed by this theoretical framework is assumed to concern all categories of actors, because right now in the model it is assumed that all the actor groups (companies, consumers, households etc.) give the same weights to the motivation factor aspects. It is then left to subsequent research steps the reformulation of the module concerning company investor to make their simulated behavior more close to the real one, which is based on profit-related evaluations.

For this reason, the theoretical framework adopted for the analysis of the current model state is drawn mostly from innovation diffusion theory, because of the similarity between the main model variables and the investment module (see subsection 2.2.1) with the elements characterizing this theory.

#### 3.3.1 Conceptual model

In more practical terms, the theoretical framework often takes the form of a conceptual model, which is “a set of assumed relationships between the core concepts” of the project (Verschuren & Doorewaard, 2010. p.17). Such a model can support the researcher in correctly formulating the nature of causal relationships among the main concepts of interest and in relating the research activity to an existing theory.

Taking the example of Elmustapha et al. (2018) to build a conceptual model that can explain consumers’ adoption in the context of (renewable) energy-related technologies, the independent variables that have been chosen are the perceived product attributes considered in Diffusion of Innovation Theory. These are relative advantage, compatibility, complexity and observability. Trialability has been left out following Elmustapha et al. (2018) and Faiers and Neame (2006) because it has been found that this factor does not relate to adoption of energy conservation intervention technologies (with an exception of electric fuel vehicles (Rezvani et al., 2015)). In addition to these,

---

2The conceptual model has been adapted from the original one by selecting only the variables that are of interest for the research on Ensysi.
that can generally be applied to every products, to reflect the specific context of Ensysi another independent variable has been added to the model: environmental concern. As defined by Zimmer, Stafford, and Stafford (1994) cited in Minton et al. (1997), environmental concern refers to the general attitude towards preserving the environment. Deriving from the environmental psychology research tradition mentioned in Section 3.2., this concept is actor-dependent rather than technology-dependent. Such an integration of elements coming from two different branches of theories is again based on the conceptual model of Elmustapha et al. (2018), that has been recently developed and empirically tested. As stated by the authors, it provides “a higher explanatory power when compared to the current monodisciplinary models” (p.350).

Moreover, the choice of Diffusion of Innovation theory is in line with an important characteristic of the model: the approach presented by Ensysi in terms of investment behavior is at an aggregate level. The considered unit of analysis is then a group of actors having a preference for one technology over another. In fact, this theory has been traditionally defined as useful in explaining “innovation adoption among aggregates of individuals” as stated by Gross et al. (1971, p. 22). The categorization in Innovators, Early Adopters etc., allows for heterogeneity with respect to different characteristic of potential adopters, giving to the modeling approach a more solid behavioral explanation (Chatterjee & Eliashberg, 1990). Finally, several studies in literature have applied to corporations the distribution of adopter categories (Mahler and Rogers, 1999), meaning that the model’s approach is not to be restricted only to the consumers-group.

According to this conceptual model built here, relative advantage, compatibility, observability and environmental concern are positively related to technology adoption, whereas complexity is negatively related to that.

![Conceptual model for actors’ technology adoption.](image)

As already mentioned, the choice of this conceptual model is due to the following reasons:

- It reflects the elements considered in Ensysi as relevant for the general investment decision module, i.e. the motivation factor aspects;
- It regards actual adoption of products and, in particular, renewable energy technologies, instead of mere intention of adoption;
- By combining theoretical concepts and views taken from different branches of theories it can provide a more powerful and complete analytical tool;

---

3While environmental concern is actor-related and, more specifically, is an intrinsic motive (Frederiks et al., 2015), the other variables from Diffusion of Innovation Theory are perceived external product attributes. The two research branches considered here have therefore different scopes in terms of variables categorization and cannot contradict each other.
3.3. Choice of the theoretical framework

- Empirical studies have confirmed the validity of the conceptual models at the basis of the one considered here (Elmustapha et al., 2018) (Faiers and Neame, 2006);

- The research approach of Diffusion of Innovation theory has a more aggregate focus (Rogers, 2003), in line with actors’ group-based aggregation of investment decision-making simulated by Ensysi.

3.3.2 Application of the conceptual model to Ensysi

The aim of this subsection is to link the conceptual model previously illustrated to the motivation factor aspects presented by Ensysi so that the theoretical validation of the model behavior can be completed. Hereafter the motivation factor aspects are listed again (in italic) and the related elements from the conceptual model are identified (quoted marks). The approach considered is the same of Faiers and Neame (2006), summarized in Table 3.2: for each attribute (that here corresponds to a motivation factor aspect from Ensysi) the positive/negative characteristics of the technology it refers to have been identified helping to classify them in the innovation attributes categories. More explanations on this link are provided below.

- **Social attitude** is divided into attitude towards climate change (climate concern) and attitude towards a technology (public resistance). Referring to the conceptual model of Figure 3.2 the first one can be reflected in “environmental concern” that is a characteristic of the individual adopter, so an actor-dependent variable (for this reason it is left out from the Table 3.4 which refers only to technology characteristics). The second factor is appreciation/resistance against a technology. Following the research approach it can be seen as a comprehensive element including perceived attributes of a technology, i.e. “relative advantage”, “compatibility”, and “observability” (Table 3.1). In fact, looking at Table 3.2 a technology might have higher public resistance because “there is a low level of grant available” (line 18) for that (relative advantage), or it seems “not compatible with modern living” (line 3) (compatibility), or it “affects the visual landscape” (line 13) (observability). However, even though this specific factor, together with the others mentioned below, is a technology-dependent variable, the weight given to it as motivation factor aspect is differentiated per actor type to simulate how different consumers value its relevance in the purchasing decision.

- **Targets** is a technology characteristic specifying the mitigation potential, so the contribution of a technology in reducing $CO_2$ emission, and in providing energy efficiency improvements and renewable energy production. It depends on the targets specified in the file dedicated to policy instruments. In the conceptual model it can be seen as a component of “relative advantage”.

- The two financial elements Costs and Investment barrier in Ensysi can be combined as reflected in the attribute “relative advantage”.

- The motivation factor Complexity explicitly represents the product attribute “complexity”.

The main purpose of Table 3.4 is thus to identify the causal relationships between the motivation factor aspects and technology adoption, so that a tailor-made conceptual model for Ensysi can be constructed. The result is shown in Figure 3.3, where a specific application of Diffusion of Innovation theory is made to the context of renewable technologies. To check whether the behavior of Ensysi reflects this set of relationships, the parameters at stake, i.e. the weights given to the motivation factor aspect, have been varied. In other words, this means increasing or decreasing those weights in order to see whether there is the theory-predicted positive/negative relationship with technology adoption. This is described in the following section dedicated to the theoretical validation of the model.
### Table 3.4: Application of the conceptual model to the motivation factor aspects (readapted from Table 3.2).

<table>
<thead>
<tr>
<th>Motivation factor aspect in Ensysi</th>
<th>Positive characteristic of the related technology</th>
<th>Negative characteristic of the related technology</th>
<th>Innov. attribute rel. advantage</th>
<th>Innov. attribute compatibility</th>
<th>Innov. attribute complexity</th>
<th>Innov. attribute observability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public resistance</td>
<td>Low public resistance</td>
<td>High public resistance</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Targets</td>
<td>Contribute to decarbonization</td>
<td>No decarbonization</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Contribute to energy efficiency</td>
<td>No energy efficiency</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Produces renewable energy</td>
<td>No renewable energy</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Costs</td>
<td>Affordable</td>
<td>Not affordable</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Investment barrier</td>
<td>High upfront costs</td>
<td>No high upfront costs</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Complexity</td>
<td>Perceived as complex</td>
<td>Not perceived as complex</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Might depend on fuel with import risk</td>
<td>Not depend on fuel with import risk</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
3.3. Choice of the theoretical framework

3.3.3 Theoretical validation

The aim of the theoretical validation here is to create some consumer profiles in Ensysi by variating the weights given to the motivation factor aspect in a way that follows the theoretical notions of the conceptual model, so that more/less technology adoption is expected. Since variations concerning only a single weight do not yield significant differences in the model’s outcome when looking at the actual realized investments, some coherent combination of changes in MFAs’ weights have been formulated according to the literature of Diffusion of Innovation theory. For this purpose some consumer profiles were realized with an increasing level of “green” attitude, meaning that the weights assigned to the motivation factor aspects are respectively increased or decreased up to a point that can lead visible variation in the output. More specifically, following the line of reasoning of the theoretical framework, to increase the “green” level of the consumer a higher weight is given to environmental concern and targets, whereas a lower weight is given to complexity, costs and investment barrier. Table 3.5 illustrates that with three examples among the profiles that have been simulated. Those variations concern only the Majority actor types (from Table 2.2), since it is the largest category and thus it can influence more the results.

<table>
<thead>
<tr>
<th>Motivation Factor Aspect</th>
<th>Profile 1</th>
<th>Profile 2</th>
<th>Profile 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public resistance</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Climate concern</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Targets</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Costs</td>
<td>0.8</td>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>Complexity</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Investment barrier</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3.5: Example of weights assigned to the motivation factor aspect for three actor profiles.

The outcomes analysed is the stock evolution of Plug-in hybrid electric vehicles (PHEV) and solar PV systems. This choice is due to the fact that they represent a prominent example of renewable energy technologies. It is assumed that technology adoption leads to investment in that technology and thus to growth of the related stock.
3.3. Choice of the theoretical framework

Figure 3.4: Stock evolution of PHEVs for the three profiles in Table 3.4
3.3. Choice of the theoretical framework

As shown by the graphs an increasing level of “green” consumer behavior leads to more renewable technology adoption. However, in Figure 3.4 this holds true only until around 2037 because after that year the more innovation averse profiles are characterized by higher adoption of PHEVs. A closer look at the output file for the stock evolution of that subsystem has provided an explanation for this apparently contradicting model behavior. In fact, as the Table shows less adoption of the Profile 1 for the final year is due to the fact that there are more investments in BEVs (0.77 millions of vehicles compared to 0.31 and 0.24 of the other profiles), that, according to the model assumptions, are even more innovative (in terms of adoption complexity) and expensive. Therefore, the Profile 1 curve appears smaller than the other two just because another “more green” technology takes the lead of the market during the final years. This does not occur in the case of Solar PV systems because they are already one of the most innovative technologies in the electricity generation sector. The adoption of technology here is more sensitive to variations of the actor profiles because of the higher weight given to the subjective parameters in the Technology characteristics input file (see the parameters in Table 2.3). Overall the model behavior is then in line with the theoretical notions of the constructed conceptual model.

As a further theoretical validation analysis, it can be observed from the graphs that such technological innovations are characterized by a stock increase function that resembles the cumulative s-shaped curve typical of Roger’s Innovation Diffusion Theory, which represents adoption of innovation plotted over time. It starts with a small rise when Early Adopters take the lead of the market, continuing the growth at a higher speed until a maximum where the majority of the individuals in the system have adopted the technology and finally stabilizing at a steady rate when the final adopters show up. What in Ensysi additionally contributes to such a behavior is the factor potential which limits the amount of investments in a technology that is considered new and therefore not yet mature. The fact that in some cases the adoption curves appear shorter or decrease for the final years depends also on the stock evolution of the other technologies within the considered subsystem that, being more innovative and “green”, are preferred at some point in time over the considered one.

Figure 3.5: Stock evolution of solar PV systems for the three profiles in Table 3.4
3.3. Choice of the theoretical framework

Conclusions

The first two sections of this chapter have presented the main notions concerning investment behavior in the energy sector, which is basically what Ensysi wants to simulate. The main theories, models and criteria considered in the literature have been reviewed to identify the one that better reflects the model. In particular Innovation Diffusion Theory with some additional elements from pro-environmental psychology studies have been chosen to build the appropriate conceptual model for Ensysi, because of the similarities with the underpinning model assumptions. The dual intention behind the formulation of this conceptual model is to verify the theoretical foundation of Ensysi, as well as providing a first analysis instrument that can guide future research steps.
Chapter 4

Extension of the Investment Module

Chapter 3 has concluded the theoretical part of the present research with the formulation of the research framework and conceptual model at the basis of Ensysi’s investment concept. The current chapter introduces then the practical part where the intervention to the model is implemented and further applied to achieve the research objective. The answer to the second research question will be provided here: How can the model be improved in order to fulfil the research objective?

The chapter firstly provides a description of the code submodules that are object of the research analysis. Secondly, the new formulated submodule is described and finally an overview of how this is integrated with the whole model’s functioning with the related assumptions and arising issues are pointed out. The main reference for the model description is the draft of the manual of Ensysi, which has not been published yet.

4.1 Overview of the model’s focal components

The part of the model this research wants to focus on concerns the investment decision-making by actors. Here there is a specific subroutine\footnote{According to the Fortran programming terminology a subroutine does not return a value like a function, but modifies its arguments (Padman, 2007).} for the investment module which is called in the main program at every time step. This subroutine is directly connected to other subroutines and functions through the variables it uses as arguments. Given the high level of integration and complexity of all these mutual links an overview of the main code structure is provided in this section.

4.1.1 Main input variables

The simulations run by Ensysi depend in first place on the scenarios specified in the input settings file of the model. In total there are seven different scenario options:

- **Global and exogenous technological learning scenarios**: the global growth of installed capacity which determines the related cost reduction according to prescribed learning curves of technologies;
- **National scenarios**: activity demand for all the considered subsystems, for example in terms of demand for energy industry products, or transport volume and number of dwellings;
4.1. Overview of the model’s focal components

- **Import and export scenarios**: concerning imports and exports of final energy carriers, i.e. the ones produced by energy production subsystems (for example production of electricity). If there is an import of a final energy carrier then the amount of imported quantity is subtracted from the national energy demand that the related energy production subsystem has to fill up, whereas in the case of an export there is an additional component to be supplied;

- **Constraint scenarios**: national constraints are given in terms of availability of certain energy carriers for instance biomass, methane and renewable heat; or amount of CO₂ that can be captured and stored;

- **Policy instruments scenarios**: they include a list of banned technologies with the starting year of the ban, investment subsidies, obligations, CO₂ prices, and targets for renewable technologies, energy efficiency and emissions;

- **Actor parameters scenarios**: weights given to the considered motivation factor aspects for technological investment decisions;

- **Method for development-space investments**: can be either based on the total motivation factor associated with each technology or some given technology choice factors.

4.1.2 Activity of subsystems

**End-use subsystems**  
As already mentioned in Chapter 2, the scenario formulation given as input to the model determines the demand for the main activity outputs of end-use subsystem such as industry products or road transport driven kilometers. Given this activity demand and the technology-stock available each year, the model then obtains the level to which the stock has to be used. For instance, in the case of transport technologies the unit of activity demand is transport kilometers and the capacity unit of stock is vehicles. However there might be the case that the technology-capacity of that year (so the number of vehicles) is not enough to satisfy end-use demand. This deficit triggers technology-investments for the following year.

**Energy-production subsystems**  
To execute their activity so as to satisfy end-use demand, the subsystems mentioned above need a certain amount of energy products or, as they are called in the model’s terminology, **final energy carriers**. In such a way end-use activity determines the demand for final energy carriers which in turn establishes the activity of energy production subsystems. These subsystems are in charge of the supply of a certain main energy output but they can co-produce also other energy carriers, as well as requiring inputs of energy from other energy production subsystems. Therefore the core mathematical calculation of the model is based on a set of iterative equations that calculate energy demand and supply concerning the production of energy outputs. For this purpose there is a specific submodule where all the subroutines that balance demand and supply of each final energy product are called.

4.1.3 Calculation of energy prices

After the calculation of demand and supply of both end-use activity and energy products, the levelized cost \( LCOE \) per energy produced is determined for each technology as the sum of the net costs incurring in the considered year. It is, in fact, the price that an energy producer needs to receive per unit of activity as a return to come out of the investment costs.

---

2The ones that in Chapter 2 have been referred to as energy conversion subsystems since they transform energetic input into final energy products.

3In line with the research scope and objective in the simulations that will be run for this research the second option will never be used.

4For the complete definition see subsection 4.2.1
4.1. Overview of the model’s focal components

\[
LCOE = \frac{1}{\text{EnProd}} \left\{ \text{AnnualCapitalCost} + \text{NetFuelCosts} + \text{O&MCosts} + \text{NetEmissionCosts} + \text{OtherCosts} \right\} \tag{4.1}
\]

The variables taken as input, that are already calculated in other model’s subroutines, are:

- **Annual Capital Cost** \(\text{[Meur/year]}\): accounts for the initial investment of the technology which is yearly spread over the whole economic lifetime as annuity payments calculated from the present value of investment, interest rate and number of periods over which the loan should be paid off;

- **Net Fuel Costs** \(\text{[Meur/year]}\): difference between the cost (calculated by multiplying the energy input needed by the technology and the corresponding energy price) and, if that is the case, the benefits of selling the co-produced energy carrier(s);

- **Fixed and Variable Operation and Maintenance (O&M) Costs** \(\text{[Meur/year]}\): annual operating and maintenance expenditures already given as inputs;

- **Net Emission Costs** \(\text{[Meur/year]}\): difference of emission allowances purchasing costs and selling revenues calculated from the technology emission and the \(\text{CO}_2\) prices of both ETS and non-ETS;

- **Other Costs** \(\text{[Meur/year]}\): costs of transport and storage of \(\text{CO}_2\) based on technology-emissions;

- **Energy Produced (EnProd) [ActUnit]**: output of the technology exploited (it is given in unit of activity since it differs for every subsystem).

These variables have been normalized in 4.1 by dividing them for the energy produced in unit of activity (PJ). The fact that they are divided by the same energy output variable is an approximation, which holds true with the assumption that all costs-terms and energy produced do not change over time.

However, the Levelized Cost inEnsisi is calculated not only for the energy generating technologies (the ones that sell the main energy carrier produced), but also for the ones involved in end-use subsystems. If that is the case, the costs of a technology are given per unit of activity (ActUnit) (e.g., per ton of steel produced, or vehicle km driven) rather than per unit of energy produced. Formula 4.1 can then be readapted as:

\[
LCOE = \frac{1}{\text{ActUnit}} \left\{ \text{AnnualCapitalCost} + \text{NetFuelCosts} + \text{O&MCosts} + \text{NetEmissionCosts} + \text{OtherCosts} \right\} 
\tag{4.2}
\]

Subsequently, based on the levelized costs of the technologies contributing to the total energy production, the prices of final energy carriers are calculated according to the following formula as the weighted average of the LCOE of the technologies contributing to the production of the energy carrier, with the exception of electricity prices that are instead based on marginal production costs:

\[
\text{EnergyPrice} = \frac{1}{\text{Stock}} \sum_{i=1}^{n\text{Tech}} \text{TechUse}_{i\text{Tech}} * \text{Stock}_{i\text{Tech}} * LCOE_{i\text{Tech}} 
\tag{4.3}
\]

where \(\text{Stock}\) is the technological capacity at disposal at the time considered, \(\text{TechUse}\) is the actual utilization level of the stock (a dimensionless number between 0 and 1) and \(n\text{Tech}\) is the number of energy-production contributing technologies within the subsystem.
4.1. Overview of the model’s focal components

**Approach for electricity production**  As already mentioned in Chapter 2, the price for electricity is calculated in a different manner than the other energy carriers. In fact, to include the effects of intermittent generation from renewable sources such as solar and wind, demand and production are matched at an hourly basis. More specifically, given the demand occurring in a certain hour, the non-dispatchable generation by wind and solar energy sources is subtracted to obtain the rest-demand that dispatchable generation units have to fulfil. Dispatchable generation capacity is then applied according to the merit-order, i.e. according to the variable cost of electricity production units. An example of merit-order function is given in Figure 4.1. The electricity price of the considered hour is then established by the variable cost of the marginal production option necessary to meet the demand. The annual average electricity price is calculated through the average price per hour weighted by the electricity demand per hour. All technologies that demand or produce electricity from non-dispatchable sources have a certain trend describing their annual variation. These profiles are based on the dataset for the Edesign1-model, which in turn is based on datasets by ECN. Based on these, the overall electricity demand for all the technologies follows the basic demand trend: slightly higher in winter time and daytime rather than in summer time or night-time. The assumed trends for Ensysi are shown in Figure 4.2 and 4.3.

![Figure 4.1: Example of merit-order. Adopted from the draft manual of Ensysi.](image)

![Figure 4.2: Assumed monthly variation of electricity profiles. Adopted from the draft manual of Ensysi.](image)
4.2 Code extension

An outline of the energy sector’s functioning as simulated in Ensysi has been provided above. Additionally recalling some other important notions from Chapter 2, the investment decision-making process is based on a set of motivation factor aspects that includes not only financial concerns such as technology costs and initial investment barrier, but also other perceived technological characteristics that have been identified as non financial elements, like technological complexity and public resistance. An actor has its own activity to carry out, and to accomplish that she has to choose among a certain number of available technologies belonging to the considered subsystem. To ensure portfolio diversification, mostly all the technologies are chosen and implemented (with some exceptions due for instance to technology-banning because of its carbon intensity) according to a certain ranking that is given by the total motivation factor score associated with each technology. The elements that steer actors’ decision making are the same for every actor-group.

Based on those elements as well as the description of how investment decisions are simulated through the motivation factor aspects described in Chapter 1, it is now possible to formulate a new concept for the next function of the model which particularly concerns the financial aspects of the decision-making process. As it has been established, the model assumes that the cost factor is mostly based on levelized cost calculations. However, those calculations refer on costs and benefits incurred only in the current year where the decision takes place, without taking into account future cash flows. Moreover, as seen in Chapter 3, the current investment module cannot fully represent how financial evaluations are made by company investors. As it has been found by Groot (2013) these mostly implement Net Present Value calculations (see subsection 3.2.2) that indeed are based on future costs and revenues as well. Therefore, what the model is currently lacking is an actor forward looking perspective, and a more accurate financial evaluation that can include future profit and cost considerations.

In fact, the model has been formulated in such a way that only the energy-business case is considered, meaning that agents are mostly looking at what is the least costly technology they can employ to carry out their activities, leaving
4.2. Code extension

out the evaluation of the actual complete business case that, for instance in the case of a manufacture industry, includes the calculation of profits derived from selling the main non-energetic output. However, an extension of the investment module can be made in this direction especially to target the activity of energy conversion subsystems, i.e. the ones producing and selling final energy carriers such as electricity. An actor forward looking perspective based on NPV calculations can make the model simulation more comprehensive and close to what happens in reality. Moreover, this represents the dynamic time-spanning element that will enable more analysis potentialities in terms of energy system long-term simulations. The first step to accomplish this part of the research is to modify and extend a part of the model coding.

4.2.1 Net Present Value calculation

The main formula at the core of the code extension is Eq. 4.4, which has been formulated following the example of De Vries et al. (2015) in their application of the NPV calculation to the power-generation context. The input variables considered here are the same used for the levelized cost module except for the \textit{Main Fuel Benefits} which are the revenues from selling the main energy products, i.e. the revenues for energy produced. In fact, these are equal to zero for the end-use subsystems that do not have energy as final product. \textit{FuelBenefits} are instead the revenues from selling co-produced energy carriers, which are final energetic products that are not the main output activity of the considered subsystem.

\[
NPV = -I + \sum_{i=1}^{EconLifeT} \frac{CashIn_i - CashOut_i}{(1+r)^i} \tag{4.4}
\]

where:

- \textit{EconLifeT} is the economic lifetimes specified as input for every technology;
- \textit{CashIn} are the cash inflows equal to: \textit{CashIn}_i = \textit{FuelBenefits}_i + \textit{EmissionBenefits}_i + \textit{MainFuelBenefits}_i;
- \textit{CashOut} are the cash outflows equal to: \textit{CashOut}_i = \textit{FuelCosts}_i + \textit{FixedO&M}_i + \textit{VariableO&M}_i + \textit{EmissionCosts}_i + \textit{OtherCosts}_i.

The NPV formula is linked to the LCOE calculation because if Equation 4.4 is set to zero and solved for the \textit{Main Fuel Benefits}, i.e. the benefit of selling the main energy carrier produced, the result is the levelized cost of energy divided by the energy produced.

The running of this calculation gives only negative values for end-use technologies, where indeed cost variables are mostly considered. In fact, being a simulation model of the sole energy sector, the profits derived from selling the main non-energetic output are not considered by Ensysi, giving a restrictive perspective on the financial terms of the considered investment projects. However, for what concerns energy production subsystems, both positive and negative NPVs are given depending on the technology. An example for heat production technology for horticulture is showed in Figure 4.4.
4.2. Code extension

The fact that for many technologies the NPV results are negative is due to the model’s calibration which entails a technology comparison based on costs (LCOE). For this reason, when the end-use subsystems are considered, and thus revenues from selling other non-energetic products are by default omitted because they are out of the scope of Ensysi, the resulting NPV is exactly equal to the total levelized cost of the technology. A brief definition of what is intended here for total levelized cost is given below.

**Levelized cost in the power generation sector** Since the early twentieth century levelized costs have represented the first cost comparisons for energy generation (McDonald, 1962). Generalizing the definition given by Borenstein (2012) the levelized cost is the constant price for energy output that would equate the net present value of revenues from the activity’s output with the net present value of the cost of production. The related formula is then:

\[
LCOE = \frac{\sum_{n=0}^{N} C_n(q_1, \ldots, q_n)}{(1+r)^n} \left(1+\frac{1}{(1+r)^n}\right) = \frac{\sum_{n=1}^{N} q_n LCOE}{(1+r)^n} = \frac{\sum_{n=1}^{N} q_n}{(1+r)^n}
\]

(4.5)

where \( N \) is the activity period, \( q_n \) the quantity produced, \( r \) the real cost of capital, \( C_n(q_1, \ldots, q_n) \) the expenditures to produce the stream of output. In this formula given by Borenstein (2012) it is assumed that capital costs occur in year zero before any production takes place. However, this does not hold true in Ensysi where the technology chosen can provide the required activity immediately.

In the original model formulation Equation 4.5 is reduced to Equation 4.1 since the cash flows are assumed to not depend on time. To extend that as well to the future discounting, Equation 4.6 has been implemented. Here the capital costs are all given in the initial year as investment cost \( I \) and the discounted cash flow is not divided by the
discounted produced quantity since the cost variables taken from the pre-existing submodule are normalized per unit of output, so already taking into account the utilization of installed capacity to produce the output.

\[ LCOE = I + \sum_{i=1}^{\text{EconLife}_T} \frac{\text{CashOut}_i - \text{CashIn}_i}{(1+r)^i} \]  \hspace{1cm} (4.6)

where:

- \( \text{EconLife}_T \) is the economic lifetimes already specified in the technology input file;
- \( \text{CashIn} \) are the cash inflows equal to \( \text{CashIn}_i = \text{FuelBenefit}_i + \text{EmissionBenefit}_i \) and normalized per unit of activity;
- \( \text{CashOut} \) are the cash outflows equal to \( \text{CashOut}_i = \text{FuelCosts}_i + \text{FixedO&M}_i + \text{VariableO&M}_i + \text{EmissionCosts}_i + \text{OtherCosts} \) and normalized per unit of activity.

The NPV calculation done for the end-use subsystems becomes the same of the equation above but with the opposite sign because the costs in NPV are considered as negative quantities.

In real life there are substantial differences among levelized cost estimates because of different assumptions behind economic variables, such as inflation and real interest rates, period of technology utilization and future costs estimates (Borenstein, 2012). Those can be the variables of interest for the subsequent sensitivity analysis of the model.

The overall result of the code expansion is therefore to have an additional calculation that discounts all the predicted future costs and, if that is the case, benefits incurred during the whole lifetime of the technology.

### 4.2.2 Verification

A verification of the new code extension for the NPV has been done to check the proper internal functioning of the code. It can be summarized in the following two steps:

1. An additional output file for Ensysi has been generated, which clearly shows for each year and each technology what are the input and output variables calculated in the two new subroutines;
2. An Excel file has been created to calculate the NPV using the same formula and processing the variables displayed in the output file of the previous step. The outcome has then been successfully verified by comparing the NPV values from the code in Ensysi and the ones from Excel.

### 4.2.3 Code for the motivation factor aspect

Following the model’s line of reasoning, as now a new criteria element has been defined for investors’ decision-making (the net present value), the related motivation factor aspect has to be coded as well. This means that each NPV value calculated for the technology investments has to be associated to a number between 0 and 1 according to a certain function. The way this function has been formulated, which is illustrated below, is based on the other function related to the cost-motivation factor to guarantee as much as possible the internal consistency of the investment module of Ensysi.

In this case the highest motivation factor score is given to the technology that has the highest NPV within its subsystem. A first loop is done for every subsystem to look for the technology that, still having a positive potential.

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5 In the model there is a constraint related to the maximum increase of the stock in a time-step.
4.2. Code extension

presents the highest NPV. Subsequently, all the other technologies’ NPVs are compared to that through a relative technology net present value. To associate each relative NPV with a motivation factor score a function has been created to linearly rescale values into the new range [0,1]. This function is assumed linear and equal to:

\[
MF_{NPV} = a \times \text{RelNPV}_{Tech} + b
\]

where:

- \(MF_{NPV}_{Tech}\) is the motivation factor score related to the NPV for each technology;
- \(a = \frac{1}{\text{maxR} - \text{minR}}\), with \(\text{maxR}\) and \(\text{minR}\) being respectively the maximum and minimum relative NPV value within a subsystem;
- \(\text{RelNPV}_{Tech}\) is the ratio of the technology-NPV and the maximum NPV for the given subsystem: \(\frac{\text{NPV}_{Tech}}{\text{MaxNPV}_{Sub}}\);
- \(b = 1 - (a \times \text{maxR})\).

An extra condition has been added to avoid the division by zero in \(a = \frac{1}{\text{maxR} - \text{minR}}\). In fact the denominator of \(a\) can be null in two cases: if only one technology has a positive potential and if the relative NPV values are all the same. In both cases the normalization function gives \(MF_{NPV} = \frac{1}{n\text{TechPot}}\) as normalized value, where \(n\text{TechPot}\) is the number of technologies with positive potential in a subsystem.

To search for the maximum and minimum relative NPV value (\(\text{maxR}\) and \(\text{minR}\)) for each subsystem two additional loops have been added. Moreover, an error message from subsequent simulation runs has pointed out that in some cases the highest net present value within a subsystem can be zero. Therefore, an additional verification statement has been added to the code assigning a small number to that variable so that the program can avoid a division by zero when calculating the \(\text{RelNPV}\).

When \(\text{RelNPV}_{Tech}\) is higher than a \textit{Cutoff} value the motivation factor is set to zero, meaning that when the NPV of a technology is relatively small compared to the highest one of the subsystem there is no incentive for that technology-investment. The \textit{Cutoff} value, which is given as input for each technology, is assumed to be equal to the one used for the Levelized Cost-motivation factor (there are no incentives for investments when a technology-cost is \textit{Cutoff} - times the cost of the cheapest one). In other words, it is assumed that the minimum boundary for the relative NPV is of the same order of magnitude of the maximum boundary for the relative levelized cost.

4.2.3.1 Sub-cases of investment typologies

A different calculation needs to be done for \textit{Unforced Investments} and \textit{Technology Transfer Investments}.\(^7\)

With regard to Technology Transfer Investments it has to be taken into account the fact that for a retrofitting investment usually there is a pre-existing power plant for which capital costs (called CAPEX A\(^8\)) have been already invested. Therefore, within a supplementary loop considering all the technologies to which the current one can transfer to, a differential NPV is calculated taking the additional investment costs of investing in the retrofitting part of the technology and the consequent exploitation costs (called CAPEX B).

\(^6\)The general formula to linearly rescale given values between \(\text{min}\) and \(\text{max}\) into a new arbitrary range \(\text{min}'\) and \(\text{max}'\) is:

\[
\text{NormValue} = a \times \text{Value} + b
\]

where \(a = \frac{\text{max}' - \text{min}'}{\text{max} - \text{min}}\) and \(b = \text{max}' - (a \times \text{max})\). In this case \(\text{min}' = 0\) and \(\text{max}' = 1\).

\(^7\)Recalling Chapter 2 Unforced Investment are not triggered by activity growth and Technology Transfer Investments consist in technology-retrofitting.

\(^8\)CAPEX (capital expenditures) are the investment expenditures to acquire equipment and appliances (Capros et al., 2016).
4.2. Code extension

\[
dNPV = -InvestTechTran + \sum_{i=1}^{EconLifeT} \frac{ExploitationCosts_i}{(1+r)^i}
\]  

(4.9)

where:

- \(EconLifeT\) is the economic lifetime of the technology to which the transfer investment has to be made;
- \(InvestTechTran\) is the additional cost of transferring from one technology to another and;
- \(ExploitationCosts_i\) is the change in the exploitation costs (including net fuel costs, operating fixed and variable costs, net emission costs, costs associated with carbon capture and storage, and subtracting the benefits of selling the main energy carrier) without the annual capital investment costs that are already considered in \(InvestTechTran\).

If \(dNPV\) results positive then it means the retrofitting investment is profitable so the motivation factor-score is set to one. Otherwise, a payback function which was already implemented in the model for this kind of investments is called.

This payback function applies to Unforced Investments as well and it is formulated in this way: if the pay-back time is lower than 5.5 years, the score is again set to 1; if it is higher than 40 years, the motivation factor score is 0; if it is between 5.5 and 40 years a decreasing value is assigned to the score as the number of years increases according to:

\[
MF_{NPV_{Tech}} = a \times PBTime^b - c
\]  

(4.10)

where: \(a = 8\), \(b = -1.2\) and \(c = 0.05\).\(^9\)

**Verification** To make a verification of the normalization function, the variables at stake for an arbitrarily chosen subsystem have been printed on the command prompt where the simulation running is displayed to check whether the correct calculations are performed by the code.

### 4.2.4 Expectations of future cash flows

The final step of the code expansion involves the introduction of actor expectations with regards to future fuel costs/benefits and emissions prices. Two additional variables have then been created in the model representing the expected fuel costs/benefits and the expected emission costs/benefits. The values assigned to these variables can be prescribed in two input files: Policy Instruments (already into the model, it has been modified to enable the insertion of expected \(CO_2\) prices for both ETS and non-ETS) and Expected Prices of Energy Carriers (a new input file added to Ensysi) where price expectations can be indicated every five years from 2010 until 2050.\(^11\) When the simulation starts these variables are called by the NPV calculation function and the future year is counted by another incrementing time-variable that starts from the current year.

### 4.2.4.1 Validation

For the validation of this last code modification the transport sector has been chosen as an example because of practical reasons since it involves a relatively small number of technologies, but the results can be applied to all the other subsystems. The following verification test wants to show that the simulated behavior of a consumer

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\(^9\)Being a variable representing costs it has been considered as a negative quantity in the NPV formula.

\(^{10}\)These values are already prescribed in Ensysi.

\(^{11}\)A function linked to the reading of the input files is in charge of interpolating these values for all the years.
that wants to buy a new car is conforming to a rational choice based on her expectations of future prices of fossil fuel for road transport: the higher are those prices the lower is the investment in a car that takes traditional fuel as main energy input. Indeed in reality there are many other factors influencing such an investment choice but this is left to subsequent research analyses in the upcoming chapters, since the purpose here is to show that the model is working as it is intended to be. In particular the object of the test are the realized investments of a traditional Internal Combustion Engine (ICE) car.

### Table 4.1: Expected prices for the three scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. price (scen1) [Meur/PJ]</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Exp. price (scen2) [Meur/PJ]</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Exp. price (scen3) [Meur/PJ]</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

The table shows three scenarios, with the first one having constant expectations of 12 Meur/PJ, the second and third one respectively an increasing and decreasing price expectations trend. The realized investment obtained are in fact relatively lower for scenario 2 and higher for scenario 3 compared to the ones obtained if gasoline prices are expected to be constant.

### 4.3 Conclusions

The results from the literature review and the analysis of the investment module provided in the first section of this chapter have led to the answer the second research question: How can the model be improved in order to fulfil the research objective? A new motivation factor representing NPV evaluation from actors has been implemented into the model in a consistent manner with regard to the other motivation factor aspects. Such extension enables to introduce the dynamic time dimension of money flows and the possibility to run the model with additional key variables for the investments in the energy transition context: actors’ forward looking expectations about future price trends.

With such extension, the code of Ensysi presents now two possibilities for the NPV function inserted in the investment module. A model user can flexibly choose among the two according to the analysis that has to be carried out:

1. **NPV-Function 1**: calculation of the net present value for each technology investment with future cash flows assumed constant and equal to the year in which the investment decision takes place (it can be called by Ensysi when actors’ behavior wants to be simulated as conservative or when the original version of investment evaluations needs to be reproduced);

2. **NPV-Function 2**: calculation of the net present value for each technology investment with future cash flows that can vary according to prescribed values in the new input file *Expected Prices of Energy Carriers*.

#### 4.3.1 Contextualization of the new model extension

The following list states how the new code extension is integrated in the main investment-decisions simulation. The variables of interest are calculated following this order for each simulated time step:

1. the levelized cost and NPV associated with each technology for all the subsystems are calculated;
4.3. Conclusions

2. investment for the technology transfers and the difference in exploitation costs are calculated for each possible transfer between two compatible technologies (in the case of technology transfer investments);

3. the motivation factor-score for NPV is determined through the normalization function according to the type of investment;

4. the values for the total motivation factor are calculated for each technology through a weighted average sum:

\[
MF\_TotTech = \frac{\sum_{i=1}^{nMF} \text{WeightMF}_i \times MF_i}{\sum_{i=1}^{nMF} \text{WeightMF}_i}
\] (4.11)

where \(nMF\) is the number of motivation factor aspects and \(\text{WeightMF}\) is the weight associated with each of those;

5. triggering elements for technological investments (such as scrapping of existing technologies and activity growth) are calculated;

6. investments in technologies are simulated based on demand (step 5) and the total motivation factor-score (step 3) for each technology.

4.3.2 Assumptions

As every model conceptualization and subsequent implementation, at the basis of Ensysi’s framework there is a set of assumptions. Those will be discussed in this section: firstly the ones at the core of the pre-existing model formulation and secondly the ones characterizing the code extension described above.

4.3.2.1 Ensysi default assumptions

- **Economic equilibrium**: Ensysi has been designed as an economic equilibrium model because it assumes that supply and demand are matching over all the energy subsystems.

- **Built capacity**: The amount of technological capacity that is installed at every time step is determined by the demand given for each year rather than by the arbitrary decisions of the investing agents. As a consequence, in Ensysi there are no over- or sub-investments.

- **Energy prices**: Another assumption in line with the market in equilibrium is the one concerning final energy prices. As shown by Equation 4.2 the final energy prices are based on the weighted average of the contributing technologies’ levelized costs meaning that the market is expected to be in equilibrium and the investment costs are recovered. The only exception is electricity since the price is based on the variable cost of the marginal option necessary to meet the demand. The assumption that the prices are set according to the levelized cost can result optimistic since in reality when the competition of energy markets takes place on the marginal costs the prices can go even below the levelized cost.

- **Demand**: In the model the demand is not elastic with regard to the quantity of energy output for end-use activities and this is consistent with the fact that there are immediate investments to fill the gap and that investments cover demand precisely. In fact, it would not be realistic to allow for excess capacity due to over investments and assume at the same time full-cost recovery.

To conclude, the main assumptions that make Ensysi a model based on perfect equilibrium market are that the right amount of capacity required to satisfy demand is generated and that there is full-cost recovery.
4.3. Conclusions

4.3.2.2 Code extension assumptions

**Rate of return:** The economic variables considered by the model are Interest Rate, to calculate annuity payment by agents and payback time for their investments, and the Discount Rate (see Table 2.1). The latter has then been taken for the NPV calculation as a discounting factor representing the project’s cost of capital and risk. However these values, that have been already defined in the input settings, are not company-specific as the WACC, since they are differentiate only per actor group.

**Actors expectations:** In the preliminary expanded version of the investment simulation module expected costs and revenues are assumed constant and equal to the ones referring to the year where the investment decision takes place. For an electricity market simulation model like the one described by De Vries et al. (2015) this might create the risk of over investments, given the fact that the main assumption for investment simulation is that actors are willing to invest up to the point that the investment makes a profit. However, the investment triggering system presented by Ensysi is different because here investments are activated by the demand for end-use activities and energetic needs. It is therefore the choice of the preferred technologies for investments the one that with the introduction of NPV as a motivation factor depends on which technology is more profitable (or less costly). The physical amount of technologies or power production capacity is in fact determined by activity demand given as an input scenario, rather than by the arbitrary investments decisions of actors. This can be referred again to the first assumption of Ensysi as a market equilibrium model. In the second version of the NPV calculation actors expectations are introduced leading to a time-dependent evolution of future cash flows. However, if not modified by changing the input file, they are assigned by default the future trends predicted by PBL based on the NEO 2016. Indeed, given the high level of uncertainty concerning these variables, future prices expectations are just assumptions made by the modelers.
Chapter 5

Model Results

The previous chapter has explained how the investment module of Ensysi has been set up and which modifications have been implemented to improve its analysis potentialities. Before exploring how the model’s results are influenced by the code’s extension and the idea behind it, the following section wants to provide the main output representations that Ensysi produces as it has been originally formulated. Afterwards, keeping the same input assumptions, the results of the simulations with the code extension will be shown to evaluate the impact of the modifications and compare them with the previous outcome. This will be followed by a validation where the last results are compared with the one from another acknowledged model (i.e. the PRIMES model) and with other predictions.

The comparison of the output results with the two different model versions (one where the single-year levelized cost calculation and one with the NPV) leads to the answer of the research sub-question: how are investments in the model influenced by differently simulated actors’ financial evaluations? This analysis is not only valid in terms of the model outcome but also to understand the mechanisms underlying investment assumptions for energy modelling and, more importantly, the overall dynamics and simulated influence of actors behavior within the national energy system.

5.1 Default simulation run

This section wants to present the outputs of Ensysi according to its default settings and input scenarios. For this purpose, given the fact that the output files are provided by Ensysi only in the form of text files, an additional coding part has been programmed in Matlab to convert the new output into more easy-readable graphs. This will be used for the subsequent simulations as well.

The choice of the results shown here has been done according to the relevance for energy policy evaluations. CO₂ emissions, total costs and investments per year, prices of energy carriers and energy production from renewable sources. The whole time-span that the model can simulate (from 2010 to 2050) has been covered. For this first output display the input settings have been set to the default scenario parameters.

5.1.1 Key model assumptions and scenario settings

Hereafter the default input factors that steer the model’s results are illustrated through a set of scenario settings. As already mentioned in section 4.1.1 there are eight scenarios that can be prescribed through input files (in a text format). For each scenarios there are often at least two predefined choices of settings, but those can arbitrarily modified according to the user’s preferences. A summary is presented below with the default scenarios choice of Ensysi (“Business as usual”) together with the main assumptions and references.
5.1. Default simulation run

**Actor Parameters Scenario** The default choice prescribed in Ensysi shows an investor profile characterized on average (the Majority group) by high concern for investment cost and slightly less concern for perceived technological complexity and initial investment barrier. The climate concern does not play a role (social attitude is set to zero) as well as there is no influence of policy targets (targets is set to zero). The new NPV factor has been left out here because it was not in the original version of the model. Table 5.1 shows the weights given to the various elements. The prescribed discount rates and value added taxes are the ones of Table 2.1.

<table>
<thead>
<tr>
<th>Innovators</th>
<th>Early Adopters</th>
<th>Majority</th>
<th>Laggards</th>
<th>Motivation Factor</th>
<th>Aspect</th>
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<td></td>
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</tr>
</tbody>
</table>

Table 5.1: Default actor parameters.

**Constraints Scenario** It specifies the maximum yearly availability of primary energy carriers such as methane, biomass and geothermal heat, as well as the maximum of $CO_2$ that can be captured and stored.

**Electricity Profiles Scenario** It consists of an input dataset concerning the hourly contribution of electricity demand and production of different technologies (heat pumps, solar, wind and hydro) to the total amount of demand and production in a year. Given its huge dimension and high level of details it has been not included in this manuscript. The data are taken from the input dataset of another model (Edesign1) and they come from the COMPETE model.

**Policy Instruments Scenario** It specifies the technologies that are banned from a certain year onward (for instance cars with an internal combustion engine characterized by high emissions) as well as other policy elements. There are three main Policy Instruments scenarios in Ensysi: basis scenario, 80 proc, and 95 proc. The one considered here is the basis:

- Investment subsidies for energy efficiency improvements: 14% of the investment cost is subsidized with 100 Meur per year;
- Budget for SDE+ subsidy: 3500 Meur per year until 2030;
- Remuneration system for small-scale solar PV: full remuneration until 2020, 30% remuneration from 2020 onward;
- Biofuel obligation for road transport (required energy share): it start in 2010 with 2.4% until 8.4% in 2050;
- Obligation for co-firing biomass in power plant: 13% until 2020;
- $CO_2$ price in the ETS: it is expected to remain low until around 2020 because of the large reserves of carbon credits owned so far until a certain point in the 2020s when the price will start to rise again. The values are provided in Appendix A. The reference here are the forecasts in the National Energy Outlook 2016.

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1 The SDE + is an incentive scheme consisting of a feed-in tariff (subsidy) for renewable energy production in the Netherlands (Netherlands Enterprise Agency (2017)).

2 Simultaneous combustion of biomass with other fuels in the same power plant for the production of energy carriers with lower emissions (Hansson et al., 2009).
5.1. Default simulation run

5.1.2 Output results

This section presents the results from a simulation run of the scenario setting described above, keeping the previous version of the investment module of Enysi (without NPV).

Use of RES

The graph shows the use of renewable energy technologies in filling up the final demand for energy production. Energy generation from RES is determined by the model at every timestep summing up for each technology (if that is the case) the contribution to gross final renewable energy demand in terms of energy input or output.

![Graph showing the use of renewable energy technologies over time]

Figure 5.1: Final share of renewable technologies on energy production (reference scenario)

After a steep increase which lasts until 2030 the total share of RES production drops again. Apparently this is because the Policy Instruments enacted for this simulation, which are in fact at the “Business as usual” scenario setting, are not enough to obtain an energy system’s evolution characterized by increasing sustainability. For instance, the fact that SDE+ subsidy budget goes to zero in 2030, the decrease in remuneration for solar PV and the loose carbon constraints explain these results because if fuel costs are not expected to be too high for the future there are not enough triggering elements for investments in renewable technologies, resulting in the declining pattern shown in Figure 5.1 after 2030.

Total emissions

Overall the $CO_2$ emissions of the energy system are declining of around 60 MTon. As it can be observed in Figure 5.1 there is a certain level of correlation between the $CO_2$ emissions and the share of renewable technologies. In fact the increase in the latter for the time-span 2010-2030 corresponds to a decrease in $CO_2$ emissions during the same period. Around year 2031 the emissions start to slightly rise again, in accordance with a decrease in renewable production, however only up to a moderate extent (13 MTon). Afterwards, for the final years there is again a drop in emissions which, looking at the policy instruments scenario, is due to a drastic increase in $CO_2$ prices occurring
5.1. Default simulation run

in the final five years. The emission shares from the energy sector considered by Ensysi are also shown in Figure 5.3.

Figure 5.2: \(\text{CO}_2\) Emissions (reference scenario)

Figure 5.3: Share of \(\text{CO}_2\) emissions per sector.
Total cost and realized investments

The total investment and cost of the energy system are illustrated in Figure 5.7 and Figure 5.4. Firstly, by total cost is intended the sum of the capital cost, fuel costs and operating costs (these variables from Ensysi are defined in 4.1.3), whereas total investment is the sum over all the subsystems of the investment costs of the new capacity added at the end of the year. The graph in Figure 5.4 reveals a first cost reduction until 2015, followed by a constant and moderate increase mostly due to an increase in capital costs, which is higher than the decrease in fuel and operating costs (see Figure 5.7).

Figure 5.4: Energy System Total Cost (reference scenario)
5.1. Default simulation run

![Graph showing capital, fuel, and operating costs](image)

Figure 5.5: Capital, Fuel and Operating Costs (reference scenario).

Again, this is in line with the increase in renewable share, meaning that higher costs have been incurred to invest in more energy saving and fuel saving technologies. In fact, as can be observed in Figure 5.6 the capital cost assumptions are, for instance in the case of electricity generation technologies, that higher upfront investments are needed for RES (the ones in the upper part of the figure) compared to the other conventional technologies. For what concerns total realized investments they present a rather steady path, with two peaks around 2015 and 2030 which are firstly due to subsidies for renewable technologies (that are prominent during the first 20/30 years according to the policy scenario) and subsequently to a combination of triggering elements, such as demand growth and the exhaustion of some technologies and plants life cycle.
5.1. Default simulation run

Figure 5.6: Capital cost assumptions for energy generation technologies

Figure 5.7: Total Realized Investments (reference scenario)

Prices of energy

The prices of final energy carriers are the ones resulting from the levelized costs of technologies except for electricity which is calculated differently and based on merit-order. Most of the energy carriers maintain a stable price
5.2. New version simulation run

pattern, except for electricity which is indeed more fluctuating. In particular, the electricity trend highlights two
downfalls around year 2031 and 2043. Looking at the electricity demand for dispatchable capacity these occur
because of a lower number of running hours of the merit-order generation technologies.

![Energy Price Chart](image)

**Figure 5.8: Final Energy Prices (reference scenario)**

From an overall perspective the outcomes resulting from the default scenario settings as well as the original version
of the investment module of Ensysi seem to be consistent among each others. CO₂ emissions are correlated with
the total share of renewable technologies on investments, as well as system costs. Moreover it has been verified
that the results from a simulation where the weight for the NPV motivation factor is set to zero are the same of the
simulation with the previous version of Ensysi (without the NPV and taking the same scenario inputs). This is an
important finding that enables a handier comparison of the two versions without switching from a model version to
another. The following section will compare the outputs illustrated above with the results of the new model version,
keeping the same scenarios.

5.2 New version simulation run

This section is dedicated to a comparison of the default output results (indicated in the graphs above as reference
scenario) with the ones resulting from the new version of the code simulation. More specifically this simulation
takes the same input scenarios of the one above except for the Actor Parameters scenario, which includes the new
motivation factor aspect based on NPV. According to the “Business As Usual” choice of the default actor parameters
scenario, a weight of 1 (the maximum) has been given to costs, meaning that this is the prioritized evaluation
element for an investment decision. In light of the introduction of a new and more accurate financial evaluation
element (the NPV-motivation factor), the research now wants to explore how investments decisions change when
this new aspect is considered instead of cost. Therefore a weight of zero has been assigned to the costs motivation.

[^3]: The first version of the NPV function (see section 4.3) is considered here, i.e. the one where the future cash flows are kept constant to the
current year values.
5.2. New version simulation run

factor and a weight of 1 to the *net present value* motivation factor. Moreover, within this simulation it is assumed that actors’ expectations about future CO₂ prices are equal to the the ones of the base policy scenario (Appendix A), whereas expectations concerning energy carriers’ prices are equal to the predictions made by PBL (Appendix B), which in turns are based on the NEO.

The graphs provided below show the same outputs variables of the previous section but with both scenarios: **Scenario 0** is the reference one and **Scenario 1** is based on the new version of Ensysi with the actors’ expectations specified above.

![Figure 5.9: CO₂Emissions (Scenario 0 and Scenario1).](image)

Figure 5.9: CO₂Emissions (Scenario 0 and Scenario1).

![Figure 5.10: Final share of renewable technologies on energy production (Scenario 0 and Scenario 1).](image)

Figure 5.10: Final share of renewable technologies on energy production (Scenario 0 and Scenario 1).
5.2. New version simulation run

The first compared graphs are the ones concerning CO$_2$ emissions and the share of renewable technologies on
5.2. New version simulation run

energy production. In first place, it can be observed that the graphs differ mostly for the final twenty years (2030-2050). This is not surprising because, keeping all the other factors constant, actors in Scenario 1 are expecting a continuous increase in CO₂ prices (from 26 Meur/Mton in 2030 to 80 Meur/Mton in 2050). In fact, with the new NPV-evaluation the EmissionCosts variable of Equation 4.1 is increasing every year of the economic lifetime of the considered technology making the overall CashOut (costs money flow) higher and thus the technologies with more emissions less attractive. The investment trend is therefore oriented towards a future scenario where the cost of producing emissions is higher of almost 50 Meur/Mton. The same holds true for the FuelCosts variable which now depends on the predicted increasing trend of the conventional energy carriers such as the price of gas.

As a result, in Scenario 1 there are more PJ of energy production from renewable technologies and therefore less emissions (with a maximum difference respectively of 13% and 30 Mton) especially in the final twenty years. The graph resulting from Scenario 1 shows that the share of renewable energy produced to fill up the gross final energy demand per year increases up to 25%. To show more in detail why this is occurring in the simulation, the analysis of some key investment-related variables is provided.

For instance, a first look at Figure 5.12 points out an increase of the solar PV stock compared to Figure 5.11, meaning that a higher profitability value has been associated to this technology with the NPV calculation. To assess that the output file with all the technologies’ motivation factors has been analysed for both scenario simulations, observing that the scores related to the NPV of solar in Scenario 1 are higher compared to the ones in Scenario 0, leading to a higher overall technology motivation factor. To check why this is occurring, the new output file that has been created to display the input values and the results of the NPV calculation done every year for every technology was examined to understand the difference in the NPV-scores of the two scenarios.

Table 5.3 and 5.4 summarize the relevant data to understand the solar PV example. Having the technology an economic lifetime of 15 years, if an actor assumes that future costs and benefits deriving from that technology’s implementation are equal to the current one (Scenario 0) (see note 3), then some costs/revenues increases or decrease are overlooked. For instance, in year 2043 if the future revenues are expected to remain at 3.5 Meur/year per unit of activity the resulting NPV is relatively lower to the one in Scenario 1 that can instead contemplate the subsequent benefit rise. The related investments for that technology are then not as high as in Scenario 1.

The same analysis can be done for all the other technologies that have been scored as more profitable in Scenario 1 because of different evaluations of future cash inflows or outflows trends. Overall it is therefore important to notice that the outputs differences determined by the NPV calculation depend on the trends of future prices expectations that are given in the related output file.

The energy prices are instead following approximately the same pattern within a range that is close to the original ones.

---

4Even if in scenario 0 the weight to the NPV motivation factor aspect is zero the NPV calculation are done by default in the program for every technology. In scenario 0 the financial elements considered for the investment decision is the levelized cost. However this leads to the same motivation factor scoring of the NPV because they differ only by a constant value (which is the monetary benefits of selling the main energy carrier assumed as constant for every technology). This allows us to compare the NPVs of the two scenarios.
<table>
<thead>
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<th>Year</th>
<th>NPV [(\text{Meur}) year]</th>
<th>Econ. Lifetime</th>
<th>Invest. Costs</th>
<th>Fuel Costs</th>
<th>Opex</th>
<th>Revenues</th>
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<td>0.1</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Table 5.2: Output cost-values for the solar PV example (Scenario 0).

\(\text{Meur} \text{year}^{-1}\) per unit of activity.
## 5.2 New version simulation run

<table>
<thead>
<tr>
<th>Year</th>
<th>NPV</th>
<th>Econ. Lifetime</th>
<th>Invest. Costs</th>
<th>Fuel Costs</th>
<th>Opex</th>
<th>Revenues</th>
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<td>146.4</td>
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<td>0.1</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 5.3: Output cost-values for the solar PV example (Scenario 1).
Having more investments in renewable technologies the total energy system costs are higher (Figure 5.14). As shown by Figure 5.15, this is mostly due to an increase in capital costs which occurs because there are more investments in renewable technologies. In fact, according to the technology cost-assumptions of the model, the capital costs for RES are generally higher with respect to the conventional ones (Figure 5.6). The fuel costs are instead slightly lower again because there is less utilization of conventional energy carriers that are overall more expensive compared to renewable technologies (for instance the fuel costs for solar PV are zero). Operating costs do not differ much, even if it is assumed that renewable technologies need more operating expenses.

The major differences can be observed again in the final twenty years because it is the long-term behavior of the energy system the one influenced most by a different set of actors’ expectations. As a consequence of more incentives toward RES, the total investments of the energy system are higher as well.
5.2. New version simulation run

Figure 5.14: Total cost of the energy system (Scenario 0 and Scenario 1).

Figure 5.15: Subcosts of the energy system (Scenario 0 and 1).
5.2. New version simulation run

The costs displayed in Figure 5.15 refer again to the ones defined in subsection 4.1.3.

Having illustrated the differences between the previous and the new version of Ensysi for the same default scenario inputs, it is now important to point out again a non indifferent assumption implied by the latter run: in the NPV the actors use as future fuel and CO₂ prices the ones indicated in the input files of Policy Instruments and Prices of Energy Carriers that correspond to the predictions made by PBL. However those prices prescribed as input are just assumptions made by the modelers and do not necessarily correspond to reality. Given the key role played by these expectations in influencing the model outputs it is now important to analyse which impact do they have on investments, not only in terms of the model sensitivity analysis but also as insights tools to answer the research question. Therefore in the following chapter the assumptions made here for the prices are compared to other assumptions.

Choice of the actors parameters

In this section a remark on the methodological choices that have been made to run the simulations above (new runs) together with their implications is made.

Set of motivation factor aspects  These settings have been modified only for what concerns the financial evaluation aspects. The explanation for this choice refers back to the main objective of the research: to provide a systematic and consistent analysis of different developments of the energy system according to the behavior of the actors involved. As the literature on energy simulation modelling has pointed out, the issue of transparency of the model assumptions has become even more important with the growing complexity of the investment-decision making processes those models want to simulate. For this reason, the model approach contribution that this research has initiated is that the actors’ behavioral component, that indeed play a role in their choices and thus need to be simulated, has to be represented in a way that is close to reality but also easily understandable and with the possibility of being validated by other sources. Therefore, the research approach wants to incorporate in the financial acknowledged component of the new motivation factor aspect NPV the risk perception element and the influence of different expectations about the future, in order to have an integrated factor whose component have a stronger theoretical background in the literature compared with the peculiar approach of Ensysi’s choice parameters. This focus is in line with the literature reviewed in Chapter 3, stating that investors generally base their choices on cost/profit considerations that are projected in the future as well.
As the sensitivity analysis mentioned in Chapter 3 has pointed out, the technological preferred choice of actors are influenced by the different consumer profiles given as input in the actor parameters setting. However, since the influence of those settings depends on the subsystem considered and cannot be generalized for the whole energy system, the research focus has shifted towards the new motivation factor aspect created that still wants to reincorporate the other subjective perceptions in the form of risk aversion factors (Capros et al., 2016). This issue will be recalled in the conclusions.

**Discount rates**  The discount rates have been left as well to the values already prescribed in the model because of the research focus on other variables. However, an additional simulation was run by setting these rates to the ones derived from the literature (see Table 3.3) to make a sensitivity analysis on the effects of these variations. The main results concerning the whole energy system (total emissions, share of renewable technologies on energy production, system cost) were not much affected by this change because of the small difference (4/3%) of the discount rates values for the company actors category, which covers a large portion of the energy system in Ensysi. Higher differences were instead observed in the sectors where consumers are the main actors because, according to literature, their discount rate has to be relatively higher (around 13/14%) than the one of company investors to take into account their tendency to value more short-term money transactions.

The conclusion drawn from such analysis are that when actors are characterized by higher discount rates there are less investments in renewable technologies. This is in line with the assumptions behind the future discounting principles of the NPV evaluation: a higher value given to short-term cash flows leads to a more conservative attitude given the assumptions on the high initial costs of renewable technologies and lower fuel costs of conventional technologies.

### 5.3 Validation of results

Before entering the more specific cases analyses that will be object of Chapter 6, this section presents a validation of the main model outcomes. In first place, a qualitative and high level validation will be shown, meaning that the main trends of the output variables will be compared with the ones from a model acknowledged at an European level, to assess the consistency of the correlation among different indicators. A subsequent validation analysis step will get more into the quantitative details of some variables’ patterns, taking as a reference the National Energy Outlook of the Netherlands.

#### 5.3.1 Qualitative validation

This first section of the validation part concerns the general predicted trends of the main model outputs, in particular \(CO_2\) emissions, share of investments in renewable technologies and total system costs. The main purpose here is to make a comparison with simulated long-term forecasts coming from an acknowledged source that can provide general trend-indications covering the whole timeline considered in Ensysi. In fact, other more specific sources, such as the NEO are indeed more accurate but limited to short term projections. Moreover, Ensysi is a simulation model for future-oriented exploratory analyses, likewise the suite of models taken as reference here. Therefore, the object of the analysis will not be the precise forecasted numbers, which indeed given the different scopes of the two models can be different, but the main trend developments that according to the scenario taken as reference will characterize the future developments of the European countries.

The main reference for this validation part is the EU Reference Scenario report from the European Commission (Capros et al., 2016). The document presents trend projections of the European energy system, transport and greenhouse gases evolution. Taking the same approach of Ensysi those trends are not intended to be exact predictions but more potential future occurrences based on a model’s simulations. In fact, unlike the results given by the NEO
which is more current-policy oriented, the Reference Scenario wants to explore future energy system developments in the long term and presents the same time-span of 50 years considered in Ensysi. The results displayed in the Reference Scenario report have been generalized at the European level but still giving indicators for each member state. Considering that this document concerns the European member states as a group of countries that are referring to the same policy targets (emission reduction and energy efficiency) to set their evolution on a sustainable development path, the purpose of taking those scenarios as a reference is to check whether the behavior of Ensysi as a national energy system simulation model reflects what should be expected from a country that is actively involved in the European energy transition.

In the following section a first description of the reference scenario for the validation is provided to better explain why it has been chosen for the validation. Subsequently, the main trends of Ensysi are compared to the ones predicted by the European Commission.

### 5.3.1.1 The EU Reference Scenario

At the basis of the projections illustrated in the EU Reference Scenario there is a set of interlinked models integrating technical and economic factors, that have been calibrated in such a way that there is continuity between past data and future prediction. Having the same approach of Ensysi, the set of models wants to represent economic equilibrium based on endogenous price calculations. At the core of the energy system modeling there is the PRIMES model, operated by ICCS/E3MLab (Capros et al., 2016), which predicts energy demands and supply, \( CO_2 \) emissions, investments, costs and prices. The modeled energy policies reflect the ones applied in Europe since December 2014, including the ETS, energy efficiency measures such as Ecodesign and the Energy Efficiency Directive (EED), RES 2020 targets and the related economic support schemes.

As seen before, among the main differences between the new and the previous version of Ensysi there is the trend of total share of renewable technologies on energy production. According to the previous version of the model after an initial growing pattern, energy production from RES starts to decrease again from around 2030 as if there are no more many incentives to invest in those. In the new model version which is based on NPV considerations rather than the single-year cost, the investments in RES are still growing after 2030 as well.

![Figure 5.17: Gross final share of renewable generation to meet energy demand (results from Ensysi)](image)

In order to validate the new trend, the results from the Reference Scenario predictions were analysed focusing on the power generation section. The report states that an initial growing pattern of renewable shares in electricity
5.3. Validation of results

generation occurs in order to achieve the European 2020 RES targets. As simulated in the suite of models of the Reference Scenario, investments in RES are a directly implied consequence of the prescribed financial incentives to meet renewable technology targets. In Ensysi the 2020 RES target is not specifically prescribed since the target for renewable energy in the Netherlands in 2020 is 14% (Energy Report, 2011), however the latter is indirectly obtained in the model through induced investments in RES that are again occurring because of simulated financial incentives, with some of them ending in 2020 or 2030. According to the Reference Scenario, once those incentives are phased out, the investments in the European member states are projected to maintain the growing trend also beyond 2020, which is due to technological learning that makes some renewable technologies more attractive, the increasing emissions prices and other market forces. These are all elements considered in Ensysi as well, since there is a growing function representing the potential for the less mature technologies, increasing emission prices and actors expectations on future fuel and CO$_2$ prices.

The inclusion of dynamic projections in Ensysi in terms of financial evaluations of the investments simulated by actors is therefore in line with the general trend predicted by the Reference Scenario because the actors still invest in RES after the scrapping of prescribed renewable point sources or after the end of some incentive measures. Moreover, according to both models’ results the most substantial changes in RES share occur during the first 20/30 years of the considered timeline because of the sustainable development boost implied by the policy targets modeled in PRIMES (Capros et al., 2016) and the default setting of Ensysi aimed at reproducing the same initial increment. Even if not as steeply as the first years, the growing trend is on average maintained afterwards.

According to the Reference Scenario the ETS determines a steady long term RES penetration and emission reduction because of increasing carbon prices and less allowances availability. As a consequence of the increase in renewable energy share, greenhouse gas emissions are also predicted to decline, which occurs in Ensysi as well even though at some point they stabilize. The reason might be that since the policy scenario implemented is the one of “Business as usual”, the long term decline is not guaranteed.

![Emissions results from Ensysi](image)

**Figure 5.18: Emissions results from Ensysi**

As a third indicator factor for the validation the total energy system cost is considered together with its sub-components, i.e. capital costs, fuel costs and operating costs. As presented by the Reference Scenario, there is a first rise due to the structural adjustments needed to cope with policy targets, whose effects can be observed also in the long-term but at a slower growth rate.

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6The potential in Ensysi is a variable associated to each technology representing the maximum increase of the technological stock in a time-step.
5.3. Validation of results

More specifically in the Reference Scenario the overall cost structure resulting from a growing share of renewable technologies presents a switch towards more capital intensity because of the higher capital investments in efficient technologies and equipment and lower fuel expenditures. In fact higher shares of renewable technologies in power generation leads to a decrease in operating and fuel costs. These trends are confirmed by Ensysi (see Figure 5.19).

![Figure 5.19: System costs results from Ensysi](image)

Concluding remarks

The reference scenario presents overall trends of RES share, emissions and energy system costs characterizing the European member states in their application of energy policies and long-term consequences of those. In this first part of the validation the same variables’ predictions resulting from Ensysi have been analysed in light of the Reference Scenario projections and the main conclusions are listed below:

- The new version of Ensysi reflects both the first initial boost in share of renewable generation due in the first 20/30 years to dedicated policy incentives and the consequent constant growth resulting from long-lasting effects of current policies that can now be captured in the model thanks to the introduction of actors’ expectations;
- Greenhouse gas emissions are thus presenting an overall decline as a consequence of reduced carbon intensity of power generation;
- The predicted substantial change in the energy system rises up the total system cost witnessing an increased capital intensity. Again this cost increase presents a slower growth rate after the initial structural adjustments driven by the energy policy directives.

5.3.2 Quantitative validation

Now that the general trends of the main model’s indicators have been validated with the ones from the Reference Scenario illustrated above, some more specific sources relative to the Netherlands are analysed to provide quantitative predictions. The documents which are now taken as reference are the National Energy Outlook (NEO) 2015 and 2016. Even though the NEO 2017 is already published, the previous versions have been chosen for the
5.3. Validation of results

validation because the creation of Ensysi occurred a couple of years ago and therefore the national scenario given as input to the model is based on assumptions and data referred to that year.

The NEO presents the observed developments of energy demand and supply, greenhouse gases emissions and other economic factors from 2000 until present, as well as future expected developments up to 2030. It is based on data concerning technologies, prices, markets and policies up to May 2015 (NEO, 2015).

For what concerns renewable energy share, the NEO 2016 shows an upturn of 3% in 2000-2013 and of 10/11% in 2013-2023. The first timespan is not entirely displayed by the results of Ensysi because of its default starting year (2010), however the second prediction is occurring right now in the model. As shown by the Figure 5.17, the overall predicted increase in renewable share is maintained. The reference table presented below indicates that the gross final share of RES production is 12.5% in 2020 and 20.6% in 2030. The predictions are in line with the ones derived by Ensysi: 13.8% in 2020 and 20.9% in 2030.

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2030</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable energy (petajoules) (calculation method as per EU directive)</td>
<td>35</td>
<td>92</td>
<td>119</td>
<td>253</td>
<td>421</td>
<td>503</td>
</tr>
<tr>
<td>Renewable energy (petajoules) (actual production) calculation method</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Share of renewable energy (%) (calculation method as per EU directive)</td>
<td>1.5</td>
<td>3.9</td>
<td>5.8</td>
<td>12.5</td>
<td>20.6</td>
<td>15.4</td>
</tr>
<tr>
<td>Share of renewable energy (%) (actual production) calculation method</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rate of energy saving (%) per year</td>
<td>-</td>
<td>1.7</td>
<td>-</td>
<td>1.5</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Energy savings according to EU Energy Efficiency Directive (cumulative petajoules 2014-2030)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>510</td>
<td>-</td>
</tr>
<tr>
<td>Energy savings resulting from measures in the Energy Agreement (petajoules)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total greenhouse gas emissions (megatones of CO₂ equivalents)</td>
<td>220</td>
<td>214</td>
<td>196</td>
<td>171</td>
<td>168</td>
<td>155</td>
</tr>
<tr>
<td>Reduction in greenhouse gases compared to 1990 (%)</td>
<td>1</td>
<td>4</td>
<td>12</td>
<td>23</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>Greenhouse gas emissions from non-ETS sectors (megatones of CO₂ equivalents)</td>
<td>-</td>
<td>123</td>
<td>107</td>
<td>95</td>
<td>86</td>
<td>83</td>
</tr>
</tbody>
</table>

Figure 5.20: Past data and future predictions from NEO (2016)

Energy consumption is expected to maintain a downward pattern during the whole period considered by the NEO. The same holds true for greenhouse gas emissions even if they present an increase in 2015 (due to “relatively cooler weather and commissioning of new coal-fired power plants” (NEO, 2016, p.12)), followed by a sharp reduction until 2020, and a stabilization pattern until 2030. This evolution is perfectly followed by Ensysi but with different quantities (lower) (see Figure 5.18).

For what concerns the electricity sector, up to 2030 the share of gas in electricity production will expand compared to coal as a consequence of decentralized production by gas-fired cogeneration plants. Despite different adjustments of coal and gas shares occurred previously, “the long term trend is clear”: the proportion of conventionally generated electricity will decrease and that of renewably generated electricity will increase” (NEO, 2015). In 2030 around 50% of electricity is expected to be generated from renewable sources. Actually the NEO 2016 has predicted an even more pronounced growth of renewable share for electricity supply especially because of the rise in offshore wind. Ensysi presents the same general trend even if solar covers a larger share than wind.
5.3. Validation of results

As stated in the previous validation part, the progressive shift of the energy system towards more renewable sources entails as a direct consequence an increase of investments capital intensity (see Figure 5.19).

To conclude, overall the results from Ensysi are respecting the trend described in the NEO except for the CO$_2$ trend that are reflecting the official trend development but with smaller quantities of around 30/40 Mton.

Conclusions

In this chapter the output results from two simulation runs of Ensysi have been presented and compared. Given the research sub-question at the basis of the chapter, how are investments in the model influenced by differently simulated actors’ financial evaluations?, it can be concluded that when current costs and benefits only are considered the preferred technological choices resulting from actors’ investment decisions are missing some dynamics that occur instead when expectations about the future play a role through the NPV. In the latter case considered, i.e. assuming that the agents have perfect foresight on the development of emission costs and the fuel costs predicted by the Environmental Assessment Agency, those dynamics consist mostly in the occurrence of additional incentives to invest in RES so that the share of RES does not decrease once the financial stimulus of the first years, according to the assumed policy scenario, has extinguished. This is because the final increase of CO$_2$ prices is taken into account as future emission costs of a technology and thus the ones characterized by more emissions result less attractive.

Those outcomes have been confirmed at a high level by the general pattern of the main outputs of the PRIMES model, as well as the more specific NEO predictions until 2030. It is then left to the following chapter a further analysis of the new model potentialities in terms of long-term influence of actors’ behavior on the energy transition.
Chapter 6

Cases Analysis

Having described the code expansion, the consequent differences of results compared to the original version as well as limitations and assumptions, this chapters leads to a closer analysis of two subsystems considered in Ensysi. In fact, so far the presented model outputs have been generally concerning the whole energy system without getting to the details of specific sectors or some technological stock developments. Once the high level general trends simulated by the model have been assessed, the purpose here is to explore and enact the original and new potentialities of the model, in order to answer the fourth research question: *How the inclusion of subjective elements, such as expectations about the future, influence investment decisions by actors?* What is intended here by *subjective elements* are more specifically the expectations about future prices. Looking for the answer to this research question entails then two important research steps:

- to determine what happen for different assumptions on the default price expectations;
- to prove the new potentialities that the new version of the model can present.

The analysis of the output results in Chapter 5 has presented, among the others, the predictions of Ensysi concerning the shares of emissions of the various subsectors of the energy system. As it can be observed in Figure 5.3, a large portion of CO$_2$ emissions is covered by the transport sector and the electricity production sector. For this reason the stock evolution of the technologies belonging to these two will be considered in the following case analyses to make the answer to the research question more specific. In particular for the transport sector the vehicles for road passengers will be considered. In such a way investment choices from both the consumer and company categories will be investigated in light of the new model formulation.

6.1 Case of Transport Road Cars

As stated by Morrow et al. (2010) if consumers are expecting a future growing trend of oil or fuel prices, it is likely that they will pay more attention to the fuel efficiency component when purchasing a vehicle and that they might switch to another form of energy input consumption. Such a research hint found in the literature has led the current section to the definition of three expectations scenarios to explore what might be the consequences for different agents’ behavior in these terms. It is important to specify that, as the model expansion has been formulated, actors expectations on future fuel (or CO$_2$ prices) can be inserted into the model through an input file and do not influence the evolution of the “real” (i.e. within the model simulations) prices that are calculated through the iterative balancing equations set (see section 4.1). Therefore, they only affect future costs and benefits considerations within the NPV calculation. Indeed, their influence relies on the discounting rate which might reduce the impact of longer-term price developments.
6.1.1 Case settings

The three scenarios chosen for the analysis are based on the default input file for the Expected Prices of Energy Carriers (Appendix B), which in turn derives from the projections of the NEO 2016. In particular, the focus is on the prices of transport road fosfuel (the one that according to Ensysi is the energy input for the traditional internal combustion engine (ICE) cars). Those are characterized by a first decrease due to excess supply in the market (NEO, 2016) which lasts until 2020 and a long term increasing trend up to around 17 \(\text{Meur/PJ}\). The actor parameters are also maintained at the default setting (Table 6.1), with the maximum concern for NPV, and a relatively high concern for complexity and investment barrier.

In “Low price” scenario the first downward trend of expected prices is maintained also after 2020 at more or less the same rate. “Default” scenario presents instead future price expectations that are assumed constant and equal to the ones of the year where the decision takes place\(^1\) (the trend plotted in Figure 6.1 for the “Default” is therefore the output result of the actual price evolution). Finally, “High price” scenario is defined as having the opposite expectations trend of “Low price” scenario. The initial price drop is still maintained, because it derives from past data, but after 2020 the prices keep on growing at a faster rate compared to the one of the “Default” scenario.

<table>
<thead>
<tr>
<th>Innovators</th>
<th>Early Adopters</th>
<th>Majority</th>
<th>Laggards</th>
<th>Motivation Factor</th>
<th>Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Social attitude</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Targets</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Costs</td>
</tr>
<tr>
<td>0.3</td>
<td>0.4</td>
<td>0.8</td>
<td>1</td>
<td></td>
<td>Complexity</td>
</tr>
<tr>
<td>0.05</td>
<td>0.1</td>
<td>0.5</td>
<td>1</td>
<td></td>
<td>Investment barrier</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Net present value</td>
</tr>
</tbody>
</table>

Table 6.1: Actor Parameters (Default setting).

Figure 6.1: Scenarios for the expected prices of transport road fosfuel

The technologies included in Ensysi to fulfill end-use activity demand of passengers for transport kilometers are:

\(^1\)To enable such “conservative” attitude the realized NPV-Function 1 of Ensysi has been called (section 4.3).
6.1. Case of Transport Road Cars

- ICE-2010: average car sold in 2010 with internal combustion engine;
- ICE-130g: ICE car that meets the emission standard of 130 g/km;
- ICE-95g: ICE car that meets the emission standard of 95 g/km;
- ICE-70g: ICE car that meets the emission standard of 70g/km;
- ICE-hybrid: hybrid ICE/electric vehicle;
- PHEV: plugin hybrid electric vehicle;
- BEV: battery electric vehicle,
- FCEV: fuel cell electric vehicle (hydrogen).

6.1.2 Results

The vehicles stock development resulting from the three actors expectations scenarios confirms what can be expected by a rational risk-averse behavior: if future fuel prices are assumed to maintain the downward pattern, the consumption of ICE vehicles is still covering around the 70% of the passenger transport sector, even if 23% of that are hybrid vehicles.

Figure 6.2: Results from “Low price” scenario.

Keeping the other scenarios constant, the parameters (i.e. the weights given to the motivation factor aspects) of the actors investment module were changed using the previous version of the model (that does not have the possibility of introducing actors expectations): these weights were increased or decreased in a coherent manner according to the conceptual model described in Chapter 3, up to the point that significant changes in the outputs occur. The result of such a focused sensitivity analysis on the previous version of the model is that the projection of Figure 6.2 cannot be simulated by the original module functioning not even with the most innovation adverse scenario (see Appendix D), meaning that the introduction of investment expectations has created some new dynamics into the model.
6.1. Case of Transport Road Cars

“Default” scenario presents a final balanced distribution of 50% ICE vehicles and the other half of electric vehicles, whereas “High price” scenario sees the conventional fuel-based vehicles reduced to a 35% total share, in accordance with the higher expected prices for traditional gasoline. Again, the same kind of sensitivity analysis was performed with the previous version of the investment module to roughly obtain the same results and identify the related actor parameters settings. In fact, with the latter two cases this was possible, meaning that simulating actors’ risk perception towards conventional car that might become too costly in the future through the NPV-function, corresponds to a “green” attitude setting of the motivation factors weights.

For all the three scenarios the FCEVs still remain a niche market because of their high initial investment costs and because of the assumptions made in the default *Global and exogenous technological learning scenario*. Here the growth of installed capacity of FCEVs is assumed to be half of the one of BEVs because a slow global technological learning for electric cars occurs.
To answer the research question posed at the beginning of this chapter with the case above, three potential profiles for consumers’ risk perception concerning the traditional fuel prices have been defined. Indeed those are only examples constructed to show what might happen to the future passenger transport sector when low/high prices are expected or when consumers just assume that the prices will remain equal to the current ones. The results prove that if the price evolution is the one of the “Default” scenario in Figure and the majority of consumers does not expect substantial changes in the current trend, a balanced stock evolution is reached where hybrid and PHEVs are mostly used. On the other hand, if there are no enough incentives to buy electric vehicles because low fuel prices are expected, a 40-50% share of traditional ICE cars is still expected, whereas in the opposite case the sector will be dominated by electric vehicles. On average for all the three scenarios the share of FCEVs and BEVs is still modest given their high perceived complexity and upfront cost.

In light of the model expansion from the case analysis of the Transport Road car sector it can be concluded that some the actors’ risk perceptions can be more easily modeled as future expectations instead of with different actors parameters settings that are difficult to validate. Moreover, there are some particular results, as the one of “Low price” scenario that cannot be obtained by changing only the weights for the motivation factor aspects, meaning that the introduction of expectations can create new mechanisms and modeling possibilities. Appendix D describes these findings and the tested scenarios more in detail.

6.2 Case of Electricity Production

This section is dedicated to another subsystem which is determinant for future CO₂ emissions and sustainability achievements, i.e. the one of electricity production. The main actors here are large companies (with consumers as co-actors, for what concerns the adoption of small-scale solar PV).

6.2.1 Case settings

The technologies considered for this sector are:

- Coal power plants;
- Gas power plants;
- Nuclear power plants;
- Biomass power plants;
- Wind farms;
- Solar PV installations;
- Geothermal power plant;
- Hydropower plant.

The Actor Parameters scenario is the same of Table 6.1.

²For the complete list of technologies and description see Appendix C.
6.2. Case of Electricity Production

6.2.2 Results

In order to define different possible actors profiles in terms of expectations about ETS prices and emission restrictions, a sensitivity analysis has been conducted considering the three Policy Instruments scenarios at disposal by default and different actors prices expectations (see Appendix A). For instance, a considered scenario setting had actors’ CO₂ price expectations kept constant to the ones of the year in which the decisions occur and actual CO₂ prices of the “basis” Policy Instruments scenario, or expectations as the “80 proc” Policy Instrument scenario and “basis” actual prices realization.

However, the resulting share of technologies utilised (shown in Figure 6.5) does not depend much on policy variations nor on actual policy realization. The share of conventional technologies turns drastically down in the first twenty years (with the disappearance of coal fired power plants) but gas plants technologies do not decrease with higher (expected) CO₂ prices and they rather maintain a stable share of around 30% also in the final years.

Figure 6.5: Average result for the technology stock of electricity production.

A closer analysis of the variable settings can explain that. In first place, looking at the single technology attributes, some gas power plants, in particular combined cycle gas turbines (gas turbines and steam turbines), are still considered relatively less costly because of their assumed parameters. Their energy efficiency starts in 2010 as 56% and increases of 2% up to 2053 so that the emissions costs are relatively low compared to the other gas-based technologies. The same holds true for the total initial investment cost. These assumptions lead then to an overall significantly lower cost even in comparison with renewable technologies.

However, this does not explain why even high CO₂ price expectations, that lead to a large difference of expected emission costs (indicated in green in the Figure), do not seem to change the overall preferred technological portfolio choice, not even with an increase in the social attitude and targets motivation factor weights.

The following two Figures show the difference in expected emissions costs (green color) when actors are assuming the “basis” CO₂ price set and the “95proc” price set.

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3 These data derives from the Technology Parameters input file related to the electricity production sector.
Actually, higher expectations for the ETS-prices lead to not only to high expected emission costs, but also to high expected revenues from selling emission allowances by investing in biomass and carbon dioxide removal technologies. In fact in the model it is assumed that when emissions are absorbed the corresponding permit to emit are not needed anymore by the plant owner so that she can sell them directly in the cap and trade market at the same price. Consequently, a steep rise of those prices makes very profitable the business case of such power plants compared to all the other investing possibilities, leading to a “re-balancing effect” of the NPV-score for each
6.2. Case of Electricity Production

This eventually results in less incentives for renewable technologies.

Concluding remarks

To conclude, the model seems to naturally tend to a long-term future electricity production scenario where on average the share of stock is roughly characterized by 30% of gas plants, 5% of nuclear and biomass, and the remaining 70% of renewable technologies. The share of gas plants is not sensitive to future high CO₂ expectations because the expected price scenarios used, that are the ones provided in Appendix A, have the highest price increases in the final 10 years. Since the assumed technological lifetime of gas plants is longer (25 years) it might be the case that the expected rise of CO₂ prices occurs too late to determine a significant variation in the final technology-portfolio composition.

Conclusions from the analyses

The results that have been obtained for the model runs described in this chapter are limited to the current model parameters (including among the others technology cost assumptions and discount rates). The research sub-question this chapter wanted to answer was *How the inclusion of subjective elements, such as expectations about the future, influence investment decisions by actors?* The subjective elements considered were actors expectations about two key future trends for the energy system: conventional gasoline for vehicles in the consumers transport sector and CO₂ prices for the electricity production activities. What can be concluded for the two considered subsystems in quantitative terms is that:

1. The simulated consumers’ investments in the road transport sector are influenced by future fuel prices in a way that if increasing prices are expected, starting from the NEV 2016 predictions, the share of electric vehicles can almost reach the 70% of the whole car stock;

2. For the electricity production sector the future CO₂ prices expectations based on pre-existing dataset from PBL (Appendix A) are not enough to arrive at a production share with less than 30% of gas plants. Those still represents a large portion of the power production because there are more incentives to invest in carbon dioxide removal technologies, that still imply conventional power plant, constraining the room for investments in renewable technologies. The result of such incentives mechanisms is that even strict low carbon policy actualizations, such as the “95proc” one, cannot deliver, according to the model results, a fully-sustainable economy by 2050.

However, what is important of such results, even more than the quantitatively predicted numbers, are the new dynamics arising from the model expansion as well as the resulting implications for the broader climate change context. Coming back to the two research steps anticipated at the beginning of this chapter, the new model function described in Chapter 4 for the NPV has led to the formulation of a new kind of scenario concerning agents’ behavior. This additional differentiation consisting of future energy prices expectations, presents an important value for Ensysi at least for two reasons. Firstly, it can be based on actual price predictions that can be derived from other models and studies, enabling to compare and eventually validate the model more easily than a setting of actors’ specific parameters, as the motivations factor aspects together with their weights. The attitude towards a technology can be systematically operationalized within the model through actors’ expectations about the incurring costs of deploying that technology, being either emission costs or fuel input costs. This represents an alternative to establishing a certain parameter such as perceived mitigation potential of a technology within a range of values that cannot easily be found in literature nor in statistical real datasets.

Secondly, the possibility to explore new runs based on actors’ expectations is completely new to Ensysi and, as both case analyses have pointed out, it might generate new outcome dynamics. For example, in the case of the transport

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4 As explained in Chapter 4 the NPV-score is determined by the relative NPV for each technology against the highest NPV in the whole subsystem.
6.2. Case of Electricity Production

sector, only the “Low price” actors’ expectations scenario has led to such a low future share of electric vehicles, even compared with the most consumer innovation adverse scenario of the sensitivity analysis concerning the original investment module (Appendix D). For the electricity production sector instead, expectations of increasing emission prices for the final years have made more profitable the business case of negative emission technologies rather than renewable technologies. Such interesting research hints will be reconsidered in the conclusions.

Despite the new model potentialities, there are still some limitations due to the model boundaries. The main one emerged from the second case is that, for what concerns $CO_2$ price expectations, actors do not take into account how these actual prices evolve according to the demand for emission allowances. This means that if they assume at some point in the future a higher level of emissions activity, and thus of allowances demand, they might overlook the resulting mechanisms occurring in the cap and trade market: those prices will increase up to the point that the demand for allowance will stabilize again. However, this might be referred to an overall limitation of the model itself which does not consider into its boundaries the dynamics of the cap and trade market because the $CO_2$ prices are given as input in the Policy Instrument file and they are prescribed as constant variables.
Chapter 7

Conclusions and Recommendations

Sustainability is no longer about doing less harm.
It’s about doing more good.

JOCHEN ZEITZ

This final chapter is dedicated to the overall review of the thesis work presented so far, as well as the main insights that have emerged. Firstly, the conclusions are provided, presenting the main results achieved in light of the research objective. The research questions are recalled again to present their answers. Afterwards, the recommendations resulting from the research analysis and literature review are given to other researchers and indeed to the users of Ensysi at the Environmental Assessment Agency for policy purposes. The chapter concludes then with the reflections part, where the whole research process is rethought in terms of the results achieved, methodological choices and overall enrichment as a part of the master study course.

7.1 Conclusions

The research process has started with a high-level contextualization concerning one of the most crucial issues energy policy is currently facing: the appropriate choice of policy directives and incentives that the European states should enact to support the energy transition. Indeed, whether or not a policy measure is successful is something that does depend on the final actors it addresses. This refers back to the concept of socio-technical system: government institutions, consumers and company investors all determine with their interrelated actions the future development of the energy system.

The core research object of the thesis was then the influence of actors’ rational and non-rational behavior on technology-investments in the energy transition. This behavioral component that covers not only the financial evaluation techniques of investment choices but also risk perceptions and future costs (or revenues) concerns, is characterized by high uncertainty but, at the same time, is a key element that needs to be considered in future scenario exploration. Following a recent trend of energy policy institutions in implementing integrated simulation techniques, the present research has taken as a tool for exploratory analysis the national energy system simulation model developed by PBL, with the aim of valorizing its research potentialities and improving its shortcomings.

The main research objective stated in the Introduction is to contribute to a systematic and consistent understanding of how actors’ behaviors can influence the future development of the Dutch energy system through the simulation of different agents-related scenarios. The overall result is that expectations about future key variables, e.g. prices
of energy carriers or policy instruments, diverging from current trends do have an impact on investment decisions and the resulting technological stock evolution, meaning that it is important for the establishment of a successful energy policy strategy to make sure that those expectations are aligned with their actual implementations. In fact, as the relevant literature research has revealed, the cost component of a certain purchasing decision by a consumer or, in the case of a company investor, the expected revenues from a project are decisive decision-making elements. These in turn are shaped by the way agents evaluate different options, as well as subjective components.

However, to make Ensysi an appropriate research tool in this sense, some modifications to the investment module were required. A set of research questions has guided the whole process aimed at fulfilling the research objective. Those are restated below, together with the provided answers.

**How are investment decisions made in the context of the energy transition according to scientific literature and to what extent Ensysi reflects that?** A careful analysis of the current investment module formulation, which is based on the motivation factor aspects, has revealed that the theoretical assumptions underlying Ensysi are reflecting Diffusion of Innovation theory with some additional elements from further studies from pro-environmental psychology. The resulting theoretical framework has been translated into a conceptual model that takes as main variables the motivation factor aspects from Ensysi. Some consumers profiles with different levels of climate concern and innovation aversion have been defined by setting different weights to those aspects according to the chosen theory and the derived variables relationships. This means that in the case of a “green” profile climate concern and targets have been increased, whereas costs, complexity, investment barrier and public resistance have been decreased. Those profiles were subsequently given as actors scenarios input to test whether the model’s actual behavior corresponded to the assumed theory, i.e. resulting in higher or lower renewable technology adoption. The results of such theoretical validation were positive since for the considered technologies a higher level of “green” innovative attitude resulted in more technology-adoption, and the other way around.

**How can the model be improved in order to fulfil the research objective?** As stated before, the research objective aims at giving a complete and systematic understanding of how actors behavior influences the developments of the national energy system. According to what has been found in the literature based on empirical data and other modelling approaches, discounting methodologies that enable to simulate future cash flows predictions are the ones most widely implemented. In particular the NPV approach has been chosen and codified into the investment module as a new motivation factor because of its simplicity and diffuse adoption in the energy sector. Two subsequent versions of the NPV function were created: one which assumes future cash flows constant and equal to the year in which the actor has made the investment decision, one that gives the possibility of specifying through an input file future energy inputs prices and CO₂ prices. The introduction of such dynamics projections and time dimension of money flows into the model represents a necessary step to overcome the previous model limitations in terms of simulated evaluation of energy projects and products purchase decisions. Moreover, it enables to answer the fourth research sub-question which concerns expectations as key variables.

**How are investments in the model influenced by differently modeled actors’ financial evaluations?** A comparison of the previous model version based on annual levelized cost calculations referred to the current year costs, and the new expanded version with the NPV has proven that overall the latter presents a higher share of RES on total energy production, meaning that the actors have more incentives to invest in this kind of technologies. This occurs in the long term because, even though the initial financial stimulus to promote renewable technologies adoption has extinguished after the initial twenty/thirty years according to the given policy scenario, actors are assumed to predict the future rise of CO₂ prices and the consequent higher emission costs. The conventional technologies characterized by higher levels of emissions appear then less profitable. In line with the increase of RES adoption there are lower CO₂ emissions for the final twenty years, and enhanced total system costs and realized investments due to an increase of capital cost expenditures that for renewable technologies are assumed to be relatively higher.
7.1. Conclusions

**How the inclusion of subjective elements, such as expectations about the future, influence investment decisions by actors?** To make the answer to this question more specific two cases were analysed: the road transport passenger cars subsystem and the electricity production subsystem. The choice of these sectors is due to the fact that they are characterized by a large emission share according to the main CO₂ emissions output of the model (Figure 5.3). For what concerns the first case, the subjective elements considered were the expectations on future gasoline prices for conventional ICE cars. The technology stock evolution was simulated for three scenarios with different expectations based on the currently predicted trend for the Netherlands. The results have confirmed that different consumers behaviors occur for each scenario. In the case of high conventional fuel price expectations, the share of electric cars covers in 2050 the largest portion of the cars stock compared to ICE vehicles. As it can be expected, the opposite outcome realizes for low projected fuel prices.

The second case analysis concerning the electricity production sector has pointed out instead that higher CO₂ price predictions do not lead to more investments in renewable technologies but, instead, it seems very profitable to employ power plants with the CCS option. This is explained by the fact that higher emission allowance prices trigger investments in carbon dioxide removal technologies that can absorb the emissions thus resulting in spare allowances that can be sold in the ETS market. Overall this leads to a reduced relative business case value of the renewable plants, even if they present less emission costs.

However, the worth of such insights lays not only in the fact that they provide an answer to the considered research question, but also in the implications that these model outcomes present for actual policy analysis. In fact, with the new simulation possibility for Ensysi of having different consumers scenarios based on expectations, some stronger model potentialities have been identified that can be referred back to the literature. Firstly, if the model user defines the actor behavior in terms of future expectations about fuel price trends, this input choice is more transparent rather than setting the social attitude or technology resistance component as motivation factor. In fact, while the former can be based on real trends and/or predictions, the latter kind of actors parameters (Table 2.3) steering investment choices in the model are very specific and subjective variables that cannot generally be found in scientific literature.

As stated by Pfenninger et al. (2014), since energy system models are not value-free and can cover not physically observed phenomena, it is important to make every choice and assumption underpinning the model as clear and verifiable as possible, especially when involving such crucial behavioral components. This is the reason why the model expansion and subsequent analyses have focused mostly on NPV, setting the maximum weight for that as motivation factor. The variations of the weights-setting for the other elements have been given a major focus in Chapter 3, when different actors profiles were defined to check the theoretical validity of the model, and for the sensitivity analysis mentioned in Chapter 6 aimed at obtaining with different actors scenarios of the previous model version (without NPV) the same results of expectations-based scenarios (Appendix D).

Secondly, such new function enables to embrace an important research tendency among current literature on consumers’ attitude. In fact, for a consumer that has to buy an energy-based durable good such as a passenger car, that might have different levels of energy efficiency, the prediction of future price of energy is an important element of the purchasing decision (Anderson et al., 2013). This holds true especially in the context of the energy transition where the transport market will expand even more the offer of electric vehicles. Therefore, a research that aims at simulating consumers’ evaluation of different vehicle options “must explicitly model consumers’ beliefs about future energy prices” (Anderson et al., 2013, p. 384) in order to cover the most crucial points of the purchasing process.

Moreover, the relationship between gasoline prices’ actual trends and consumers response to them through different buying choices based on their own projections, can provide additional room for market and economic mechanisms that, according to economic research, are currently influencing consumers’ estimations (Busse et al., 2013) (Klier & Linn, 2010). For instance, a steep growth of current prices could result in even higher price expectations, leading to an overall amplification of the incurred price shock. Those kinds of dynamics can now be simulated within Ensysi in other sector as well, offering valuable insights on the effect of policy instruments and directives, as well as reactions to economic exogenous phenomena (e.g. national price shocks).

Similar considerations can be made for the other sector considered, i.e. the electricity production sector. Here investors’ choices are again steered by expectations concerning emission allowance prices, being this sector one of the first affected by the ETS (Dobos, 2005). The additional complication of the investment choice due to these
regulatory constraints has brought the attention of private investors on the development of this additional “expense stream” (Rentizelas et al., 2012, p. 622) for conventional fuel-based power plants. However, the case illustrated in Chapter 6 has demonstrated that higher ETS prices can also create additional revenues from selling those permits, triggering investments for those kinds of technologies, that still imply the existence of traditional emitter plants. This might result in reduced investment room for renewable technologies. Those mechanisms can now occur in the model enabling a more complete simulated evaluation by the agents involved thanks to the additional profits/costs considerations based on expectations.

What can be concluded from the analysis’ results in terms of how energy analysts should deal with simulation modelling and what implications can be derived for energy policy makers and technology managers? What can be concluded from the analyses performed with the extended version of the model, in light of the overall energy transition context, is that actors’ expectations about future energy price trends are an important component of profits/costs considerations when an investment decision occurs. As stated by Franke (2006) “prices influence behavior and ultimately some element of behavior needs to change if CO₂ emissions are to be reduced” (p. 8). Therefore, a clearly established policy path can steer agents’ expectations, and the resulting behavior, towards the appropriate evolution of the energy system. For instance, if higher conventional fuel prices are expected because of well acknowledged low carbon policy targets, actors with a long-term investment perspective will be more encouraged to include more renewable technologies in their investment portfolio. Less policy fluctuations can eventually result into less agents’ deviations from the aimed goal of sustainable development. The whole society needs in fact to harmoniously contribute to such commitment and the energy transition process can be largely favored when expectations about future energy price developments and the resulting implications are shared by the majority of the contributing actors.

Looking at the research work from an overall perspective, the added value given to Ensysi as a simulation model for the Environmental Assessment Agency, lies in first place in the theoretical framework and literature background provided in Chapter 3. Secondly, the new motivation factor based on NPV has introduced in the model actors profit considerations and the temporal dynamic dimension to their cash flow evaluations for long-term investment decision-making. Lastly, the new scenarios based on actors’ expectations have brought to life the aforementioned interesting mechanisms resulting from new scenarios based on actors expectations. As discussed in Chapter 6 this allows for new simulation possibilities in terms of energy system’s stock evolution.

The following sections provides the recommendations resulting from the research analysis.

## 7.2 Recommendations

The recommendations provided in this section are directed firstly to PBL, being specific suggestions for Ensysi itself, and secondly to other researchers in the context of energy system modelling. They are based from the insights collected during the literature review, the practical issues incurred during the code implementation part, and eventually from the observations resulting from the cases analysis.

### 7.2.1 Recommendations for the model settings

A first practical recommendation given to the model refers to the current setting for the scenario parameters. The model gives in fact the possibility to change the weights given to the motivation factor aspects only per actor type (early adopters, majority etc.) but not per group type (consumers, large, small, companies etc.). This means that for instance if a change is made to those weights to simulate the scenario of a “green” agent profile such a modification applies to all the actors group, without giving the possibilities to differentiate among different attitudes of agents groups. According to the literature review of Chapter 3 this is indeed not the case because the behavior of a consumer might differ a lot from the one of a company investor in first place because of the different costs/profits...
7.2. Recommendations

needs and secondly for the unequal evaluation of the time occurrence of money transactions (e.g. consumers usually value more initial costs than long-term benefits).

The second advice for the model settings, which is also the main recommendation resulting from the research as a whole, is to substitute the “Costs” motivation factor aspect with the new one “NPV” and to give that the maximum weight of 1. In fact, the net present value represents a comprehensive element that includes not only the main concerns faced by every investor, i.e. the total investment cost, but also other more subjective components, such as risk perception and expectations about the future, that can be included in the discount rate used in the NPV formula.

The other motivation factor aspects have to be considered as scenario variables enabling to explore additional different actors’ behavior profiles. Following the conceptual model provided in Chapter 3, those profiles can be defined by giving different weights to the motivation factor aspects in a coherent manner that refers back to Diffusion of Innovation theory. The weights can be increased or decreased respectively according to the positive/negative relationship between the technology attributes and technology adoption (Figure 3.3). This approach gives a sound theoretical background to the choice of the “Actors parameters” and it additionally provides an interesting application of one of the main theories of management of innovation to the energy transition context. The agents profiles will be different for every subsystem because they are based on different technology perceived characteristics (specified for every subsystem input file) so that some technologies are, for instance, more sensitive to public resistance with respect to other technologies. An example of that is in the first case analysis of Chapter 6 for the “transport road car sector”, where the diffusion of the most renewable vehicles (BEVs and FCEVs) is constrained by the perceived complexity of their adoption. The prescribed actor scenario will then depend on the subsystem of interest and the technology-attributes assumptions need to be acknowledged first.

However, the whole value of having the NPV function as a motivation factor in the model is that the discount rate of the formula can already include the perceived technological or market risk component. The recommended approach of how to deal with the discount rates is based on the comprehensive review presented by Capros et al. (2016), which in turn derives from surveys of actually applied rates of return.

<table>
<thead>
<tr>
<th>Type of investment</th>
<th>Discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulated monopolies and grids</td>
<td>7.5%</td>
</tr>
<tr>
<td>Companies in competitive energy supply markets</td>
<td>8.5%</td>
</tr>
<tr>
<td>RES investment under feed-in tariff</td>
<td>7.5%</td>
</tr>
<tr>
<td>Investment under contract for differences</td>
<td>7.5%</td>
</tr>
<tr>
<td>RES investment under feed-in premium,</td>
<td>8.5%</td>
</tr>
<tr>
<td>RES obligation and quota system with certificates</td>
<td></td>
</tr>
<tr>
<td>RES investment in competitive markets</td>
<td>8.5%</td>
</tr>
<tr>
<td>Risk premium specific to immature or less accepted technologies</td>
<td>1-3%</td>
</tr>
</tbody>
</table>

Table 7.1: Discount rates in energy supply sectors. Adopted from Capros et al. (2016).

The discount rate of energy utilities operating in the power sector ranges between 8% and 12%. A size-related risk premium of 1-3% can be added for small and medium size companies, as well as for different levels of market competitiveness. Moreover, a diffuse practice when dealing with immature or less accepted technologies, or projects characterized by high regulatory uncertainty is to set in the discount rate a specific risk factor of 1-3% for immature or less accepted technologies (Capros et al., 2016). With regard to private consumers, the implicit discount rates used for investment choices in the energy sector can vary according to the product considered as illustrated in Table 7.2. The third column of Table 7.2 indicates downwards adjusted values for discount rates when policies promoting energy efficiency utilizations are operating. An example of that are policy-based promotions of energy efficient appliances to reduce households’ perceived technical and financial risk. This provides a valuable alternative the subjective factors, whose range values are not based on empirical findings. Following the suggested approach, the discount rates prescribed in one of the input files of the model can be given a stronger theoretical foundation and validation potential, since they are based on collections of data used also by other models.
7.2. Recommendations

<table>
<thead>
<tr>
<th>Product</th>
<th>Discount rate</th>
<th>Modified discount rate due to policies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private cars</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>Heating equipment for households</td>
<td>14.75%</td>
<td>12%</td>
</tr>
<tr>
<td>General households appliances</td>
<td>13.5%</td>
<td>9.5%</td>
</tr>
</tbody>
</table>

Table 7.2: Discount rates of individuals in energy demand sectors. Adopted from Capros et al. (2016).

7.2.2 Recommendations for future researches and model improvements

As already mentioned in Chapter 4 the model has been calibrated in such a way that the investments evaluations are based, from a financial perspective, only on the annual levelized cost. The revenues considered are the ones concerning the energy sector, thus the selling of final energy carriers. For all the other activities, for instance the sale of industry products, the cash revenues are out of the scope. For this reason, the net present values resulting from the financial evaluations related to technological investments in these sectors are mostly negative, meaning that in absolute terms they represent the discounted value of future cost per unit of activity, i.e. the levelized cost defined in section 4.1.3.

This shortcoming does not represent a substantial limitation for the model if, as it now occurs for the profits deriving from the energy production and sale activities, the price per quantity is assumed to be the same for each energy-generating technology. In such a way the difference with the real NPV is only by a constant factor. In this sense, a potential overcoming of the current model boundaries could be to set the revenues for the non energy-production activities in the form of constant functions representing the market value of the products considered, assuming a constant demand and a constant price. These values can be calibrated either with empirical data or in such a way that the NPVs do not result negative. A similar extension can be done for consumers’ activities as well. When investing in a new car or house appliance a householder is not making any profit at all, however, the utility derived from the purchase or the end user’s willingness to pay for it can be considered as a revenue or benefit. The function representing utility can be kept constant also in this case and defined n-factor higher than the costs in order to get an inflexible demand (which is the case in Ensysi for all end-use activities since demand is prescribed in the input files). Consumers would then still choose the cheapest options, irrespective of that constant factor added to the revenues.

With regards to the implementation of the NPV as motivation factor a simplistic approach, which follows the same approach of the “Costs” motivation factor has been taken for the function that takes the relative NPV of each technology and gives a score from 0 to 1. This function is assumed linear but this might not be the case in reality. Further model implementations that might want to be more realistic in this sense can consider an exponential function or a multinomial logit function.

A final specific recommendation is given with regard to the simulated ETS. The second case analysis of the electricity production sector in Chapter 6 has pointed out that the investment preferences are sensitive to high expected revenues created by the sale of spare emission allowances, i.e. the ones that are not needed because of the negative emissions due to CCS plants. As a result, the business case for these technologies (in Ensysi those are mostly biomass plants with the CCS option) might be very high compared to others, including renewable technologies. In the model there is the possibility to offset the benefits derived from selling the emission allowances, however, if the researcher might still want to take that into account, to analyse the mechanisms occurring in the cap and trade market, such an influential effect can be reduced through a weighting factor. However, the actual investments in biomass plants cover only a very small portion of the total realized investments for that subsystem, being in line with the real constraints in biomass availability and storage capacity (Hauck & Hof, 2017). This means that only the estimated relative NPVs of the other technologies are affected, overlooking the advantage of RES as zero-emission technologies. A weighting factor can then be assigned in the investment module to control the overvaluation of expected revenues.
7.3. Reflections

Working with Ensysi with a particular focus on the investment module and actors’ behavior means taking up one of the biggest challenges the model presents, i.e. to determine the choice of the actors parameters scenario. From the overall perspective of the energy transition problem, this means to bring the attention on the human dimension of energy production and utilization. Given the countless investigation potentialities, such a broad topic has called for a more specific definition of the behavioral element considered in order to not make the research question and objective too vague. The first research challenge has been in fact to find the right research scope and related methodology. The literature review as well as some research hints given by the current National Energy Outlook have provided the triggering elements that helped to set the path for the overall analysis.

From a methodological perspective, the literature has pointed out the absence of a certified way to quantitatively integrate social aspects in energy modelling, despite the acknowledgement of their key role as determinant factors for the development of an energy system (Pfenninger et al., 2014). For this reason, to make this approach more transparent and verifiable, the research approach has shifted towards the integration of rational and non-rational evaluation factors into a single element, the NPV, which has been largely used both in real life and in other models when it comes to profit-based decision-making. In fact, the establishment of environmental restrictions, e.g. obligations for renewable technologies penetration in the energy mix and for emissions reduction, and the deregulation of the electricity market has increased even more the competitiveness among generators, bringing the attention of private investors to a careful consideration of costs and profits (Rentizelas et al., 2012). The additional risks created by the uncertain regulatory context, for instance in terms of emission allowances prices, has also increased the importance of making predictions about future trends. The adoption of renewable technologies might be then not always the result of a genuine interest for the climate change issue, but a way to ensure portfolio diversification to eventually hedge risk in the case of strong carbon policies.

The research choice of focusing on these kinds of financial estimations has eventually led to a more straightforward methodological justification of assumptions and validation process. Different attitudes and actors’ scenarios have been simulated maintaining at the same time the transparency of choices, because the scenario variables were expected price trends rather than subjective parameters.

For what concerns the consumers group, several studies concerning adoption of RES, have identified costs and likely fuel savings as primary elements for investment decisions (Caird et al., 2008). Also the importance of the social context has emerged from the literature review (Frederiks et al., 2015), but because of the model boundaries and the general difficulty of introducing and operationalizing those aspects in a virtual framework, the present research has not covered such issue.

A singular aspect presented by the current work is that the theoretical foundation of the actor investment module has been done from scratch since there is no published theoretical reference about the model yet. However, this gave an additional incentive to make a good literature review that could cover the main aspects touched by the approach of Ensysi, but still without getting lost in all the amount of studies currently available. In fact, the literature on investment decision-making by agents in the energy transition context is so huge that keeping always in mind the main focus of the research and the scope of Ensysi helped a lot in maintaining the right timing path on the initial research stages.

Once the main studies concerning how investment behavior occurs in reality have been reviewed, the first reflection point that has risen is how to translate that behavior into modelling, and how to take into account actors heterogeneity as well as different scales of influence, while maintaining the appropriate aggregation level. In fact, from a local perspective the daily choice of consumers can affect the demand in the markets of energy products and services, whereas from the national perspective the overall societal behavior largely contributes to the (un)success of policy directives or technology-adopt. The constructed theoretical framework, based on Innovation Diffusion Theory, represents an interesting application of a theoretical milestone of technology innovation management to the context of the energy transition. The theory gives a well acknowledged classification of consumers profiles (innovators, early adopters, majority etc.), providing a methodological background to the grouping of the agents playing a role in Ensysi and to the choice of the main actors’ parameters. The idea underlying this multidisciplinary merging
7.3. Reflections

is that for the companies in charge of the creation of more sustainable, low-carbon, energy efficient technologies, it is important to consider the societal aspect of technology, i.e. the perceived characteristics that stand out in consumers’ eyes, sometimes even more than the technical featuring.

The coding part has been very challenging since it is one thing to run simulations and analyse the outcome of a model as it is, another matter is to operationalize the variables of interest for the research and implement a new piece of code in a program that someone else has created. The variables involved in the actors’ investment simulations are given as arguments in several different functions of the model. This means that a careful and deep analysis of the model was a necessary precondition for a correct subsequent model expansion. Looking for points of improvement of the model has required a good level of analytical skills and critical thinking that have matured during the research process leading to the identification of shortcomings and feasible solutions proposals. Moreover, the implementation of a part of the Graphic User Interface in Matlab\(^1\) has led to a rethinking of the way the user can approach and interact with the model, enhancing some previous theoretical notions of programming with a real-life issue, whose application has speeded up the subsequent simulations and analysis process.

After the conceptualization and implementation of the model expansion, other triggering reflection points have emerged from the resulting cases analyses. The first one concerning the transport sector has raised the question on how to model price forecasts by consumers. The concept of individuals’ reaction to policy-driven or market-based price shocks or fluctuations draws back to the macro-economics studies on human response to inflation and growth/recession. Future expectations might have the power of actually determining the real expected matter. For instance, if future high prices of conventional energy carriers are presumed, then a large part of the investments will go to RES or high energy efficiency technologies, that can eventually result in lower prices for the latter. It is then important for policy makers to take into account with some scenarios formulations, these phenomena when looking at the future of evolving and dynamic sectors such as the one of automobiles. Indeed this holds true for all the other sectors where energy prices play a role.

The second case analysis has drawn out instead another common issue resulting from the introduction of the emission allowances market. Companies within this scheme face the trade-off between buying allowances to emit or committing to plants equipped with carbon dioxide removal options that enable to scale down their emission level (Abadie & Chamorro, 2008). However, as simulated by the model, the adoption of these technologies not only result in lower greenhouse gas emissions payment but also in extra revenues derived from spare allowances. As the case analysis has shown, the possibility of receiving these revenues, that become higher with increased CO\(_2\) prices, can lead to an overvaluation of the business case of these plants. As a consequence, the room given to RES investment is reduced, compared to conventional emitter plants. Now, regardless of whether the assumptions in Ensysi leading to this outcome have been well formulated or not, a higher-level question arises on how the cap and trade mechanisms should be established, and if it would be better to focus on policy incentives from renewable technologies adoption rather than emission restrictions. In fact, bringing the attention of corporate power investor on such emission trading market, where additional opportunity for financial gain can emerge via manipulation, might actually result in a distortion of the structural and behavioral change our society needs to undertake to become more sustainable. Putting a price on something that is not quantifiable and that harms human health and the environment, such as carbon emissions, represents an attempt to justify the status quo, creating possibility of windfalls based on the trade of the allowances. These kinds of effects can let us rethink of the establishment of some policy measures, focusing the attention on the collateral incentives created.

The stage of model validation has represented another main challenge of the research, given the difficulty of comparing the model at stake with data from reality or other models. The model expansion based on the NPV-calculation has nevertheless helped with this issue, since there are other models, such as the aforementioned PRIMES, that make use of such simulated evaluation techniques. In fact, the high level of variables interconnection and the set of constraints for the model calculations have made difficult other validation approaches such as offsetting demand input variables (in fact demand is one of the main driving variables determining all the other model calculations) to arrive at a stable equilibrium of investment outcomes.

\(^1\)All the credits for the main idea and implementation of the GUI go to my colleague Manuel Sanchez. The section of the GUI that has been part of this thesis work is described in Appendix E.
The main lesson learned from looking at the energy transition through the eyes of Ensysi is to think in terms of a dynamic socio-technical system where each action or choice is influenced and, in turns, steers other actions and choices. This was reflected in the model functioning as well. In fact, the main issue that has some point has emerged from the research process has been the one of overlooking some important assumptions underlying the model when looking for explanations of the outcomes. Sometimes the urgency of obtaining results has led to a too hurried look at the overall framework assumed, resulting in a waste of time when subsequently looking for explanations. Indeed, the complexity of Ensysi and the large volume of input variables and scenarios has sharpen this issue even more, so a careful acknowledgment of all the input scenarios together with their related assumptions is recommended for future researches.

From an overall perspective, using Ensysi as an exploratory research tool can offer several potentialities in terms of scenario design, in particular with the investment module expansion; however, as every model, the results rely on a set of assumptions that can steer somehow the results. This does not mean that the predictions made by the model are not valuable. In fact, some interesting mechanisms have emerged from the cases analysis (recalled above) shedding light on how future policy instruments or actors attitudes can influence the energy system. The value of such considerations is to make future model users and policy analysts aware of the importance of the agents behavioral component that, once simulated, can lead to enriched scenario outcomes compared to the ones of optimization models.
A Policy instruments scenarios

Those are the three main policy scenarios defined by PBL: the *basis* policy path, the 80 proc (80% of emissions reduction within 2050) and the 95 proc (95% of emissions reduction within 2050).

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**Figure 7.1: Basis scenario**

**Figure 7.2: 80proc scenario**
Figure 7.3: 95proc scenario
# B Default Prices for Energy Carriers

<table>
<thead>
<tr>
<th>Year</th>
<th>Anthracite</th>
<th>Uranium (3.5% U235)</th>
<th>Waste</th>
<th>Crop wood</th>
<th>Waste wood from forestry</th>
<th>Waste wood from industry</th>
<th>Sugars</th>
<th>Starch</th>
<th>Grasscrops</th>
<th>Other dry organic matter</th>
<th>Manure</th>
<th>Other wet organic matter</th>
<th>Final solid biomass</th>
<th>Crude oil</th>
<th>Vegetable oil</th>
<th>Waste oil</th>
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<tbody>
<tr>
<td>2010</td>
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<td>8.50</td>
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<td>12.75</td>
<td>5.80</td>
<td>0</td>
<td>7.40</td>
<td>7.17</td>
<td>10.62</td>
<td>15.40</td>
<td>14.40</td>
<td>9.62</td>
<td>6.68</td>
</tr>
<tr>
<td>2100</td>
<td>3.70</td>
<td>0.38</td>
<td>0</td>
<td>12.00</td>
<td>5.30</td>
<td>3.70</td>
<td>10.40</td>
<td>12.75</td>
<td>5.80</td>
<td>0</td>
<td>7.40</td>
<td>7.17</td>
<td>10.62</td>
<td>15.40</td>
<td>14.40</td>
<td>9.62</td>
<td>6.68</td>
</tr>
</tbody>
</table>

Table 7.3: Expected prices for final energy carriers (taken from the input file of Ensysi).
<table>
<thead>
<tr>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>Unit</th>
<th>Energy carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.00</td>
<td>10.06</td>
<td>10.22</td>
<td>16.27</td>
<td>18.23</td>
<td>18.23</td>
<td>Meuro/PJ</td>
<td>Road transport fuel</td>
</tr>
<tr>
<td>13.00</td>
<td>10.06</td>
<td>10.22</td>
<td>16.27</td>
<td>18.23</td>
<td>18.23</td>
<td>Meuro/PJ</td>
<td>Jet kerosine</td>
</tr>
<tr>
<td>11.00</td>
<td>8.06</td>
<td>8.22</td>
<td>14.27</td>
<td>16.23</td>
<td>16.23</td>
<td>Meuro/PJ</td>
<td>Heavy oil for shipping</td>
</tr>
<tr>
<td>6.32</td>
<td>6.64</td>
<td>5.69</td>
<td>8.85</td>
<td>10.43</td>
<td>10.43</td>
<td>Meuro/PJ</td>
<td>Imported natural gas</td>
</tr>
<tr>
<td>6.32</td>
<td>6.64</td>
<td>5.69</td>
<td>8.85</td>
<td>10.43</td>
<td>10.43</td>
<td>Meuro/PJ</td>
<td>NL natural gas</td>
</tr>
<tr>
<td>6.32</td>
<td>6.64</td>
<td>5.69</td>
<td>8.85</td>
<td>10.43</td>
<td>10.43</td>
<td>Meuro/PJ</td>
<td>NL shale gas</td>
</tr>
<tr>
<td>8.32</td>
<td>8.64</td>
<td>7.69</td>
<td>10.85</td>
<td>12.43</td>
<td>12.43</td>
<td>Meuro/PJ</td>
<td>Hydrogen</td>
</tr>
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<td>6.32</td>
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<td>5.69</td>
<td>8.85</td>
<td>10.43</td>
<td>10.43</td>
<td>Meuro/PJ</td>
<td>Final gas</td>
</tr>
<tr>
<td>10.62</td>
<td>7.68</td>
<td>7.84</td>
<td>13.89</td>
<td>15.85</td>
<td>15.85</td>
<td>Meuro/PJ</td>
<td>Natural gas liquids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Meuro/PJ</td>
<td>Deep geothermal heat</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Meuro/PJ</td>
<td>Other extracted heat</td>
</tr>
<tr>
<td>9.48</td>
<td>9.95</td>
<td>8.53</td>
<td>13.27</td>
<td>15.64</td>
<td>15.64</td>
<td>Meuro/PJ</td>
<td>Heat - SHT for industry</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat - HT for industry</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat - LT for industry</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat - LT for OS with infra</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat - LT for OS no infra</td>
</tr>
<tr>
<td>13.61</td>
<td>11.94</td>
<td>14.44</td>
<td>19.44</td>
<td>19.44</td>
<td>19.44</td>
<td>Meuro/PJ</td>
<td>Electricity</td>
</tr>
<tr>
<td>12.62</td>
<td>9.68</td>
<td>9.84</td>
<td>15.89</td>
<td>17.85</td>
<td>17.85</td>
<td>Meuro/PJ</td>
<td>Road transport fosfuel</td>
</tr>
<tr>
<td>25.40</td>
<td>25.40</td>
<td>25.40</td>
<td>25.40</td>
<td>25.40</td>
<td>25.40</td>
<td>Meuro/PJ</td>
<td>Road transport biofuel</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat for horticulture</td>
</tr>
<tr>
<td>7.58</td>
<td>7.96</td>
<td>6.82</td>
<td>10.62</td>
<td>12.51</td>
<td>12.51</td>
<td>Meuro/PJ</td>
<td>Heat for other agriculture</td>
</tr>
</tbody>
</table>

Table 7.4: Expected prices for final energy carriers (taken from the input file of Ensysi) II.
C Electricity Generation Technologies

1. Old pulverized coal plant: 46% conversion efficiency when built in 2010, and lower efficiency in the years before 2010;

2. New pulverized coal plant: 46% conversion efficiency in 2010, and higher efficiency when built in later years;

3. Pulverized coal plant with CCS (post combustion): 20% fuel penalty (20% higher energy input), 80% CO$_2$ removal efficiency. This means that the conversion efficiency drops to 38% (for years after 2020);

4. Integrated gasification combined cycle coal plant with same energetic efficiency assumed for the pulverized coal plants;

5. Same as above but with CCS (pre-combustion): 20% fuel penalty, 80% CO$_2$ removal efficiency;

6. Combined cycle gas turbine (gasturbine and steamturbine): efficiency when constructed in 2010 is 56%; for earlier and later construction years efficiency decreases and increases, respectively;

7. Same as 5 but with CCS (post combustion): 20% fuel penalty, 80% CO$_2$ removal efficiency. This means that the conversion efficiency drops to 48% (for years after 2020);

8. Gas-fired combined heat-power (CHP), with heat delivered to a heatnet and used outside industry. 82% overall conversion efficiency (sum of electricity and heat);

9. Same as above but with CCS (post combustion). 20% fuel penalty, 80% CO$_2$ removal efficiency. 66% overall conversion efficiency;

10. Same as 8, but with heat used by industry;

11. Same as 9: but with heat used by industry;

12. Gas-fired plant combining gasturbine and steamturbine, but different from CCGT. 45% conversion efficiency;

13. Gas-fired power plant (steamturbine only). 38% conversion efficiency;

14. Gasturbine only; 30% conversion efficiency;

15. Gasturbine CHP that produces heat for industrial installations on-site (in addition to electricity). 88% conversion efficiency;

16. Uranium based nuclear power plant;

17. Biomass power plant. 37% conversion efficiency in 2010, improving to 41% for newly built plants by 2030;

18. Biomass gasification plant. 37% conversion efficiency in 2010, improving to 41% for newly built plants by 2030;

19. Same as above, but with CCS (pre-combustion). 20% fuel penalty, 80% CO$_2$ removal efficiency;
20. Onshore wind; 2500 full load hours;
21. Offshore wind; 4200 full load hours;
22. Large scale Solar PV installations; 1000 full load hours;
23. Small scale Solar PV installations; 850 full load hours;
24. Geothermal thermal power plant;
25. Hydropower plant.
D Sensitivity Analysis on Actors Parameters for the Transport Passenger Car Sector

This Appendix refers to the first case analysis of Chapter 6 and specifies which actor scenarios have been considered when trying to simulate the same results of the expanded version of the model with the original version (without the NPV-function).

Three scenarios with different consumers expectations were run giving to the NPV motivation factor the maximum weight: “Default”, “Low price”, and “High price”. The following tables show the actors parameters settings given to the original version (public resistance, climate concern, targets, complexity, investment barrier) of the investment module of Ensysi for “Low price”, and “High price”. The indicated actors parameters are related to the Majority, i.e. the largest actor type in Ensysi, that has then the largest influence. The results reported concern the share of electric vehicles (excluding hybrids vehicles) in 2040 and 2050.

“Low price” scenarios

The three main scenarios tested (other scenarios were tested but those are the ones chosen for display purposes since for the others there are not significant variations) have high weights for the variables that, according to the conceptual model defined in Chapter 3, are negatively correlated with technology adoption, i.e. costs, complexity and investment barrier. The share of electric cars in the final year does not decrease more than around 48% of the total passenger cars technology stock, whereas the “Low price” scenario, based on low price expectations for conventional gasoline rather than innovation adverse motivation factors settings (see Chapter 3 for the theoretical underpinning of those parameters). This means that in this case the new input scenario for the model based on expectations offers new outcome possibilities. It is interesting to notice that roughly the same results are obtained when public resistance has the maximum weight (Scen 1) and climate concern has the weight of zero (meaning that social attitude, which is the sum of the weights given to climate concern and public resistance, is set to 1 as well), and when social attitude is set to zero (Scen 2 and 3) (because both climate concern and public resistance are set to 0) meaning that the results are not very sensitive to public resistance.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Actor Parameters</th>
<th>Share of Elec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name</td>
<td>Publ. res.</td>
</tr>
<tr>
<td>Scen 1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Scen 2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Scen 3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7.5: Actor Parameters scenarios and related results.
However, testing some scenarios with the rate of interest for consumers changed instead of the weights to the motivation factor aspects has resulted in a similar outcome to the “Low price” expectations scenario. More specifically, increasing that rate to 11% has determined a reduced estimation of the future fuel benefits due to the purchase of electric cars and then to a lower final market share for those as in the case of lower expected prices for gasoline. This finding is in line with the research choice of shifting the focus on the NPV and its components (such as the rate of interest that represents different actors attitudes) rather than the weights to the motivation factor aspects.

“High price” scenario

Other three scenarios were tested to arrive at the results obtained with high gasoline price expectations. Relatively high weights for costs, complexity and investment barrier are maintained because according to the literature reviewed on consumers behavior in this sector, those are their first concerns when evaluating a purchasing options. Therefore, the other weights (for social attitude and targets) were increased to define a consumer profile that has more willingness to adopt green and innovative technologies. However, those scenarios do not result in a share of electric vehicles higher than 54%, whereas in the new scenario with high expectations for conventional fuel prices this arrives at 67%.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Actor Parameters</th>
<th>Share of Elec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name</td>
<td>Publ. res.</td>
</tr>
<tr>
<td>Scen 4</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Scen 5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Scen 6</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.6: Actor Parameters scenarios and related results.
E Graphic User Interface for Ensysi

The present thesis work has contributed, among the others, to the implementation of a part of the initial version of a graphic user interface (GUI), in collaboration with another student who has defined the main concept. This application enables to easily modify the input files of Ensysi, run simulations and graphically display the results.

The function created for this work is the one that enables to change the input parameters directly through a table that can be interactively modified within the “Scenario development” window of the app, without opening singularly the text files connected to the input folder of Ensysi. This function was done through a series of script files in Matlab. The purpose for this functionality is to enable a handier and quicker scenario development within the same environment and screen window, for both sensitivity analysis and scenario testing.

Figure 7.4: Main window of the GUI.
Figure 7.5: Scenario development window of the GUI.

Figure 7.5 shows the table where the *Actor Parameters* can be changed to create different scenarios.
References


Burgess, M., King, N., Harris, M., & Lewis, E. (2013). Electric vehicle drivers’ reported interactions with the public: Driving stereotype change?. *Transportation research part F: traffic psychology and behavior, 17*, 33-44.


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References


References


Padman, R. *Programming in Fortran 95-Self-study guide 2* (2007). Computational Physics, Department of Physics, University of Cambridge. OpenMP.
References


References


List of abbreviations

ABM  Agent Based Modelling
ACE  Agent-based Computational Economics
BEV  Battery Electric Vehicle
CAPM Capital Asset Pricing Model
CGE  Computational General Equilibrium
CPB  Central Planning Bureau
DES  Discrete Event Simulation
DFC  Discounted Cash Flow
DS   Dynamic Systems
ECN  Energy research Centre of the Netherlands
ETS  Emission Trading Scheme
FCEV Fuel Cell Electric Vehicle
ICE  Internal Combustion Engine
IEA  International Energy Agency
LCOE Levelized Cost of Electricity
NEO  National Energy Outlook
NPV  Net Present Value
PHEV Plug-in Hybrid Electric Vehicle
PBL  Planbureau voor de Leefomgeving (Environmental Assessment Agency)
PV   Photovoltaic
RES  Renewable Energy Sources
ROA  Real Option Analysis
SD   System Dinamics
SEMBE Sustainable Energy Management and the Built Environment
WACC Weighed Average Cost of Capital