PBL NETHERLANDS ENVIRONMENTAL ASSESSMENT AGENCY

MASTER THESIS

ENERGY SYSTEM FLEXIBILITY INTERACTIONS

ANALYSIS ON THE INTERACTION BETWEEN CROSS-BORDER INTERCONNECTIVITY AND DECENTRALIZED DEMAND-SIDE RESPONSE IN THE FUTURE DEVELOPMENT OF THE NETHERLANDS ENERGY SYSTEM

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Declaration of Authorship

I, Manuel SÁNCHEZ DIÉGUEZ, declare that this thesis titled, "ENERGY SYSTEM FLEXIBILITY INTERACTIONS" and the work presented in it are my own. I confirm that:

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Signed:

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"All human wisdom is contained in these two words:
-wait and hope."

The Count of Monte Cristo
Alexandre Dumas

UTRECHT UNIVERSITY

Abstract

Faculty of Geosciences
PBL Netherlands Environmental Assessment Agency

Master in Environmental Sciences

ENERGY SYSTEM FLEXIBILITY INTERACTIONS

by Manuel SÁNCHEZ DIÉGUEZ

The way in which humanity is sourcing its energetic requirements to fulfill the economic activities is experiencing a drastic transformation, this is characterized by a potentialized electrification trend in every industrial sector, and by intermittent renewable energy sources (IRES) carrying the decarbonization of the power sector. Given the uncertain unfolding of both cross-border power interconnectivity (XBIC) and decentralized demand-side response (DDSR), an integrational study is proposed to understand their impact and interaction within the energy system of the Netherlands. Here, after proposing and successfully implementing a novel electricity dispatch methodology within the PBL's energy system integration model (ENSYSI), a series of exploratory scenarios were performed with combinations of different deployment levels of IRES, XBIC, and DDSR. Important observations are provided, such as the breach of national emission targets in all scenarios. Moreover the indirect impact of the scenario variations in other sectors (e.g. the heat and hydrogen sectors), are exposed. Findings in this study indicates that both DDSR and more strongly XBIC, have the potential to alleviate the increased costs of the decarbonization significantly. Furthermore, an analysis to show the lack of market alignment of DDSR as the root of a lower cost mitigation potential relative to XBIC is provided. Based on the findings, a demand-side response mechanism coordinating with the market is proposed as a promising topic for future research, as a means to further reduce the expected transitional cost.

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List of Abbreviations

BE	Belgium
BEV	**B**attery **E**lectric **V**ehicle
CCS	**C**arbon **C**apture (and) **S**torage
CO_2	Carbon dioxide
CTF	**C**heap **T**echnological **F**actor
DDSR	**D**ecentralized **D**emand **S**ide **R**esponse
DE	Germany
DK	Denmark
DSR	**D**emand **S**ide **R**esponse
ECN	**E**nergy (research) **C**enter (of the) **N**etherlands
EJ	**E**xa**J**oule
ENTSO-E	**E**uropean **N**etwork (of) **T**ransmission **S**ystem **O**perators (for) **E**lectricity
ETS	**E**missions **T**rading **S**ystem
EU	**E**uropean **U**nion
EV	**E**lectric **V**ehicle
FCEV	**F**uel **C**ell **E**lectric **V**ehicle
FDC	**F**oreign **D**emand **C**urve
GB	**G**reat **B**ritain
GCA	**G**lobal **C**limate **A**ction
GHG	**G**reen**H**ouse **G**as(es)
GIEC	**G**ross **I**nland **E**nergy **C**onsumption
GT	**G**as **T**urbine
GUI	**G**raphic **U**ser **I**nterface
GW	**G**iga**W**att
GWh	**G**iga**W**att **h**ours
HDV	**H**eavy-**D**uty **V**ehicle
ICE	**I**nternal **C**ombustion **E**ngine
ICPC	**I**nter-**C**ountry **P**rice **C**orrelation
IEA	**I**nternational **E**nergy **A**gency
IEC	**I**nland **E**lectricity **C**onsumption
ImEx	**Im**ports (and) **Ex**ports
IPCC	**I**ntergovernmental **P**anel (on) **C**limate **C**change
IRES	**I**ntermittent **R**enewable **E**nergy **S**ources
LCOE	**L**evelized **C**ost **O**f **E**nergy
LDV	**L**ight-**D**uty **V**ehicle
LGF	**L**ogistic-**G**rowth **F**actor
MAF	**M**id-term **A**dequacy **F**orecast
MFS	**M**aximum **F**raction (of the) sub-**S**ector (activity for the technology)
MOC	**M**erit **O**rder **C**urve
MWh	**M**ega**W**att **h**ours
NGCC	**N**atural **G**as **C**ombined **C**ycle
NO	Norway
NUCL	**NUCL**ear

PBL	**P**lan**B**ureau (voor de) **L**eefomgeving
PHEV	**P**lug-in **H**ybrid **E**lectric **V**ehicle
PV	**P**hoto**V**oltaics
RES	**R**enewable **E**nergy **S**ources
SDE+	**S**timulering **D**uurzame **E**nergieproductie
SRMC	**S**hort **R**un **M**arginal **C**urve
TYNDP	**T**en-**Y**ear **N**etwork **D**evelopment **P**lan
XBIC	**X**(for cross) **B**order **I**nter**C**onnectivity

Chapter 1

Introduction

1.1 General Background

The stress that human activity has applied on our environment has reached a point where international leaders were forced to agree on a target to start limiting our unfavorable impact. The target focuses on holding back anthropogenic GHG emissions within a magnitude allowing temperature rise to stay well below 2°C above preindustrial levels (*Adoption of the Paris Agreement* 2015). This target is crucial to maintain realistic probabilities of minimizing unwanted planetary degradation (IPCC, 2013), and to avoid huge adaptation and mitigation costs (IPCC, 2014a, IPCC, 2014b). Unfortunately, despite current mitigation efforts, emissions are still increasing, proving that further policy strengthening is required to set the track to achieve the goals (IEA, 2018).

In this regard, the Netherlands' government has decided to strengthen the decarbonization target of 40% emission reduction by 2030 compared to 1990 levels, set by the European Commission, by making it now of 49% for the same period (*Coalition Agreement 'Confidence in the Future'* 2017). The power generation industry plays a fundamental role in the strategy to achieve the new target, implying that the transformation process being experienced by the sector will accelerate further. For instance, the installed capacities of renewable generation sources (RES) are expected to increase from less than 10 GW in 2017 to more than 20 in 2023, and more than 30 by 2030. This would imply a shift from a current share of about 15% in electricity generation[1] to nearly 60% by 2030, where most of the transformation will be carried by wind and solar power sources (ECN, 2017b).

Under these requirements, the variability of the power generation related to such technologies emerges as a topic of particular relevance to understand the dynamics of the upcoming power system. Intermittency (or variability) of the power generation refers to the fact that some renewable energy generation sources, such as wind and solar, have uncertain predictabilities as they respond to meteorological variants. When a power system strongly relies on intermittent renewable electricity sources (IRES), fluctuations become an ambitious challenge to provide the electricity at the times where the service is demanded on an accessible and decarbonized way (Ueckerdt, Brecha, and Luderer, 2015, Widén et al., 2015).

1.2 Future Integrated Energy System

As a consequence of variability, one of the most significant changes in the energy system of the near future relates to how the power system will guarantee the required flexibility to address the variability challenge. One way of achieving this is by increasing markets interconnectivity, where countries can source their electricity shortages and redirect their generated surpluses

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[1] In 2015, out of the total 110,070 GWh of electricity generation in the Netherlands, 15,329 GWh came from renewable sources consisting of 2,933 GWh from Bio-fuels (mainly co-firing coal power plants), 3,631 GWh from Waste, 93 GWh from hydro-power, 1,122 GWh from solar PV, and 7,550 GWh from wind turbines (IEA, 2017).

from and towards neighboring markets. At the same time, the countries should experience a narrower gap between their average generation costs of electricity and will allow regions to avail their local energy resources better. In this context many studies place cross-border transmission lines as one of the most important sources of flexibility for the Netherlands (ECN, 2014, Frontier Economics, 2015, Brouwer et al., 2016, ECN, 2017a). Furthermore, this is in line with the European Parliament's desire of increasing transnational interconnection capacity with the aim of fully integrating the European power markets (*Making Europe's electricity grid fit for 2020 (2015/2108(INI))* 2015). And it is also in line with the expected highly interconnected future scenarios for the Netherlands (ECN, 2017b, ENTSO, 2018).

However, the energy system consists of more sectors than the power sub-system, and under a future scenario in need of flexibility, all its intertwined components must be considered, in order to provide this flexibility and take advantages of the new opportunities delivered by the evolving panorama. Industries, services, and households require energy to meet their activities, which are not exclusive of a specific type of energy carrier, meaning that what before was traditionally done by burning fuel or using heat, in the future may be fueled with electricity if it ends up being more convenient for the business and customers (or vice-versa).

Figure 1.1 illustrates a very simplistic representation of the conceptualization of the system integration present between the power sectors and the remaining energy elements of the energy system.

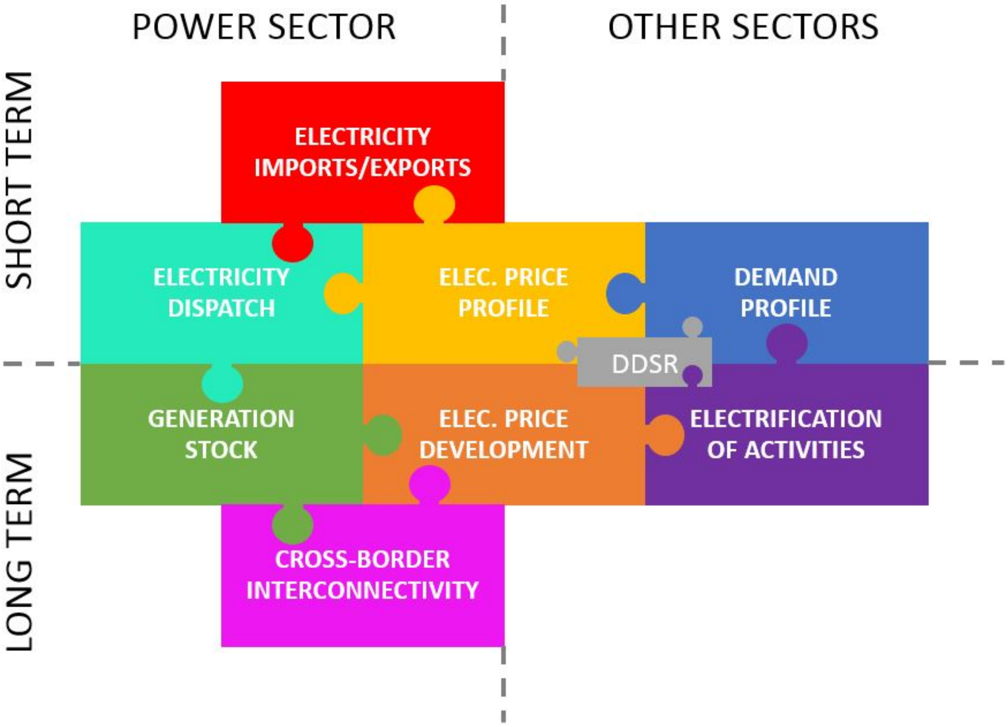

FIGURE 1.1: Energy system's feedback interaction. Conceptual representation of the impact of cross-border interconnectivity and decentralized demand-side response in the energy system.

Currently, the development trend indicates that many sectors of the system are electrifying their activities and that this trend could extend even more (World Economic Forum, 2017, Tsao et al., 2018). This means that changes in the power sub-system could echo in other energy sectors and at the same time feedback the power sub-system both in the short and long term. The mechanism of the sectoral interactions reacts to changes in the electricity price and its variability, where the development of these can potentially impact the energy system. In the long term, for example, sector investments could lead to the adoption of electricity fueled technologies if electricity prices develop to be a cheaper energy source than other options. Similarly if electricity prices develop a high variability, investors could prefer flexible technologies able to exploit low electricity price events. In the short term, actors may optimize their energy consumption schedule as much as their technological flexibility allows it.

Another crucial concept to understand the energy system integration, and the idea of system flexibility is "demand-side response" (DSR). DSR, as the name may suggest, stands for the action of reshaping the power demand profile as a response to supply variability, and many forms of it are available (e.g., a flexible hydro-power plant purchasing electricity to refill its reservoir or a household's smart meter, which operates appliances at low-load times). In this report, a particular distinction is made for decentralized demand-side response (DDSR) to differentiate the demand shaping mechanisms that occur inside the electricity market (centralized), from the uncoordinated rescheduling efforts responding to electricity price events or the load profile (decentralized).

The integration described above exposes the importance of understanding the development of the possible interactions between cross-border interconnectivity (XBIC), and decentralized demand-side response, as they both can decrease the variability within the electricity price profile. The following situation depicts a straightforward example of such interaction.

If XBIC increases, inducing import and export flows that will end up decreasing electricity price variability, the abundance of technologies profiting from these variances[2] can fall, or develop slowly. The repercussion of the changes in the electricity price profile may change the profitability of generation plants (Brouwer et al., 2015), determining the development of future generation stocks, and with this, the future of electricity price profiles. The latter will affect the need for more XBIC or DDSR, in a complex cycle that can only be understood when quantified simultaneously.

The challenge of studying the potential future system dynamics from such a thorny perspective is further increased by the number and magnitude of sub-systems within the national energy system. The latter explains why the energy system is usually studied separately, however, this sets aside the interdependency of the whole energy system dynamics and increases the risk of overseeing crucial co-dependencies among subsystems.

1.3 PBL's ENSYSI

The energy researching group within the National Environmental Agency of the Netherlands (Planbureau voor de Leefomgeving, PBL), is currently exploring outcomes within low-carbon future scenarios (PBL, 2016). Against this backdrop, it aims to add to the current existing repertory of analyses an integrated vision of the national energy system and the impact that transnational interconnectivity and demand-side response may have on it. To do this, a model has been developed by PBL which perfectly qualifies for this endeavor. ENSYSI (ENergy SYstem SImulation) is a model which integrates the energy transfers occurring within the energy system and accounts for the future development of the stocks of the technologies using different energy carriers forms in each energy sector. Using ENSYSI to study the current problem is a logical choice within PBL for many reasons.

Based on the level of economic activity of the sectors (production in different industries, travel

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[2] These can be decentralized technologies used by industries, households, and services to reschedule their power demand (which can be seen as a form of energy storage), or also centralized plants profiting from the temporary lower prices of electricity.

requirements, household sector development, etc.), this model balances the yearly energy carriers requirements with the energy generation sectors (heat, fuels, electricity, and others). ENSYSI also predicts technology choice investments not only by considering rational decisions but also by including other criteria used by actors. To make it even more suitable, the model also considers the implementation of different policy tools, such as the SDE+ subsidies program, banning of technologies, CO_2 prices, and other regulatory mechanisms.

Furthermore, by using a modular approach, ENSYSI is very versatile and can be easily adapted to include novel technologies and other potential system features that are uncertain in the future energy system of the Netherlands. The latter, together with its high level of agility, underlines why ENSYSI is the most suitable tool to analyze the integration of the future energy system. This agility can be noticed when a forty years simulation in ENSYSI takes about two minutes to be computed at PBL facilities, which enables to perform many scenario explorations without spending exorbitant amounts of computing time.

However, some adaptations are required in ENSYSI to integrate transnational interconnectivity into the energy system correctly. Specifically, as it is not conceived to be a power system model per se, ENSYSI makes use of some idealizations to determine the hourly electricity dispatch. The idealizations proposed in this study, provide an innovative way to reliably account for cross-border electricity flows without compromising ENSYSI's agility.

1.4 Research Aim

The main goal of this study is to quantify and understand the impacts that transnational power transmission, in combination with decentralized demand-side response, may have on the energy system of the Netherlands. The research builds on a certain level of detail, which provides a general perspective for the complete system and its sectors, while it also enables a deeper understanding of the power sector dynamics. The perspective must cover the following three pivotal axes of the energy transition: environment, economy, and technology. Therefore providing a robust development panorama of the energy-related emissions, the costs of the transition, the activities' electrification, and the technologies involved in the process. In this way, the results provided here aim to increase the existing understanding of the challenge that renewable energy variability represent for the energy transition of the Netherlands, mainly from a perspective in which flexibility from interconnection and demand-side response can help to ease the challenge. An integrated scope in which all the sectors of the energy system are considered simultaneously had not yet been fully explored for the Netherlands before. The latter happening gave the lack of a tool that can handle the magnitude and complexity of the problem. Now that PBL has assembled such utensil, another aim of the project is to test it and open the track to further similar studies to be made using ENSYSI. Eventually, increasing the understanding in this field will have a positive effect on the strategies used to mitigate social and environmental costs that must be paid to carry out the unavoidable and indispensable energy transition.

But besides that, there is an essential goal in testing the modifications made to ENSYSI in this project: to provide an agile and high-resolution electricity dispatch methodology that enables this type of colossal integration models to perform stochastic analyses and to include complex approaches to replicate and predict social dynamics. This will offer the scientific community not only a new dispatch methodology, but also a new machine learning alike purpose to the traditional highly detailed power system models.

In a nutshell, this study aims to benefit society by further unraveling the challenges of the contemporary crucial topic of energy transition and seeks to increase the arsenal by which the scientific community can address it.

1.5 Research Questions

To meet this aim, the following research question is answered:

How do cross-border interconnection (XBIC) and decentralized demand-side response (DDSR) interact under possible development paths of the Netherlands' energy system 2010-2050 transition?

In the process of answering this question, four research sub-questions are answered. The first two questions relate to the tools used to measure and describe the interaction between XBIC and DDSR. Sub-question number one provides a tool to fit the purpose by saying:

1 Which approach can be used to integrate international electricity trading into a model which uses a simplified merit order curve methodology to determine the electricity dispatch?

By means of answering the second sub-question, the performance of the selected approach in relation to a highly reliable power system model is used to evaluate the adequacy of ENSYSI for this study. It states as follows:

2 What is the performance of the selected electricity dispatch methodology when compared with a top-class power system model?

After the tool for this study is provided and evaluated, the modified version of ENSYSI is used to provide a quantification of the impacts and interaction of XBIC and DDSR by answering the following question:

3 What are the environmental, economic, and technical impacts of XBIC and DDSR in the different sectors of the energy system of the Netherlands under different transitional paths?

The last question attempts to expose the main mechanisms of the XBIC-DDSR interaction, to explain the observed impacts, completing the collection of the elements required to answer the main research question. The fourth research sub-question is presented below:

4 Which fundamental mechanism is leading to the observed impacts of the XBIC-DDSR interaction?

In the next section, it is outlined how these questions are integrated and answered within this research project.

1.6 Research Framework

The aforementioned questions are answered in a sequence of steps divided into three phases, as shown in figure 1.2.

Phase 1

The first phase sets the conceptual and contextual foundations of the research. In order to describe the energy system boundaries and elements, and to define the concepts behind the electricity dispatch, the research proceeds as follows:

i. Literature review and expert consultation to underwrite the electricity dispatch methodology that is used to adapt ENSYSI to meet the project requirements.

Phase 2

In the second phase the model modifications are designed, adapted, and tested in ENSYSI after collecting the external materials required[3]. The steps of this phase are shown below:

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[3] These materials are, the current version of ENSYSI, the model COMPETES to obtain the data required for the modifications, and the set of EU power system scenarios used within PBL and ECN, that is being used to feed into COMPETES to gather the data and to back-up the scenario designs of the third phase.

ii. Design and create the masks that contain the frequency of foreign electricity price distribution in correlation with local variables.

iii. Design and integrate into ENSYSI the approach that enables it to include cross-border trading into the electricity dispatch by using the previously created masks. The first research sub-question is answered here.

iv. Evaluate the performance of the ENSYSI's predictions before and after the modifications as using COMPETES' predictions as a reference. The second research sub-question is answered here.

Phase 3
In the last phase, ENSYSI is used to explore potential transition paths of the Netherlands energy system and use the outcomes of such explorations to understand the impacts of the interaction between cross-border interconnectivity and decentralized demand-side response.

v. Define and describe the scenarios that are explored in this study.

vi. Use ENSYSI to run the previously defined scenarios to quantify the impact of XBIC and DDSR on the energy system of the Netherlands. In this step, the third sub-research question is answered.

vii. Analyze the previously obtained results to explain the underlying mechanism of the XBIC and DDSR interaction, answering in this way the last sub-research question.

viii. Integrate the outcomes of the last two steps to address the main research question.

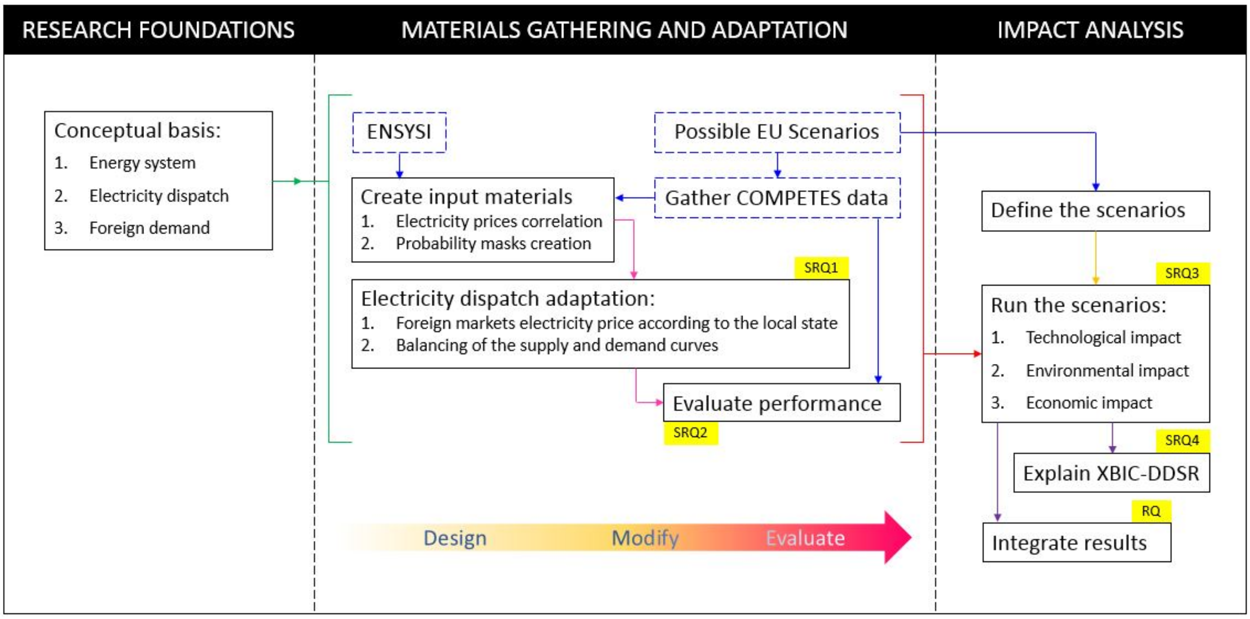

FIGURE 1.2: Research Framework. In blue: External materials used in the research. In black: The sequence of actions in which this research was conducted. Highlighted with a yellow tag: The steps in which the research questions are answered.

Chapter 2

Conceptual Basis

The proposed method to answer the first sub-research question is based on two pillars, ENSYSI and the concepts behind the impact of cross-border electricity trading in the power sector. Accordingly, this chapter focuses on providing the parsimonious description of ENSYSI required to understand the project and introduces the logic behind the new electricity dispatch method used to modify ENSYSI.

2.1 ENergy SYstem SImulation

ENSYSI is a model developed by PBL[1] to quantify the development of the demand and supply of energy within the Netherlands, and the related GHG emissions and monetary flows corresponding to it. Figure 2.1 illustrates the approach in which ENSYSI models the energy system. By using the yearly development for the activity level of the different sectors of the economy (e.g. the amount of steel produced in a year, the passenger kilometers, the number of households, etc.), and the current technological stock available in the system to meet those activities (e.g., the steel generation plants, the car fleet, the built environment technologies in the houses, etc.) as an input, ENSYSI determines the demand of both process and final energy forms required to meet those activities. Then it matches those yearly energy requirements accordingly to the energy generation stocks (e.g. the available industrial heat sources, refineries, power generators, etc.), which at the same time creates the demand of other energy forms (e.g., the production of heat requires gas, the production of fuels requires oil, etc). This enormous set of equations is solved using an iterative numerical approach towards a certain tolerance requirement[2].

Almost at the end of the loop, when the energy requirements are determined and the local power demand of the year is calculated, the electricity demand profiles for the year with an hourly resolution are obtained using historical profiles, and modified accordingly with the technologies present in the system (e.g., electric vehicles or heat pumps). Just before the electricity is dispatched, the decentralized demand-side mechanisms redistribute the load based on the fraction of the load that can be shifted, and the flexibility time range. This final demand profile is dispatched hourly by the available generation stock taking into account their generation profiles (it is relevant to know the availability of intermittent energy sources). After the electricity is dispatched, and the electricity price is calculated all the technologies responding to low electricity prices redistribute their load. And after this, the loop is closed.

After the balance and supply of energy is matched, and the stocks are scrapped in accordance with their lifetime and level of use, the investments occur. This step is crucial as it determines the available stock for the next year, simultaneously by adding new technologies into the system and

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[1] The development of the model started in August 2013, and its still being constantly improved. Thanks to those cumulative efforts of Robert Koelemeijer, Jan Ros, Klara Schure, Jan Matthijsen, and Liesbeth de Waal is it possible to perform this study.

[2] In this study 1.5 PJ was used as function tolerance

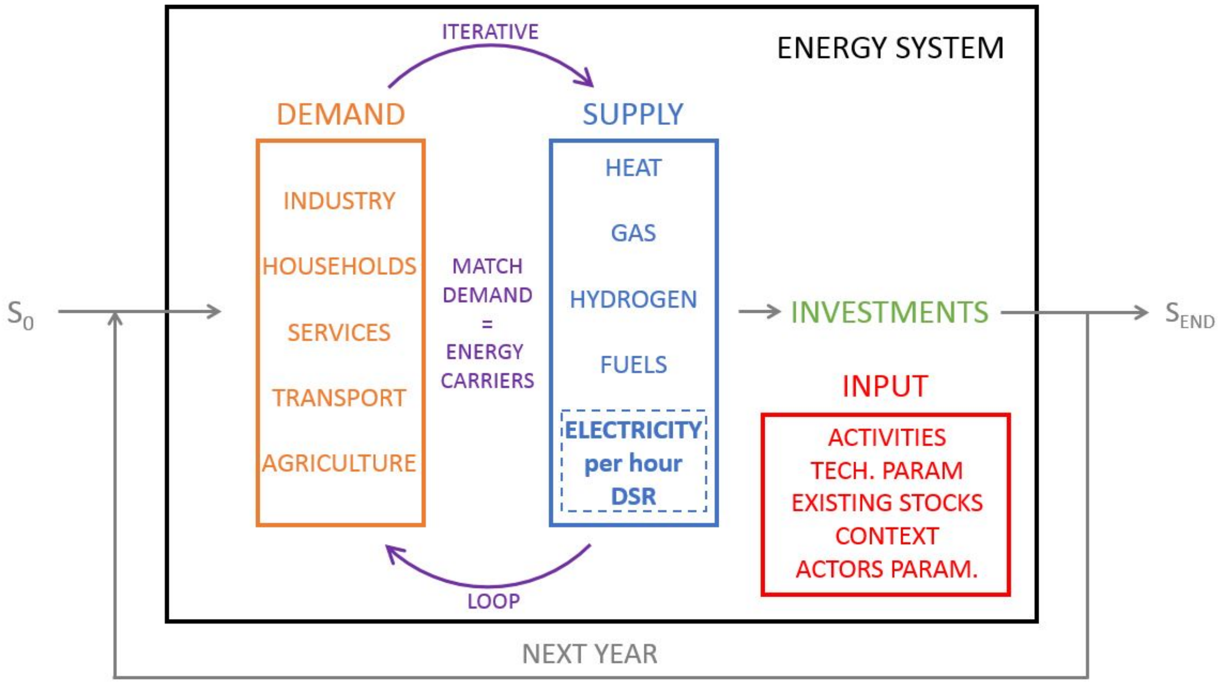


FIGURE 2.1: Description of ENSYSI. This figure presents a visualization ENSYSI's structure. The purple loop represents the internal iterative loop to balance the demand and supply of energy carriers that occurs in every year. The gray loop represents the yearly time steps in which the model describe the system state S_i (except the power sector which is described with an hourly resolution).

by modifying existing technologies (e.g., carbon capture and efficiency improvements). These investments are performed by different actors (e.g., companies, consumers, farmers, etc.), based on different investment criteria (e.g., costs, investment barriers, social attitude, and complexity), taking into consideration different actor types distribution within the population (e.g., innovators, early adopters, majority, and laggards). This is one of the most significant advantages of the model, as it considers multiple perspectives towards the development of the technologies in the system, and is what gives ENSYSI a multi-agent based modeling approach at least for the long-term picture.

ENSYSI performs all of these calculations relying on external data that is provided as inputs via a large set of extensive text files. This input information contains the activity drivers for all the sectors of the system, the parameters required to describe all the technologies within the subsystems (e.g. efficiencies, energy requirements, costs, learning rates, capacity factors, etc.), the existing technologies in the national system at the beginning of the simulation time (2010), the context of the system (e.g. policy regulations, physical constraints, development of technologies in the world, interconnection capacities, prices of the energy carriers, etc.), and the parameters describing the investment behavior of the actors.

Nevertheless, it is important to remember that the above description is oversimplifying all the elements that ENSYSI takes into consideration, as it summarizes in less than one page what, the already compact, model documentation shares in more than 70 pages (PBL, 2017).

2.1.1 System Boundaries

Testimonial of ENSYSI's proportions are the sectors, sub-systems, and the technology stocks within it, which together with the considered energy carrier forms, and the description of the Netherlands' activities, integrate the system boundaries of the model. ENSYSI organizes the energy system in 26 different sectors. Of these, 7 are related to Transport, 6 to the Industry, 8 to the generation of energy services, and 5 more for households, services, agriculture, waste handling, and energy infrastructure. Within these 26 sectors, more than 60 sub-systems are described, where each sub-system can either use energy, convert energy, or provide required energy infrastructure. Each sub-system is described by many substitutable technologies able to fulfill their activity requirements, accounting for more than 300 technologies in total within ENSYSI. The list of all the sub-systems contained in ENSYSI, including the number of considered technologies, and the sector to which they belong can be found in table 2.1.1.

TABLE 2.1: Sectors and sub-systems described by ENSYSI (PBL, 2017)

SECTOR	SUB-SYSTEM	n TECHS
Waste Handling	energy conversions related to waste combustion	1
	energy conversions related to waste combustion	1
	energy conversions related to waste combustion	1
Road Transport	energy demand passenger cars	8
	energy demand LDV s	8
	energy demand HDV s	3
	energy demand other road transport	1
Machinery Transport	energy demand mobile machinery	1
	energy demand defense	1
Rail Transport	energy demand rail	1
Ship Transport	energy demand recreation shipping	1
	energy demand inland shipping	2
	energy demand ships at NCP	2
Air Trasport	energy demand airplanes (LTO)	1
Fishing	energy demand ships fishing	2
International Transport	energy demand international shipping	2
	energy demand international air transport	1
Households	heat demand terraced houses	21
	heat demand dwellings	21
	heat demand flats	21
	regular electricity demand of households	1
	energy production for heat networks	5
Services	heat demand car dealers and reparation	5
	heat demand education	5
	heat demand hospitality	5
	heat demand nursery and health care	5
	heat demand offices	5
	heat demand other services	5
	heat demand stores	5
	heat demand wholesale	5
	regular electricity demand services	1
	production of heat for service-sector	9
Agriculture	heat demand horticulture	1
	heat demand other agriculture	1

TABLE 2.1: Sectors and sub-systems described by ENSYSI (PBL, 2017)

SECTOR	SUB-SYSTEM	n TECHS
	regular electricity demand agriculture	1
	heat production horticulture	5
	heat production other agriculture	2
Ammonia Ind.	energy demand ammonia production	7
High Value Chemicals	energy demand plastics production	9
Other Chemicals	energy demand other chemical industry	3
Non-Ferro Ind.	energy demand non-ferro metal	3
Ferro Ind.	energy demand iron and steel production	8
Other Ind.	energy demand other industry (ETS)	3
	energy demand other industry (non-ETS)	3
Energy Trades	import and export of energy	1
Losses	energy losses	1
Prod. Heat Industry	production super high temperature heat industry	2
	production high temperature heat industry	9
	production low temperature heat industry	5
Prod. Electricity	production electricity	25
Prod. Fuel	production biofuel	10
	production fossil transport fuel	8
Prod. Final Gas	production methane	10
Prod. Hydrogen	production hydrogen	6
Prod. Final Biomass (s)	mixing solid biomass streams	1
Energy Infrastructure	onshore electricity transmission	1
	offshore electricity transmission	1
	infrastructure for charging EV-cars	1
	gas infrastructure	1
	heat networks	1
	hydrogen infrastructure	1

All the above presented technologies consume and/or convert different energy forms either to provide an energetic requirement (e.g. electricity to light a bulb in a household), or a process requirement (e.g. coal required to source the carbon content in the steel alloy, or natural gas to produce hydrogen via methane reformation). ENSYSI contemplates 40 different types of energy carriers that can be used as an energy input, process input, or both. These are categorized as either primary or final energy forms as shown in table 2.1.1.

TABLE 2.2: Energy carriers considered in ENSYSI and their type (PBL, 2017)

ENERGY CARRIER	ENERGY	PROCESS	TYPE
Anthracite	yes	yes	Primary
Uranium	yes	no	Primary
Waste	yes	no	Primary
Crop wood	yes	yes	Primary
Waste wood from forestry	yes	yes	Primary
Waste wood from industry	yes	yes	Primary
Sugars	no	yes	Primary
Starch	no	yes	Primary
Grass crops	no	yes	Primary

TABLE 2.2: Energy carriers considered in ENSYSI and their type (PBL, 2017)

ENERGY CARRIER	ENERGY	PROCESS	TYPE
Other dry organic matter	no	yes	Primary
Manure	no	yes	Primary
Other wet organic matter	no	yes	Primary
Final solid biomass	yes	no	Final
Crude oil	no	yes	Primary
Vegetable oil	no	yes	Primary
Waste oil	no	yes	Primary
Residual light oil products	yes	yes	Final
Road transport fuel	yes	no	Final
Jet kerosine	yes	no	Final
Heavy oil for shipping	yes	no	Final
Residual heavy oil products	yes	no	Final
Imported natural gas	no	yes	Primary
NL natural gas	no	yes	Primary
NL shale gas	no	yes	Primary

2.1.2 Model Outputs

The primary output around which the deployment of the energy system is predicted relates to the use and development of the technology stocks. By endogenously determining the evolution of the presence of the technologies that produce and consume energy, and by quantifying those flows, all the other model outputs are obtained. These results are represented by the performed investments, and by the use of the technologies in a year. There are two following relevant outputs of ENSYSI, provided in a global, sectoral, sub-system, and technology scale. First the emissions in the year taking into account the ones coming from bio-resources and the ones captured. And then the system costs, distinguishing between capital, operational, and fuel costs. Beyond that, ENSYSI also reports some other intermediary outputs that are relevant for the description of the system, such as the fuel costs, the levelized costs of energies, the load duration curves, and the power curtailment among others.

2.2 Electricity Dispatch

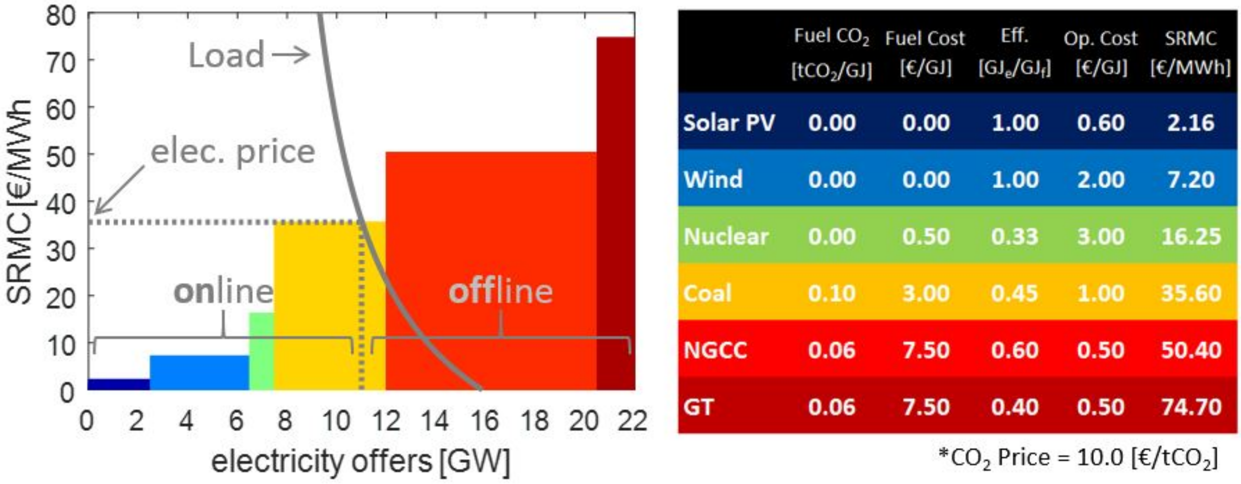
Perhaps one of the most complex dynamics within the energy system is to coordinate the balance of the supply and the demand of electricity with the power market operations. This complex system integrates the schedules of consumers, producers, prosumers, and their diverse magnitude flows under a certain set of geographical arrangements, transmission and distribution abilities, market structures and regulations, and now, with the growing presence of wind and solar sourced power generation, a determinant meteorological impact.

In reality, the power supply process occurs in two different markets, the wholesale and the retail markets. Being the first one, the most relevant to study, as it is directly exposed to the inherent variability of the dynamic power system. The wholesale market is divided in the long-term market, day-ahead market, and intra-day market, and is filled with major participants, such as the centralized generators, industries with large power requirements and or surpluses, and the retailers that provide fix contracts to smaller entities in the retail market. The wholesale market takes place in the form of tenders, where the load needs and the generation options are matched via biding and offering under a regulated environment (Erbach, 2016).

To be able to quantify long and short-term predictions for such a complex system, models often recur to idealized abstractions of the wholesale market. And the solidity of the assumptions backing up the approaches used by the models studying this system has a significant impact on their reliability. While there may be many different approaches to this process, the vast majority of them start with the same fundamental concept: the merit order curve.

2.2.1 Merit Order

Given the liberalized structure of the tenders, the availability and transparency of the information, and a large number of participants, it can be assumed that the wholesale market operates under perfect competition. This means that the participants are not following strategies to fix their mark-ups, so the price of their offers approaches considerably to their generation costs. Meaning that producers place their offers based on their variable dispatch costs, also called short-run marginal costs (SRMC), without adding any marginal profit. The logic behind this is funded by the intention of entering into the dispatch, where profits will occur if they are not the closing offer (marginal generator) and if they are the closing offer they have nothing to lose (at least on a short-term perspective).
Assuming that this is the ruling mechanism behind the dispatch, it is relatively simple to predict the hourly electricity price, and the generators sourcing that electricity, if their technological characteristics, their capacities, and the demanded load are all known. To do so, the SRMC of the producers must be calculated accordingly with their technological characteristics and the known fuel and emitting costs. Then it is only necessary to pile up the available capacities of the generators by increasingly ordering them in line to their respective SRMC, until the hourly demand is reached. This process, represented in figure 2.2, is known as economic dispatch, and the formed supply curve as merit order curve (MOC). However this approach considers only local demand and local generators, so in order to be able to analyze the cross-border interconnectivity within the electricity dispatch, another less simplified approach is required.



	Fuel CO_2 [tCO_2/GJ]	Fuel Cost [€/GJ]	Eff. [GJ_e/GJ_f]	Op. Cost [€/GJ]	SRMC [€/MWh]
Solar PV	**0.00**	**0.00**	**1.00**	**0.60**	**2.16**
Wind	**0.00**	**0.00**	**1.00**	**2.00**	**7.20**
Nuclear	**0.00**	**0.50**	**0.33**	**3.00**	**16.25**
Coal	**0.10**	**3.00**	**0.45**	**1.00**	**35.60**
NGCC	**0.06**	**7.50**	**0.60**	**0.50**	**50.40**
GT	**0.06**	**7.50**	**0.40**	**0.50**	**74.70**

*CO_2 Price = 10.0 [€/tCO_2]

FIGURE 2.2: Merit order curve. This figure exemplifies the merit order curve concept. On the right: A dummy table with the data behind the short run marginal costs (SRMC) of the generators. On the left: The MOC resulting from those SRMCs, the intersection between the demand curve and this curve defines the generators that will supply electricity (online), and the electricity price.

2.2.2 Foreign Markets

The electricity flows of interconnected countries have a large impact on the local system and are key to determine the final state of the dispatch. For instance, if an interconnected market is experiencing electricity prices lower than in the local market, it will be the case that the local demand will be sourced with imported electricity, displacing the expensive generators out of the curve and lowering the local electricity price. Similarly, if the opposite happens, and the prices of the interconnected market are higher than in the local power market, then electricity will be exported to that region. In this way, the demanded electricity for the local generators will increase, including new more expensive generators into the dispatch, thus increasing the local electricity price.

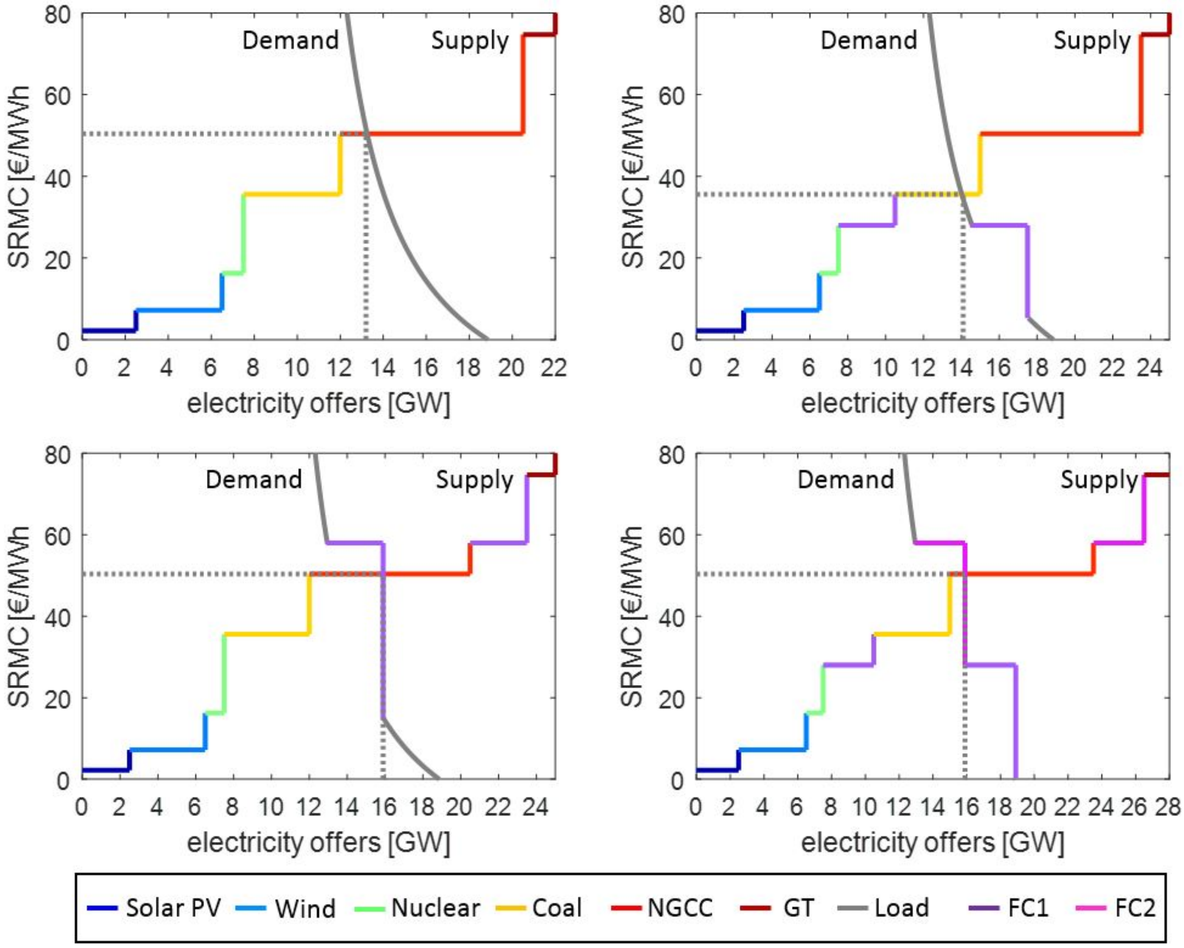


FIGURE 2.3: Interconnected dispatch. Top left: An exemplary MOC of a power system. Top right: Impact of an interconnected foreign country in the MOC, with a lower dispatch price. Bottom left: Impact of an interconnected foreign country in the MOC, with a higher dispatch price. Bottom right: Simultaneous impact of two interconnected foreign countries in the MOC, with both higher and a lower dispatch prices.

Furthermore, if more than one neighboring market is connected to the local system, the dispatch process is more complicated. For example, if a neighbor country presents low electricity prices, while another country experiences very high rates, it can be the case that even when the electricity from the cheap neighbor country would not enter by itself into the local dispatch, the domestic system imports electricity from one country to export it to the other country if there is no more available cheap local generation capacity. This process is visualized in figure 2.3.

In the particular case of the Netherlands, there are existing transmission lines with Belgium, Germany, Great Britain, and Norway, and as of 2019 the cobra cable connecting Netherlands and Denmark will be put into operation (TenneT, 2017). So to include their influence on the modeling approach, without obtaining the simultaneous dispatch for the whole interconnected generators of the North-Western European region, the following assumption is required. Given the case that the electricity prices of the interlinked areas are known, these countries can be assumed to participate in the local electricity dispatch as individual generators that can deliver as much electricity as the cross-border capacity allows it, at the given electricity price. Furthermore, at the same time, they can participate "as buyers" in the market if the local electricity price is lower than the electricity price of that country, and their purchasing capacity is also restricted by the cross-border transmission size.

To determine the dispatch under this assumption the local supply and demand must be balanced under the influence of those markets. This means that on the one hand, the merit order curve with the neighboring markets as providers will constitute the supply curve. And on the other hand, the same markets seen as buyers can be piled up together in decreasing order, to form what is here called the foreign demand curve. When the local system demand is merged with the foreign demand curve, the total demand curve results. Under this assumption, the electricity dispatch will be obtained by matching the supply and demand curves as shown in figure 3.3.

2.2.3 Current Electricity Dispatch in ENSYSI

The previous ENSYSI's electricity dispatch, before the proposed modification explained in chapter 3, lay only on the MOC concept, which ignores the impact of the foreign markets in the power system. It receives as an input the expected total yearly value of the electricity imported (or exported) and is subtracted from (or added to) the local demand. Then the residual load of each hour is calculated as the difference between the hourly local load and the sum of the available intermittent generators and the must run power plants. That residual load is the one that is used to find the marginal technology in the MOC, determining in this way the electricity prices and the online generators for that hour.

As previously mentioned, there are many elements from the real power system that this methodology ignores, such as the ramping constraints, the minimum on-line and off-line times, the grid-distribution constraints, and the effect from the adjacent markets. But there is evidence suggesting that a significant driver in the current electricity price dynamics is provided by the coupling of the markets (Newbery, Strbac, and Viehoff, 2016). Thus including the effect of the interconnection with the foreign market into the methodology is a priority for ENSYSI.

Chapter 3

Modifications to ENSYSI

In order to take a global perspective within the analysis and to provide an overview of all the energy sectors, a model with an integrated system perspective is required. ENSYSI is the most suitable tool that PBL possesses for such an endeavor. However, as a first step some modifications of the model are necessary, in order to address the research objective, which is to analyze the interaction between cross-border interconnectivity and decentralized demand-side response. Due to the level of integration in which ENSYSI was originally configured, it already includes critical considerations for potential demand-side response mechanisms. Certainly, these aspects of the model can still be further strengthened, but ENSYSI already suffices in that regard, and improving them is not part of the goals for this project. But since the previous targets of ENSYSI were related to the whole energy system rather than specifically to the power sector, the assumptions in which the electricity dispatch occur are still broad, and therefore the predictions may still be diverging from real behaviors. This is why, if the cross-border power flows are to be measured, and their impact analyzed, improving the electricity dispatch within ENSYSI is an intermediate target of the project.

3.1 Electricity Dispatch

The straightforward solution to improve ENSYSI's electricity dispatch would be to include a traditional more detailed power system model approach, including ramping constraints, transmission, and distribution constraints, and integrate it with generators of the western European power market. But this solution would considerably decrease ENSYSI's agility and would deviate from its primary purpose. Therefore after an internal period of consultation among PBL's experts in the field, another approach was proposed, based on observations of these when elaborating the FlexiNet report (Sijm, 2017), pointing out that transnational electricity flows have the most significant impact in the setting of the electricity prices.

The proposed electricity dispatch approach consists in using trans-borders flows data obtained from COMPETES, a super-high resolution model of the European power system, to "teach" ENSYSI how to stochastically predict the hourly electricity price of the neighboring countries by using its internal parameters. Then, the electricity prices are used to build a foreign demand curve and are also integrated into the merit order curve. Afterwards the local electricity dispatch, the import, and export flows, and the local electricity prices are simultaneously determined when balancing these supply and demand curves. However, it should not be overseen that this approach builds on several assumptions and simplifications, such as the lack of consideration of the flexibility generators, the geographical and regional nature of the supply and demand, and the distribution constraints. Therefore, if ENSYSI is to be used for this study using the proposed approach, it has to be tested first to prove its reliability.

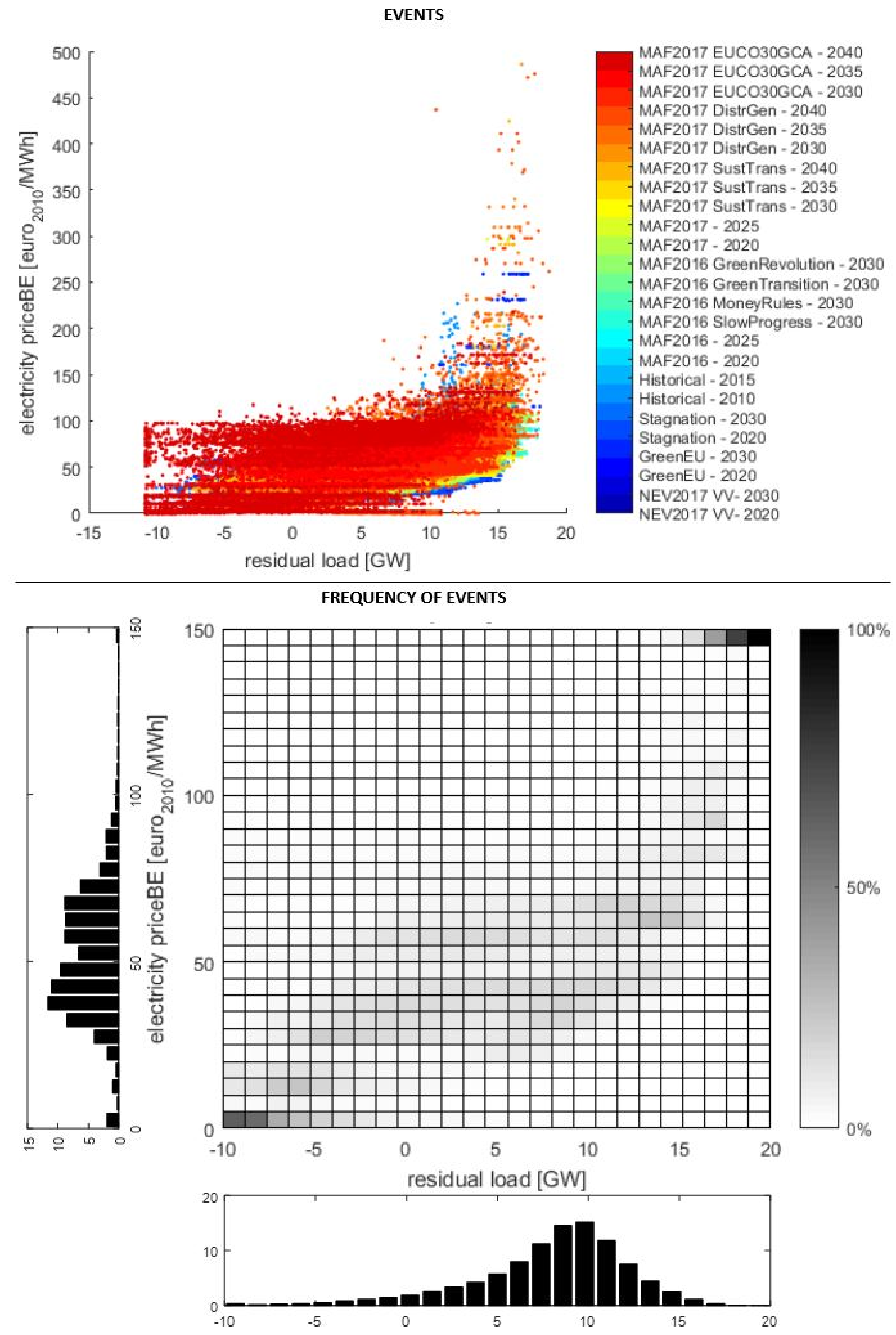


FIGURE 3.1: Correlation matrix between the electricity price (BE) and the residual load (NL). Top: COMPETES' data events used to obtain the matrix containing the probability distribution histogram. Below: Visualization of the matrix containing the aforementioned correlation.

3.1.1 Foreign electricity price correlations

Data from existing twenty-five COMPETES simulations were used to correlate the prices of the neighboring countries of the Netherlands[1] with internal characteristics of the energy system already present in ENSYSI. For this six different characteristics of the local system were used to obtain such correlations:

1. The residual load, defined as the difference between the local power demand and the IRES[2] electricity generation.
2. The fractional yearly availability of IRES, weighted by the capacities of each of them.
3. The installed capacity of IRES.
4. The CO_2 price.
5. The fossil fuels price, obtained as a mix consisting of 80% the gas price and 20% the coal price.
6. The hypothetical European scenario of interconnectivity and IRES installed capacity.
7. The year. Given the relatively low short-term uncertainty, this variable is considered in the correlation only after 2030.

The correlations are provided with a bi-dimensional matrix for each country and each correlation variable. In this matrix or mask, the columns contain the normalized histogram of the electricity price events in a country, and each column corresponds to a range of the correlation variable. Then, when a certain state of this correlation variable occurs in the system, the corresponding histogram is delivered by this matrix. In this way, an accurate approximation for the probability of a certain electricity price in that specific country under a certain local system state is provided. A visualization of the matrix containing the correlation between the electricity price in Belgium, and the residual load is shown in figure 3.1.
The final products are 30 matrices (six[3] correlation variables and five countries). These matrices are fed as an input in ENSYSI, which uses them to deliver hourly price predictions for the aforementioned foreign countries. The matrices do not need to be modified to run any simulations unless for some reason it is desired to consider different correlation data.

3.1.2 Foreign electricity price predictions

The previously described matrices are used within each hour of the simulation just at the beginning of the routine that determines the electricity dispatch in ENSYSI. Here for each country the six histograms are obtained accordingly with the system state of each of the corresponding correlation variables. Then, as illustrated in figure 3.2, the geometric average of all the six histograms is obtained and integrated to determine a final representative cumulative histogram for each country at that current hourly system state. These cumulative histograms are used by calling a random number for each country and comparing it with the vertical coordinate of this curve, then the hourly electricity price of a country is determined by the horizontal coordinate of the intersection.

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[1] Neighbors in a way that their electricity network is or will be interconnected to the Netherlands. These countries are Belgium (BE), Germany (DE), Denmark (DK), Great Britain (GB), and Norway (NO).

[2] IRES refers to the intermittent renewable energy sources. ENSYSI considers these to be onshore and offshore wind turbines, small and large photovoltaic, and hydro-power.

[3] the European scenario matrix contains the year effect by presenting several columns depending on the year for each scenario.

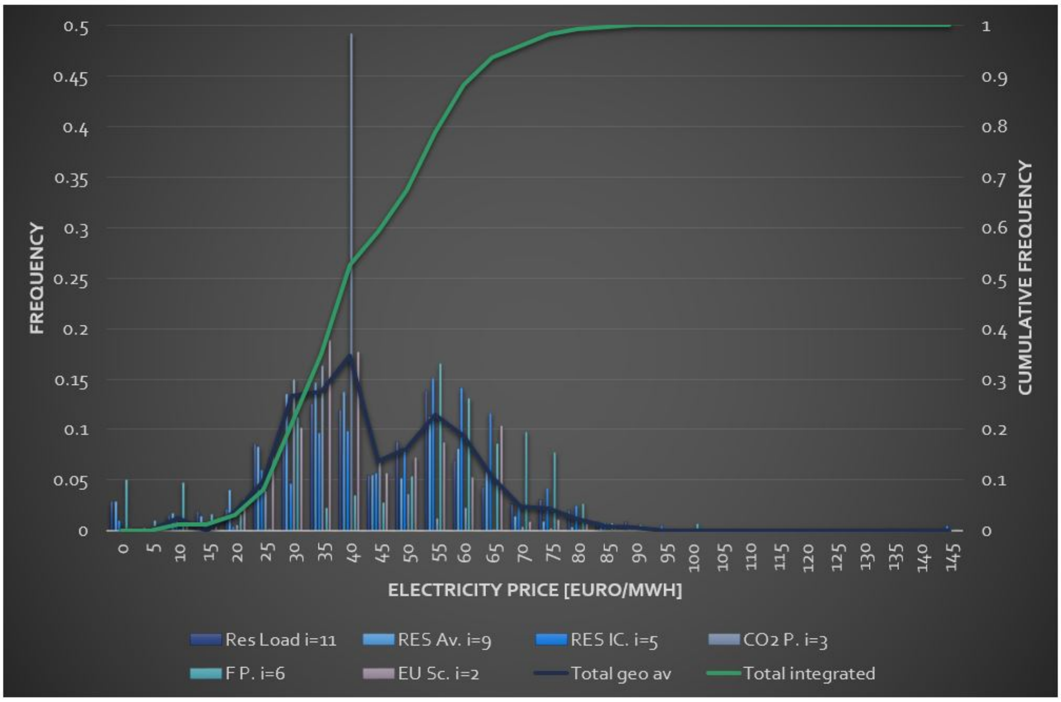

FIGURE 3.2: Integration of the frequency curves. Example of the integration of the frequency curves of each correlation variable given a determinate system state.

This simple and straight-forward process also presents its complications, as the random numbers cannot be completely random if real behavior must be replicated by the approach. For this, there are two main concepts that ENSYSI must take into consideration before determining the random numbers to be used for each country. These are the inter-country price correlation (ICPC), and the inertia.

TABLE 3.1: Inter-country price correlation and inertia data.

Parameter	Units	2010	2015	2020	2025	2030	2040	2050
ICPC NO-DK	[%]	100	100	98	95	97	97	97
ICPC DK-DE	[%]	50	50	96	99	98	98	98
ICPC NO-DE	[%]	50	50	95	94	95	95	95
ICPC DE-BE	[%]	56	56	96	86	99	99	99
ICPC DK-BE	[%]	21	21	92	86	97	97	97
ICPC NO-BE	[%]	21	21	91	82	94	94	94
ICPC BE-GB	[%]	57	57	66	92	96	96	96
ICPC DE-GB	[%]	22	22	60	79	95	95	95
ICPC DK-GB	[%]	7	7	58	79	95	95	95
ICPC NO-GB	[%]	7	7	57	76	92	92	92
Inertia	[%]	82	87	90	80	88	80	80

Inter-country price correlation. This property refers to the likelihood of the system in any given hour to present a difference lower than $5€/MWh$ between a determinate par of countries. The values used as input in ENSYSI for such variables were extracted from COMPETES data and are reported in table 3.1.

Inertia. Similarly to the above, this property refers to the likelihood of the system in any given hour to present an electricity price state of the system with a difference lower than $5€/MWh$ with respect the previous hourly state. In contrast to the ICPC, this variable describes a system state and not a country state. Therefore there is only one parameter per year and the yearly values, extracted from COMPETES' data, are also reported in table 3.1.

The way in which these two concepts are integrated into the model is by helping to obtain the five random numbers that are required for the electricity price determination. The inertia factor works as a lever to determine if the random numbers of the previous hour should be used or not for this hour. For this, a new auxiliary random number is called, and if this number is smaller or equal to the inertia parameter of the year, then the random numbers of the last hour are used. Otherwise, a new set of random numbers is created.

On the other hand, the inter-country price correlation parameters help to obtain the new set of random numbers when there is no inertia in the system, and the process in which this is done is a bit less straightforward. The first step to do this is to create the matrix, M, shown below:

$$\mathbf{M} = \begin{array}{cc} \begin{array}{ccccc} \text{Order} & & \text{Inter-country price correlations} & & \end{array} & \\ \left[\begin{array}{ccccc} 1 & - & - & - & - \\ 2 & ICPC_{NO-DK} & - & - & - \\ 3 & ICPC_{DK-DE} & ICPC_{NO-DE} & - & - \\ 4 & ICPC_{DE-BE} & ICPC_{DK-BE} & ICPC_{NO-BE} & - \\ 5 & ICPC_{BE-GB} & ICPC_{DE-GB} & ICPC_{DK-GB} & ICPC_{NO-GB} \end{array}\right] & \begin{array}{c} \text{NO} \\ \text{DK} \\ \text{DE} \\ \text{BE} \\ \text{GB} \end{array} \end{array}$$

Here the order was selected based on the observed pattern in which Norway is the country with the highest correlation with other countries followed by Denmark, Germany, Belgium, and at the end Great Britain. Then, the routine assigns the random variables to each country accordingly to this order using the following logic:

1. A random number is assigned to Norway.
2. An auxiliary random number helps to determine if there is a correlation between Denmark and Norway. If there is a match, the same random number that was assigned to Norway is then assigned to Denmark. If there is no match, a new random number is assigned to Denmark.
3. An auxiliary random number helps to determine if there is a correlation between Germany and Belgium. If there is a correlation, the same random number that was assigned to Denmark is then assigned to Germany. In case of no correlation, it takes into account if Norway and Denmark are correlated to decide to check or not for a correlation between Germany and Norway. Depending on this process Germany may end up with the same random number than Norway, or with a new random number.
4. The same algorithm as above is used to determine the random number for Belgium, but with an additional step.
5. (Again), the same algorithm as in the former steps is used to determine the random number for Great Britain, but with another additional step.

With these modifications it is ensured that the random numbers are now taking into account the inertia of the system and the inter-correlations between countries. Without these two concepts being included, the performance of the model utilizing this methodology drops drastically.

3.1.3 Balancing the power supply and demand

After the foreign electricity prices are determined for every country in a certain hour, they are used now to built the merit order curve (supply curve), and the foreign demand curve (demand curve). The merit order curve now includes the adjacent markets as another generators of the system, whose marginal costs are determined by the hourly foreign electricity prices, and the generation capacities by their available interconnection capacities. Similarly, the foreign demand curve is built by adding to the local demand in the hour the interconnection capacities of the countries arranged by a decreasing electricity price order, assuming for the Netherlands the highest possible price. A visualization of the curves is shown in figure 3.3.

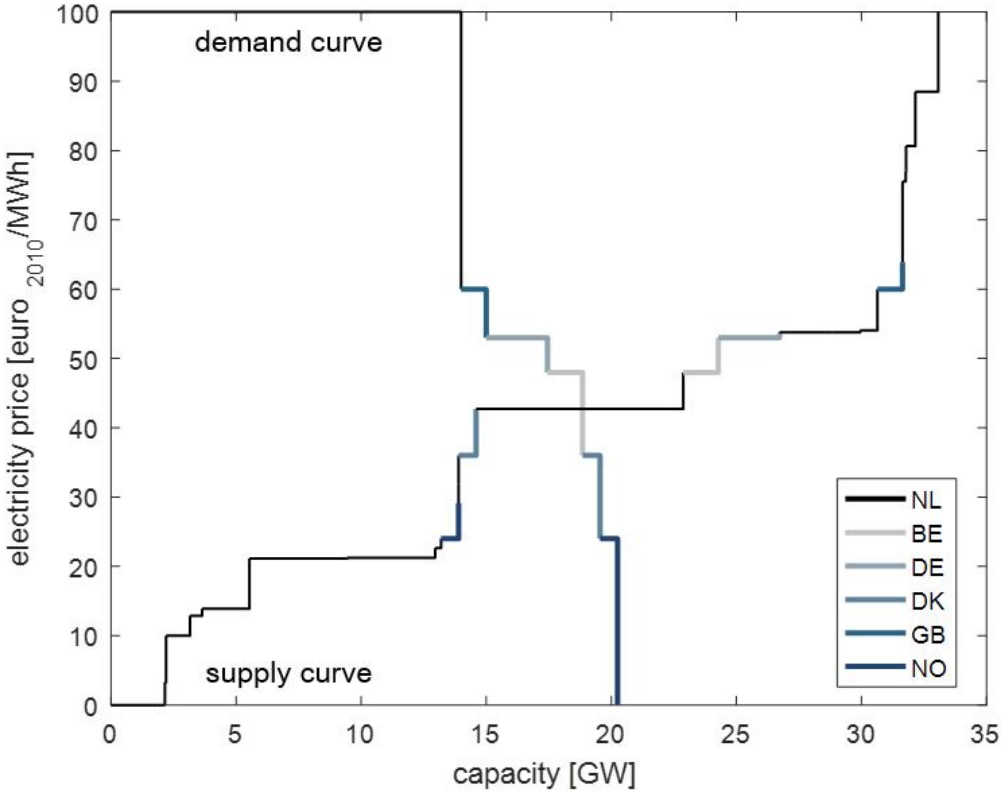

FIGURE 3.3: Electricity supply and demand curves. Impact of the foreign markets in the supply and demand of the local electricity system.

After the two curves are created, ENSYSI iterates to find the intersection point of the supply and demand curves. This intersection point determines the electricity price in the Netherlands for that hour, together with the power produced by each generator, the electricity import and export flows for each country. Besides the modifications described in this section, ENSYSI needed few other adjustments.

3.2 Collateral Modifications

Some minor modifications were required to ensure the adequate functioning of the new modifications within the environment of the other already existing ENSYSI's modules and subroutines. The main issue after the modifications to the power dispatch is that ENSYSI can now source its power requirements to a large extent from the foreign markets. This opened the door to some scenarios with a lot of interconnectivity where a large amount of the local demand is sourced externally due to the decrease in power generation investments.

The above mentioned happened because ENSYSI determines part of the investment expansions from a parameter named "activity deficit" which for the power sector was originally determined by the amount of electricity that was not met by internal capacity[4]. Therefore in the new version two adaptations were required: one around the way in which the power sector activity deficit is determined. And another one to include a constraint to exogenously determine a degree of dispatch-able generation in the system to prevent over investments in renewables that would end up being unused[5].

3.2.1 Activity deficit

For this modification[6] it is assumed that investments are triggered by the electricity price of the system. More concretely, investments may occur due to the amount of electricity that is produced in a year with high generation prices. Then a reference price, P_R, is needed to quantify this value, and for this purpose, the value of the average electricity prices in a year including the foreign countries is used. The contribution of each hour to the newly defined activity deficit is assumed to follow an asymptotic path towards the local load, in accordance with how expensive the electricity is in an hour as shown below:

$$A_D = \sum_{h/P_h > P_R} L_h (1 - e^{C_1 F_{P_h}}) \tag{3.1}$$

Where $h/P_h > P_R$, refer to the hours in which the hourly price is higher than the reference price, $C_1 \in [-\infty, 0]$ is a calibration constant, L_h is the local power demand of the hour, and F_{P_h} is the electricity price gradient factor in an hour defined as:

$$F_{P_h} = \frac{P_h}{P_R} - 1 \tag{3.2}$$

Furthermore, this value is assumed to be the maximum value by which capacity expansions may be triggered, and it is assumed to be limited by the fraction of exports in the trading flows, f_X, the fraction of the hourly demand that could be sourced externally, f_{T_h}, and the fraction of generation capacity of IRES in the system, f_R. Then the final expression for the activity deficit is:

$$A_D = \sum_{h/P_h > P_R} W_X \cdot f_X \cdot W_T \cdot f_{T_h} \cdot W_R \cdot f_R \cdot L_h (1 - e^{C_1 F_{P_h}}) \tag{3.3}$$

Where $W_X, W_T, W_R \in [0, 1]$, are the weighting factors to account for the relevance of the previously mentioned fractions. It was observed that when using a value of one, the same as for C_1, the obtained results resembled the shown by the previous version. Then for this study the activity deficits are defined as:

$$A_D = \sum_{h/P_h > P_R} f_X \cdot f_{T_h} \cdot f_R \cdot L_h (1 - e^{F_{P_h}}) \tag{3.4}$$

---

[4] Remember that in the previous version of ENSYSI imports are an exogenous parameter.

[5] In a scenario with a lot of intermittent generation, a huge activity deficit could be reported due to the hours in which generation is not available. Therefore if IRES are the cheaper option, investments will occur without satisfying the activity deficit. This, of course, would never happen in reality and therefore has to be constrained.

[6] Located in the get_EcoPotDeficit.f90 module

3.2.2 Backup capacity requirements

The previous modification enables ENSYSI to determine the amount of power generation that could enter into the system to substitute expensive generation. However, there must be a constraint towards the level of dispatch-ability of the new investments. This was simply added by including it as an input parameter called backup capacity constraint[7]. The role of this parameter is to ensure that a certain amount of the activity capacity is covered by non-intermittent technologies. Based on this, the dispatchable capacity deficit is derived[8], and is used to determine the technology composition of the new investments in the power sector[9].

The first step in which the power sector investments of the year are determined is still the same and is obtained in accordance with the existing motivation factors approach. The difference is that now ENSYSI checks if the investments in dispatchable technologies are enough to meet the dispatchable capacity deficit. And in case they don't, ENSYSI proportionally increases the investments enough to meet such deficit; then the adjustment is later proportionally subtracted from the other technologies expansions.

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[7] This parameter is provided in the Scenario_parameters_NL.xlsx file

[8] Also within the get_EcoPotDeficit.f90 module

[9] Within the make_investment_DevSpace.f90 module

Chapter 4

Evaluation of the Modifications

This chapter provides an assessment of the electricity dispatch modifications that were performed in ENSYSI for this study. The changes described in the previous section attempt to predict the impact of foreign power markets in the local electricity system. This builds on the assumptions that the electricity dispatch of a well-interconnected region is predominantly described by the balance of the merit order curve (including the possible electricity imports), and the foreign demand curve. Then this evaluation is necessary to both test the solidity of the assumptions, and to measure the electricity dispatch performance of ENSYSI.

TABLE 4.1: Reference evaluation scenarios

CODE	Storyline Source	Category	Year
C-10	COMPETES' dataset	C1	2010
C-15	COMPETES' dataset	C1	2015
M16-20	MAF 2016	C1	2020
M16-25	MAF 2016	C1	2025
M17-20	MAF 2017	C1	2020
M17-25	MAF 2017	C1	2025
T161-30	TYNDP 2016 - Slow Progress	C2	2030
T162-30	TYNDP 2016 - Money Rules	C2	2030
T163-30	TYNDP 2016 - Green Transition	C3	2030
T164-30	TYNDP 2016 - Green Revolution	C3	2030
T181-30	TYNDP 2018 - Sustainable Transition	C2	2030
T181-35	TYNDP 2018 - Sustainable Transition	C2	2035
T181-40	TYNDP 2018 - Sustainable Transition	C2	2040
T182-30	TYNDP 2018 - Distributed Generation	C3	2030
T182-35	TYNDP 2018 - Distributed Generation	C3	2035
T182-40	TYNDP 2018 - Distributed Generation	C3	2040
T183-30	TYNDP 2018 - EUCO30	C3	2030
T183-35	TYNDP 2018 - GCA	C3	2035
T183-40	TYNDP 2018 - GCA	C3	2040

4.1 Description of the evaluation process

As the power system in reality has not yet faced the expected high interconnection and intermittent power generation, measuring the performance of the modeled electricity price predictions requires else than a comparison with historical data.
That's why the ENSYSI's dispatch predictions are evaluated with the predictions of COMPETES,

one of the best available Netherlands' models used by ECN and PBL to explore the possible future development of the European power system. For this, a comparison is made between the predictions of the old and the new electricity dispatch approaches of ENSYSI, using the COMPETES' predictions as a reference. The performances are measured by aligning the three models under diverse scenario combinations in different years. And the performance is measured for those features of the model that must be improved with the modifications.

4.1.1 Scenarios used as reference

COMPETES is often used to analyze from the Netherlands' perspective the Midterm Adequacy Forecasts, MAF, (ENTSO, 2016a, ENTSO, 2017), and the Ten Year Network Development Plans, TYNDP, (ENTSO, 2016b, ENTSO, 2018), both elaborated by the European Network of Transmission System Operators of Electricity, ENTSO-E. Therefore it was decided to use for this evaluation some of these existing COMPETES' simulations as references for the different scenario storylines, and group them in three different categories as shown in table 4.1. These categories are C1 for those scenarios that will occur in the near future and therefore are carrying low uncertainties, C2 for scenarios in which the deployment of renewable electricity generation is assumed to occur modestly, and C3 for scenarios assumed to present a high and accelerated development of renewable electricity generation. The idea of this categorization is to be able to group the evaluation not only by year but also by similitude of the storylines beneath them.

4.1.2 Definitions of the metrics used to evaluate the modifications

The main features of the model that are aimed to improve with the modifications correspond to such elements of the dispatch that have strong repercussions on the system from an integrated analysis perspective. These are the average electricity price, the variability in the electricity price, the electricity price events distribution, and the use of the generation technologies, as explained below.

Average electricity price: This is measured as the average of the electricity price events in a year, and plays a key role from an integrated system perspective as it can strongly influence the level of electrification on the different sectors.

Electricity price variability: This metric accounts for the average of the absolute hourly electricity price gradient, and it has a twofold effect. In the short term, it can influence the power demand profile by incentivizing flexible users to shift to cheap hours. In the long term, it can promote investments in flexible electricity demanding technologies that profit from the irregularities in the electricity price profiles.

Electricity price distribution: Is measured as the proportion of the overlapped frequency distribution function of the electricity price events. This feature has a similar effect on the integrated system perspective than the electricity price variability but is necessary as it is providing information on the price domain on which the fluctuations take place. The relevance of having proper predicted electricity price distributions in a model is that it can reliably account for the potential of the deployment of the flexible electricity demanding technologies, as not all of them will be only triggered by high variable electricity prices, but also for the number of events in a year that satisfy their profitability requirements.

Dispatch of the generation technologies: This feature has a strong impact in many dispatch descriptions such as the energy carriers demand, the profitability of the generators, the degree of de-carbonization of the sector, the net heat sector requirements, all variables that feedback the system states in short and in the long term. This is directly measured by both the net power generated by technology in a year and the share of the technology in the total yearly power generation.

Imports, Exports, and net Imports of electricity: For this particular metric, only the new version of ENSYSI will be evaluated, as the old version was not endogenously predicting its development. It is measured as the total imported and exported electricity from the five neighboring countries, and the difference between this two is reported as the net imports of a year. Similarly to the use of generation technologies, these can influence the stock development of generation technologies, the profitability of the sector, and the energy carriers demand.

4.2 Outcome of the evaluation

In this section, two key results are reported. Firstly, a comparison of the predictions of the three models, the current version of ENSYSI (old), the version of ENSYSI with the modifications (new), and COMPETES. The comparison is shown for the five elements of the metrics selected for the evaluations. Secondly, the outcomes are synthesized in a final figure that enables to perform the evaluations objectively using COMPETES' predictions as a reference.

4.2.1 Results of the evaluation

To be able to compare the dispatch predictions of the three models it was required to adapt a version of ENSYSI which only performs the power dispatch given a specific set of system characteristics, for both the older and the newer versions of ENSYSI. In total nineteen simulations were performed, each one replicating the conditions fed to COMPETES in the previously mentioned scenarios. Below, a visual comparison of the results obtained for each evaluation metric described above is given.

Average electricity price

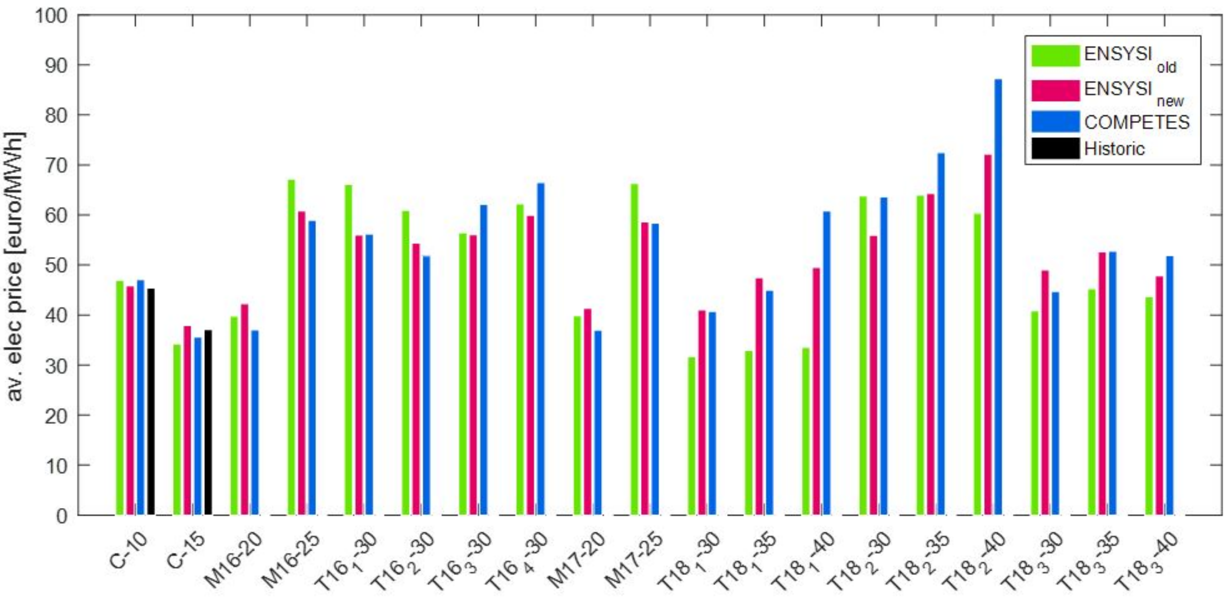

FIGURE 4.1: Comparison of average electricity price. Predictions of the three different models for each scenario setting. In green the older version of ENSYSI, in red the newer version of ENSYSI, in blue COMPETES.

The results for the first metric are shown in figure 4.1, here it is possible to recognize that for most of the scenarios, the new modifications enable ENSYSI to replicate COMPETES predictions more closely than before. It is also relevant to read that for the scenarios of the TYNDP 2018, the modifications deliver significant improvements to ENSYSI's predictions. Finally it is important to highlight that the 2010 and 2015 predictions of the three models are in line with the historical behavior of the market (EPEX).

Electricity price variability
This metric yielded similar results as can be derived from figure 4.2. The first observation is that, again, the modifications resulted in an improvement in ENSYSI's predictions. However a curious pattern appears, when the predictions of the old ENSYSI were closer to COMPETES, the modifications ward off the results a bit. But when old ENSYSI's predictions were far away from COMPETES predictions, the modifications significantly thinned the gap.

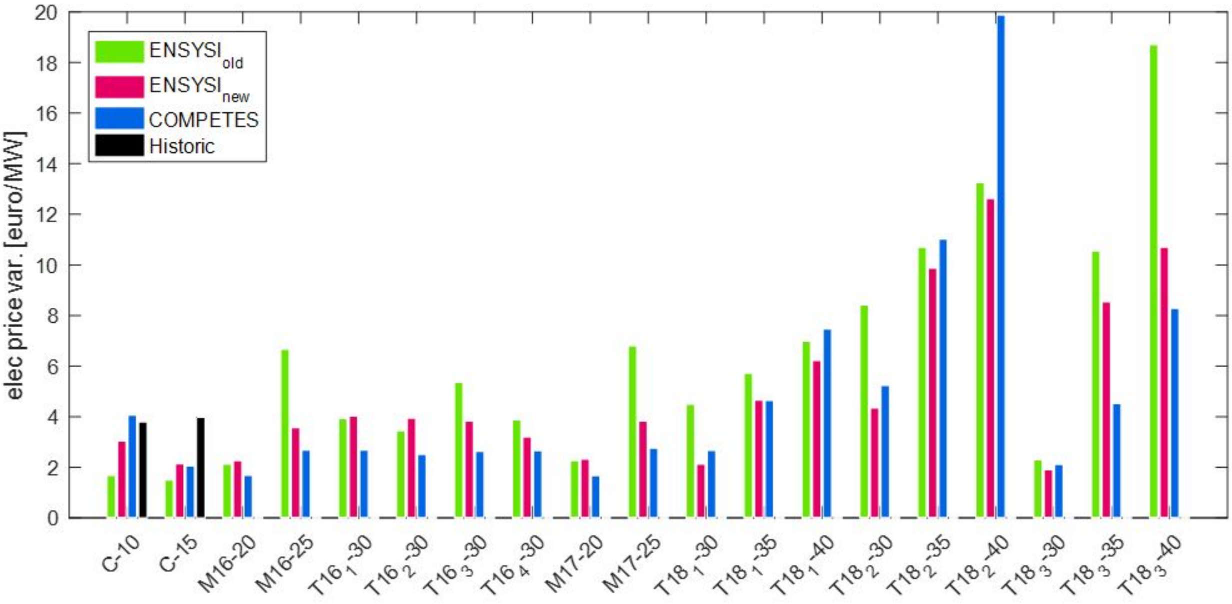

FIGURE 4.2: Electricity Price variability. Predictions of the three different models for each scenario setting. In green the older version of ENSYSI, in red the newer version of ENSYSI, in blue COMPETES.

Electricity price distribution
From all the perceived improvements of the model modifications, the most laudable ones are the ones achieved around this metric. As can be perceived in figure 4.3, the distribution profiles of the electricity price events in a year predicted by ENSYSI before the modifications, hardly resembled the ones from COMPETES'and denoted being cloistered in a behavior strongly determined by the local merit order curve. The inherent stochasticity of the modifications got ENSYSI out of that behavioral pattern and delivered a softened distribution profile which approaches more to the ones from COMPETES and historical data. This is a meaningful improvement which allows the model to simulate in an adequate way how technologies responding to low electricity price events may develop.

However, in this particular category, it can be observed that COMPETES predictions are also limited by its dispatch considerations when compared with historical data. This suggests that a potential way of further improving the model is with a more stochastic approach.

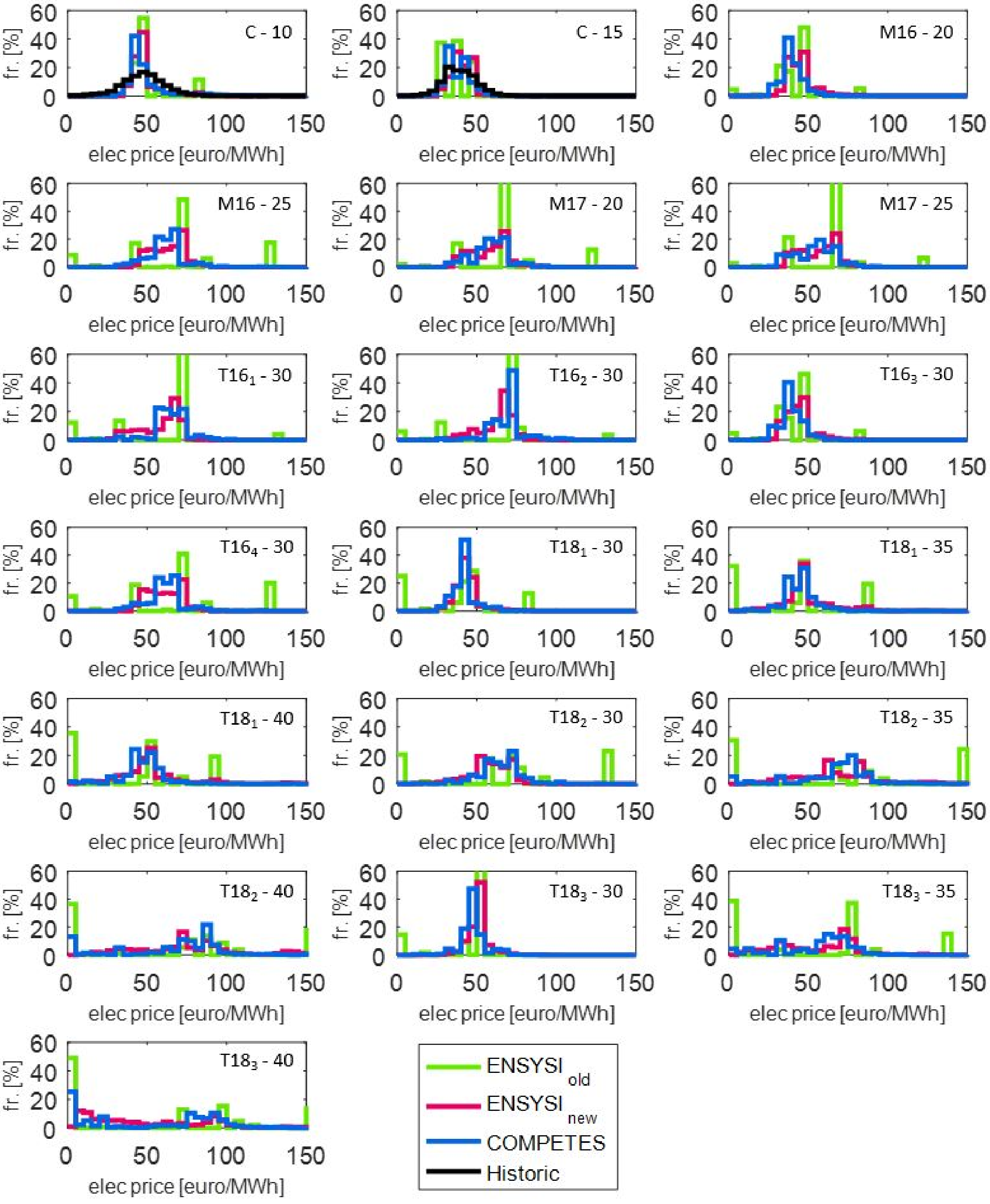

FIGURE 4.3: Comparison of electricity price events distribution profile. Predicted by the three different models for each scenario setting. In the colored bar plot the supply is shown, in the gray shadows bar plot the demand is represented.

Dispatch of the generation technologies

On first sight the results shown in figure 4.4 may indicate that the old version of ENSYSI yields better predictions of the mix of the power generation sources than the new modified version.

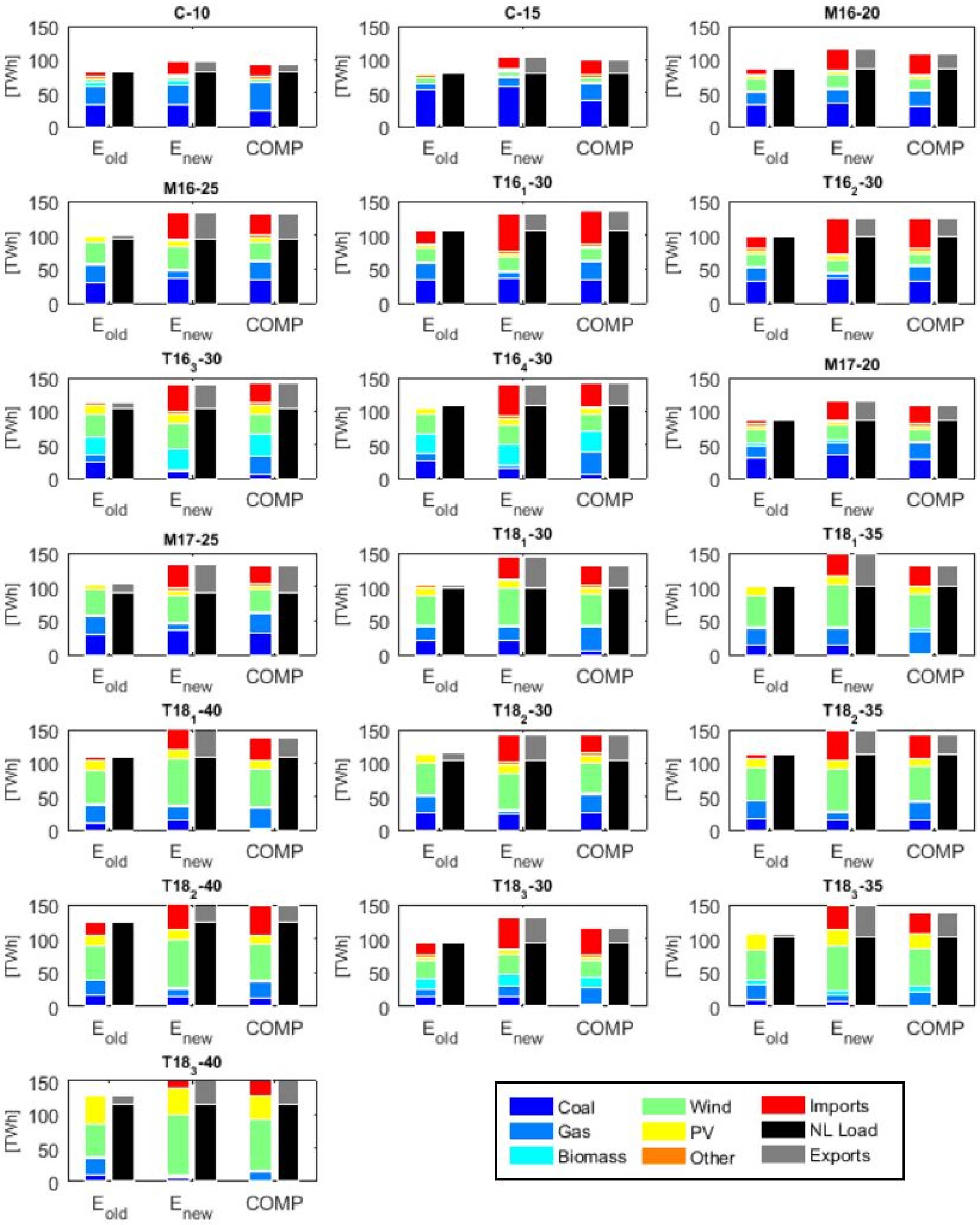

FIGURE 4.4: Comparison of demand and supply yearly profiles. Predicted by the three different models for each scenario setting. The colored bar shows the composition profile of the yearly power supply in the scenario. The black and gray bar shows the local and foreign power demand.

This is true when only focusing on the energy delivered by the available sources. However, it is important to remember that the old version of ENSYSI is not able to predict the power trading flows, so the net imports and exports were exogenously fed into the model using the ones predicted by COMPETES.

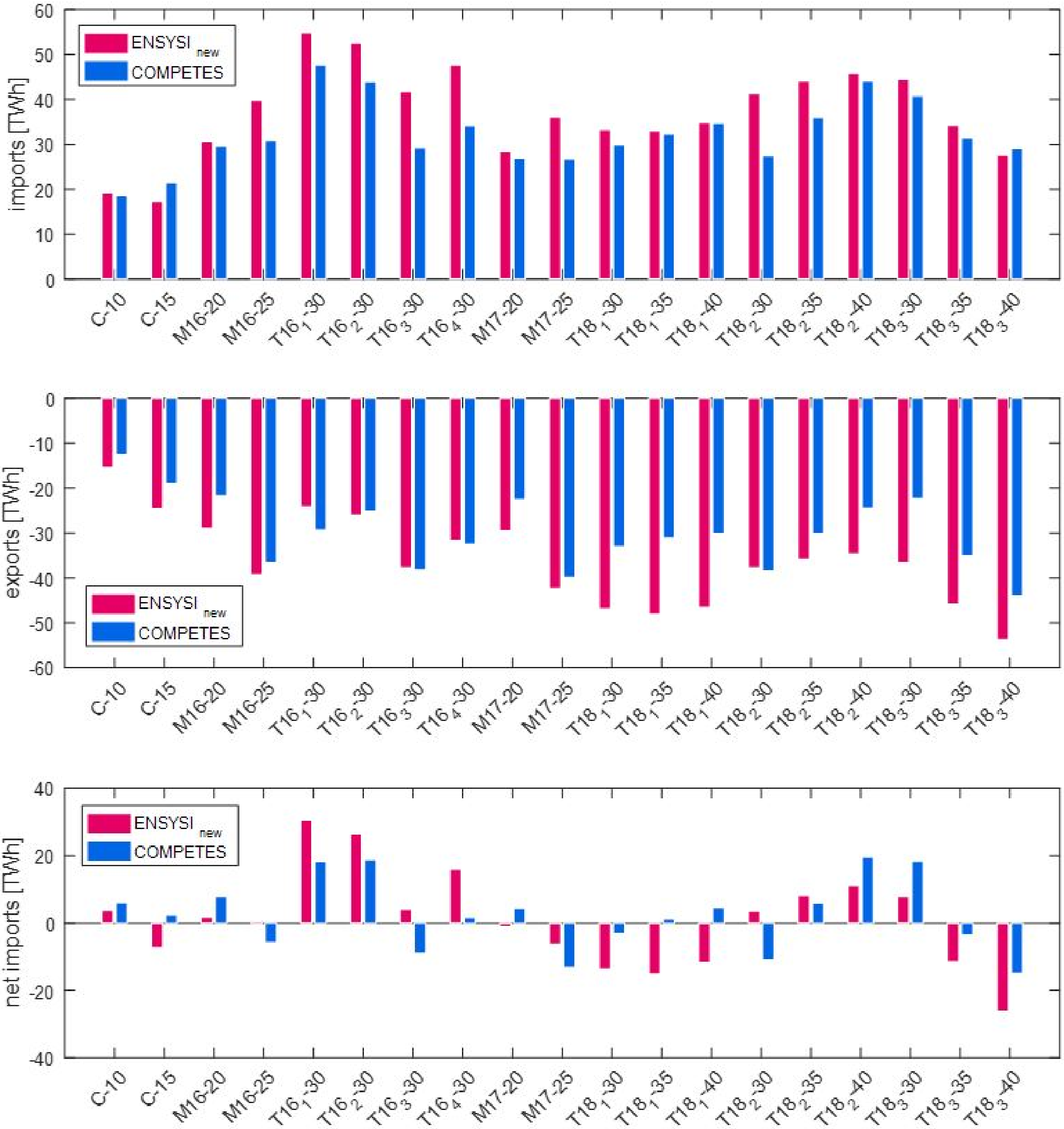

FIGURE 4.5: Comparison of electricity trading flows. Predictions of the three different models for each scenario setting. In red the newer version of ENSYSI, in blue COMPETES. The top graph shows the imports flows, the mid graph shows the exports flows, and the bottom graph shows the net imports flows.

Then for this metric, the older version has an advantage over the modified version, as it predicts the dispatch using the same national demand than COMPETES. The new ENSYSI version endogenously predicts the import and export flows for each scenario, causing the predicted differences of this flows to echo into the generation sources predictions, thus slightly decreasing the performance in this category. Nevertheless, it must be highlighted that despite this, the modified version delivers very acceptable predictions. Similarly to the older version of ENSYSI, the main differences towards COMPETES lay in the fact that neither of the versions considers ramping up and down constraints as COMPETES does, resulting in a relative lower need of flexible generation.

Imports, Exports, and net Imports of electricity

In this particular metric category, whose results are reported in figure 4.5, there are no reported predictions for the older version of ENSYSI. This is because, as mentioned before, ENSYSI wasn't determining the import and export flows of electricity before the modifications.

The first thing to notice is that ENSYSI is now following a similar pattern of prediction than COMPETES, an indication that the underlying assumptions of the modifications are not far from reality. However, in many of the scenarios, ENSYSI is predicting slightly more imports and exports than COMPETES, which of course rebound into the net imports predictions. This overestimation is mainly because ENSYSI is not including any further constraints other than the cross-border interconnection capacities when COMPETES also include distribution information at a more local scale. The main risk of this difference is that ENSYSI may underestimate both curtailment and flexible generation requirements.

Regardless of those scenarios presenting such differences, it is also observed that in many scenarios ENSYSI deliver predictions close to the COMPETES ones. And when it doesn't the differences are not substantial: in only five scenarios the differences reach the 30% threshold.

4.2.2 Analysis on the performance of the modifications

Based on the results discussed in the previous section, the relative match of the predictions as compared with COMPETES was calculated to evaluate the performance of the older and the newer versions of ENSYSI. In this metric, a higher match percentage indicates better performance of the method. Two tables are provided which report these performances for each of the metrics analyzed. To synthesize the circumstances on which ENSYSI may perform better or worse, the reports are grouped in table 4.2, by time (based on the year of the scenario), and in table 4.3 per category (based on the criteria introduced in table 4.1). The performances of each scenario are provided in Appendix A.

In general terms, it can be observed that the newer version of ENSYSI performed better than the older version in all the metrics, except for the dispatchable generation and the intermittent renewable generation (IRES). However, as previously mentioned, this is due to the fact that the newer version of ENSYSI endogenously determines the imports and exports flows, where the older version receives the COMPETES predictions as exogenous data fed into the model. Remarkably even with this extra source of discrepancies, the new version of ENSYSI presents a very acceptable overall performance for the dispatchable, 81.1%, and IRES generation predictions, 78.9%, as can be appreciated in table 4.3.

It is remarkable that in table 4.2 that in no year and no metric the new version of ENSYSI scores less than 60%. Furthermore, a great achievement is that the average electricity price of the newer version performs exceptionally for all the years when the older version decreases the performance for the final years. Together with this, the electricity price profile of the new ENSYSI version is another highlight of the improvements, by almost doubling the performance of the older version. With this improvement, now it can be ensured that the technologies whose deployment is very sensitive to the distribution of the electricity price events, will behave more realistically within the model.

TABLE 4.2: Performance evaluation per years

Variable	Model	Units	2010	2015	2020	2025	2030	2035	2040
Av. Elec. Price	$ENSYSI_{new}$	%	97.3	93.5	87.0	98.1	93.2	94.3	85.5
	$ENSYSI_{old}$	%	99.7	96.1	92.4	86.2	88.3	82.5	69.5
Elec. Price Var.	$ENSYSI_{new}$	%	74.8	96.0	62.9	63.9	68.4	66.8	72.5
	$ENSYSI_{old}$	%	41.2	73.0	69.0	-48.1	46.9	46.9	44.8
Elec. Price Profile	$ENSYSI_{new}$	%	75.6	64.5	70.1	60.0	68.8	67.6	63.2
	$ENSYSI_{old}$	%	57.2	30.6	41.0	10.6	34.2	31.4	39.5
Dispatchable Gen.	$ENSYSI_{new}$	%	98.5	88.3	97.7	78.9	77.5	77.2	75.5
	$ENSYSI_{old}$	%	98.3	97.7	93.5	92.1	94.2	86.9	54.9
IRES Gen.	$ENSYSI_{new}$	%	77.4	78.2	78.6	79.1	79.1	79.5	78.8
	$ENSYSI_{old}$	%	77.4	78.2	81.5	85.2	87.7	94.0	90.5
Elec. Imports	$ENSYSI_{new}$	%	96.8	80.7	95.4	68.1	73.2	88.9	96.9
Elec. Exports	$ENSYSI_{new}$	%	77.0	70.5	67.8	93.3	81.0	65.2	60.4
Elec. Net Imports	$ENSYSI_{new}$	%	88.8	75.9	83.3	82.6	78.8	77.0	80.5

Similar observations occur when analyzing table 4.3, where there is also no scenario category in which the modified model performs below 60%. Next to that, the new version presents a uniform performance, and in all the three categories reports equivalent behaviors for all the metrics except for the dispatchable generation, whose performance decreases in scenarios with high renewable electricity generation. However, as this is a consequence of the lack of ramping constraints, this pattern occurs also in the older version of ENSYSI. From this can be concluded that the modified version of ENSYSI can predict the electricity dispatch with a very acceptable degree of reliability, regardless of the circumstances assumed for the explored scenarios.

TABLE 4.3: Performance evaluation per category and total

Variable	Model	Units	C1	C2	C3	Total
Av. Elec. Price	$ENSYSI_{new}$	%	93.5	94.0	90.3	92.3
	$ENSYSI_{old}$	%	92.2	74.2	87.9	85.6
Elec. Price Var.	$ENSYSI_{new}$	%	70.7	71.0	67.7	69.5
	$ENSYSI_{old}$	%	26.0	63.6	35.7	40.0
Elec. Price Profile	$ENSYSI_{new}$	%	66.7	76.0	61.7	67.1
	$ENSYSI_{old}$	%	31.8	33.7	35.5	33.8
Dispatchable Gen.	$ENSYSI_{new}$	%	90.0	87.5	70.4	81.1
	$ENSYSI_{old}$	%	94.5	92.3	77.9	86.9
IRES Gen.	$ENSYSI_{new}$	%	78.5	79.4	78.9	78.9
	$ENSYSI_{old}$	%	81.5	89.0	90.4	87.2
Elec. Imports	$ENSYSI_{new}$	%	84.1	90.4	77.2	82.8
Elec. Exports	$ENSYSI_{new}$	%	78.3	65.5	77.1	77.0
Elec. Net Imports	$ENSYSI_{new}$	%	82.8	77.9	79.3	80.0

Based on table 4.3 is can be acknowledged that in overall the scenarios, the new version of ENSYSI outweighs the older version, except the generation predictions which, as explained before, were something to be expected. Significant improvements were achieved particularly for the electricity price variabilities and the electricity price distributions profiles, as the older version of ENSYSI already performed well for the average electricity price determinations. It can be concluded that after the new modifications made in the ENSYSI's power dispatch module, it has increased its reliability as a tool to perform energy system integration analyses.

Finally, it is important to remember that COMPETES, despite being one of the most advanced power system models available, may end up carrying its own sources of uncertainties. And the decision of using it as a reference does not emerge from the likelihood of the future power system behaving as COMPETES predicts it. It is used as a reference because the power system is expected to change so drastically, that using historical information to calibrate the stochasticity of ENSYSI's dispatch would be a gross mistake. Therefore the added value of the new version of ENSYSI is that besides of delivering estimates close to the ones delivered by such a complete model as COMPETES, it also includes some stochasticity into the dispatch, providing a different perspective into the power dispatch predictions. This is even more relevant under the current scientific environment, in which there is an increasing need for agile approaches that are suitable to include multi-agent learning methods to replicate possible uncertain social conducts.

Chapter 5

Scenario Design

To understand the impact on the Netherlands' energy system of *cross-border interconnectivity* and its potential interference with *decentralized demand side response*, under different levels of *renewables development*, it is required to simulate a set of combinatory scenarios considering different unwrapping states for each of the three components (from now on addressed as scenario dimensions). Then, the combinations devised for this study integrate two development paths for each scenario dimension (namely low and high development), resulting in a total of 8 scenarios ($2^3 = 8$). This chapter describes and defines the aspects of the model that influence the development of each of the three dimensions.

5.1 Parameters influencing the development of renewables

The path of development of renewable energy sources will undoubtedly depend on the landscape resulting from the combination of different economic, societal, political, and technological circumstances. ENSYSI approaches this by including different input libraries that translate this context into quantifiable model elements. The libraries influencing the development of this first scenario dimension can be categorized into three topics, the available policy instruments, the actors' parameters determining investing criteria, and other general characteristics influencing the technological development. The two storylines considered to analyze this dimension are named low and high RES scenarios, R_L and R_H respectively, and are adopting most of the parameters configurations within the current existing scenarios that are used to work with ENSYSI.

5.1.1 Policy Instruments

This library collects all the relevant system elements emerging from public policies. ENSYSI considers the following: the different banning of technologies in specific years, subsidies for energy efficiency improvements, subsidies from the SDE+ program, the remuneration fraction of small PV[1], bio-fuel share obligations, the ETS and non-ETS CO_2 prices, and the obligation to close coal power plants in a certain year. The obligation to close coal power plants, the energy efficiency investment subsidies, and the banned technologies are assumed to be the ones considered in the standard ENSYSI scenarios considered, and does not change between the low and high RES scenarios. The other parameters are reported to change within the scenarios in table 5.1, and are defined as follows:

SDE+ budget: Stimulation of Sustainable Energy Production (Stimulering Duurzame Energieproductie), is a subsidy provided by the government of the Netherlands aiming to encourage the production of renewable energy (RVO, 2018). This input model parameter determines when and how much of this subsidy will be applied.

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[1] Fraction of the electricity price that is paid to prosumers for their electricity surplus.

Bio-fuel share obligations: This parameter informs the model how the Netherlands will implement the future uncertain EU low carbon economy plans regarding bio-fuels obligations in transport (*Climate strategies and targets*). There are two parameters that ENSYSI considers, the bio-fuels obligations in the road transport sub-system, and the bio-fuels obligations in other transport sub-systems.

ETS CO_2 price: For those sectors contained within the emission trading scheme (European Commission, 2017), this parameter informs the model about the expected clearance price of the ETS market.

Non-ETS CO_2 price: This parameter describes a potential emission tax to be applied to those sectors not considered within the ETS scheme.

TABLE 5.1: Policy input parameters varying in the scenarios

Parameter	Units	Scen.	2010	2015	2020	2025	2030	2040	2050
SDE-budget	[M€/year]	R_L	1200	3500	3500	3500	3500	0	0
		R_H	1200	3500	3500	3500	3500	3000	3000
Biofuel share road	[%]	R_L	2.4	6.3	8.4	8.4	8.4	8.4	8.4
		R_H	2.4	6.3	8.4	15	20	25	25
Biofuel share other	[%]	R_L	0	0	0	0	0	0	0
		R_H	0	0	0	10	20	25	25
ETS CO_2 price	[€/ton CO_2]	R_L	15	8	11	18	26	55	80
		R_H	15	6	44	72	104	220	320
Non-ETS CO_2 price	[€/ton CO_2]	R_L	0	0	0	0	0	0	0
		R_H	0	0	88	144	208	440	640

5.1.2 Actor Parameters

This library comprises the parameters that define the postures towards investments for each one of the eight different kinds of defined actors (national, consumer, housing association, farmer, government, and small, medium, and large companies). The parameters here included are: the VAT, the discount rates, the population distribution of the four different actor types (innovators, early adopters, majority, or laggards), the weighting factors for the four considered aspects towards the investments' motivation factors (societal attitude, costs, complexity, and investment barrier), and the level of climate concern of the different actors types. From all of these, only the below described social climate concern and weighting factors differ between the low and high RES scenarios. For all the other parameters the values from the standard ENSYSI scenarios are considered (ENSYSI working group), and does not vary between scenarios.

Social climate concern: Parameter ranging from one (low concern) to three (high concern), representing the scale of importance given to the mitigation potential of a technology.

Weighting factors: This set of parameters describe the relative importance, measured from zero to one, that each of the four actor types gives to certain criteria to define their positions towards the different technological alternatives when investing. This criteria covers four different motivations.

1. The societal attitude. Responding to the public-resistance factor of a technology, and the mitigation potential of a technology. Both factors are qualitatively defined within the technology characteristics library.

2. The costs. Parameter which describes the importance that an actor gives to the levelized cost of energy of a technology, determined within the model, in relation to the other alternatives to satisfy a subsystem activity need.

3. The complexity. Corresponding to the mixture of the complexity of a technology and the resource-supply risk of its corresponding fuel, also both defined within the technology characteristics library.

4. Investment barrier. This parameter takes into account the relative difference between the investment costs of the technological alternatives. Investment defined within the technologies parameters module, and adjusted towards the assumed learning curves and expected global developments.

The input values fed into the model for the above described system elements are shown in table 5.2 for both the low RES, R_L, and high RES, R_H, scenarios.

TABLE 5.2: Actor input parameters varying in the scenarios

	Actor Types:	Innovators		Early Ad.		Majority		Laggards	
Parameter	Units	R_L	R_H	R_L	R_H	R_L	R_H	R_L	R_H
Societal Attitute	[weight]	0.6	0.8	0.4	0.5	0	0.2	0	0
Costs	[weight]	1	1	1	1	0.7	0.7	0.5	0.5
Complexity	[weight]	0.1	0.1	0.5	0.5	1	1	1	1
Inv. Barrier	[weight]	0.05	0.05	0.5	0.5	1	1	1	1
Climate Concern	[index]	3	3	2	3	2	2	1	2

5.1.3 Other Parameters

The parameters considered here correspond to different input files and therefore cannot be grouped as one single category. There are many other types of parameters that influence the development of the technologies within the system, for instance the fuel costs, the assumed cumulative produced stocks and the learning parameters of the technologies, the investments and operational costs of the technologies, the performance parameters of the technologies, and many others. However, most of these are also taken from the standard ENSYSI scenarios (PBL, 2017), and won't change between the low and high RES scenarios. The ones that will vary from scenarios are: the global development of electric vehicles (eV), the natural gas prices, the required dispatchable backup capacity, and the renewable and grid developments in the regional interconnected power sector (EU scenario).

Development of eV: This parameter determines the relative growth of the cumulative production of different electricity powered vehicles, and is used to include the learning effect in the

development of the investment costs of these technologies.
Natural gas prices: The relevance of this exogenous parameter speaks for itself. The natural gas prices strongly influence the development of technologies in the power sector, the heat sector, and in different industrial sectors.
Dispatchable backup capacity: This parameter was previously introduced in chapter 3, and corresponds to one of the minor modifications to the model. It relates to a constraint demanding a minimum dispatchable generation availability.
EU scenario: Another parameter that was newly included into the model. It relates to the last set of correlation matrices described in chapter 2, and it relates to a set of attributes of the neighboring electricity system such as the development of IRES in the area, the level of interconnection with other regions, and other parameters describing general EU scenarios. The values are integers, varying from 1 to 4, where 1 stands for a slow development of renewables increasing until 3, which stands for a high development of renewables. A value of four stands for a high development of renewables maintaining relatively low electricity prices in the neighboring regions.

TABLE 5.3: Other input parameters varying in the scenarios

Parameter	Units	Scen.	2010	2015	2020	2030	2040	2050
Road ICE Hybrid development	[index]	R_L	1	1	1	1	2	15
		R_H	1	9	26	115	310	700
Cars PHEV development	[index]	R_L	1	1	1	4	30	31
		R_H	1	1	26	80	220	500
Cars BEV development	[index]	R_L	1	1	1	4	30	31
		R_H	1	1	26	80	220	500
Cars FCEV development	[index]	R_L	1	1	1	1	2	15
		R_H	1	1	9	20	55	125
LDV Hybrid development	[index]	R_L	1	1	1	2	15	15
		R_H	1	3	9	20	55	125
LDV PHEV development	[index]	R_L	1	1	1	4	30	31
		R_H	1	9	26	80	220	500
LDV BEV development	[index]	R_L	1	1	1	4	30	31
		R_H	1	9	26	80	220	500
LDV FCEV development	[index]	R_L	1	1	1	4	15	15
		R_H	1	9	26	80	220	500
HDV FCEV development	[index]	R_L	1	1	2	4	15	15
		R_H	1	9	26	80	220	500
Machinery development	[index]	R_L	1	1	1	4	30	31
		R_H	1	9	26	80	220	500
Ship recreation development	[index]	R_L	1	1	1	4	30	31
		R_H	1	9	26	80	220	500
Natural gas prices	[index]	R_L	6.3	6.6	5.7	8.9	10.4	10.4
		R_H	6.3	6.6	6.2	9.6	11.5	11.8
Backup capacity	[%]	R_L	25.0	25.0	25.0	25.0	25.0	25.0
		R_H	25.0	25.0	25.0	22.5	17.5	15.0
EU Scenario		R_L	cheap prices and moderate RES					
		R_H	slightly higher prices and higher RES					

An important consequence of the mixture of all of the parameters is the development of the

Levelized Costs of Energy (LCOE), of the technologies in a certain sector. Figure 5.1 illustrates the development of the LCOE for some of the power generation technologies resulting from the low and high RES scenarios. It is key to understanding that the resulting values of these LCOEs for each sector have an important influence in the general development of the scenarios.

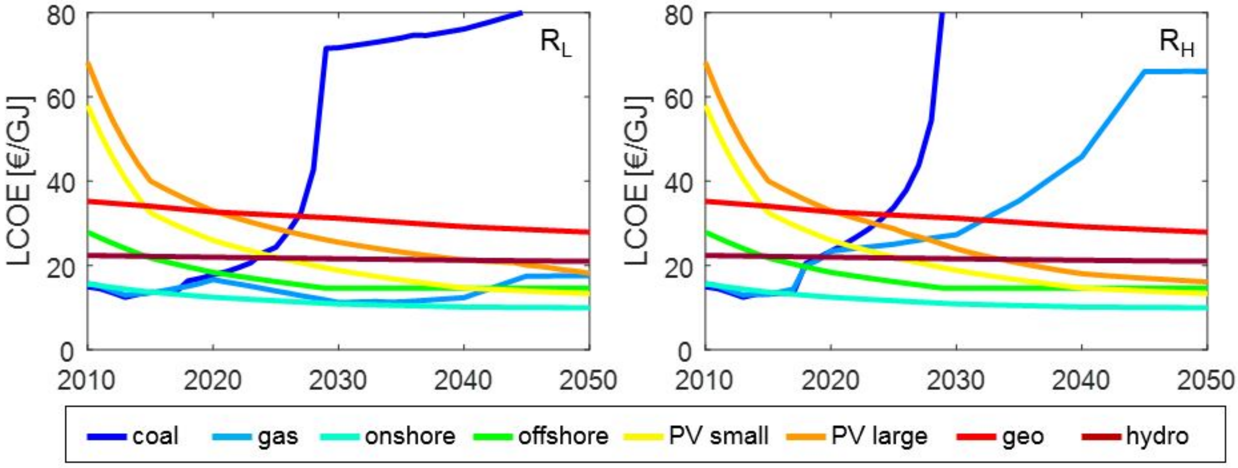

FIGURE 5.1: LCOEs power sector. Development of the levelized costs of energy for certain power generation technologies in the model. Left: low RES scenarios. Right: high RES scenarios.

5.2 Model's parameters that enable DDSR

These parameters are all condensed in ENSYSI within the same input library including all the flexibility parameters. Nevertheless, there are three considered mechanisms through which decentralized flexibility is provided in ENSYSI, demand-side respond (DSR) in households, DSR from electric vehicles, and technologies present in some industrial sub-sectors that are fueled by cheap hours of electricity to meet their activity requirements. The two scenarios considered for this dimension are the low and high decentralized flexibility, F_L and F_H respectively, and are elaborated from the inherent numerical constraints of the modeling approach considered in ENSYSI as shown, and defined below.

TABLE 5.4: Demand side response input parameters varying in the scenarios

Parameter	Units	F_L	F_H
Fraction of the household demand that can be rescheduled in 2010	[%]	1	1
Maximum fraction of the household demand that can be rescheduled	[%]	20	50
Logistic grow parameter for the household demand fraction	[1/year]	0.20	0.25
Fraction of the eV demand that can be rescheduled in 2010	[%]	1	1
Maximum fraction of the eV demand that can be rescheduled	[%]	40	85
Logistic grow parameter for the eV demand fraction	[1/year]	0	0

DSR in households: The description of households demand-side response consists of the development of one parameter. The fraction of the households' load that can be redistributed to other hours. This development is described by three parameters, the value of this fraction is 2010, the potential maximum value that this fraction is assumed to achieve, and the logistic growth parameter (k) at which the s-curve development occurs.
DSR from eV: This flexibility source uses the same mechanism than the households demand-side response in the model. Therefore the same three parameters are used to describe the fraction of the demanded electricity to charge electric vehicles. The parameters used as input for the two flexibility scenarios for both DSR mechanism are described in table 5.4.
Flexibility in industry: This flexibility source is mainly determined by two factors. The first one refers to the development of the fraction of the sub-sector activity that can be sourced with a flexible technology. This factor is described by two parameters the maximum fraction of the sub-sector activity for the technology (MFS), and the logistic growth factor for the s-curve development (LGF). The second refers to the cheap technological factor (CTF), described as the number of cheap hours of electricity at which this technology can operate. Of course, the smaller this factor, the more flexibility it provides. The values used for these elements under the different flexibility scenarios are reported in table 5.5.

TABLE 5.5: Industry flexibility input parameters varying in the scenarios

		MFS		LGF		CTF	
Sub-sectors	Technologies	F_L	F_H	F_L	F_H	F_L	F_H
Ammonia	NH3 SSAS	20	100	0.16	2.00	1000	800
Super-high temp heat	SHT Gas Hybrid	20	100	0.00	2.00	2000	1600
Super-high temp heat	SHT Gas Hybrid CCS	20	100	0.40	0.50	2000	1600
High temp heat	HT Gas Hybrid	20	100	0.00	2.00	2000	1600
High temp heat	HT Gas Hybrid CCS	20	100	0.40	0.50	2000	1600
Low temp heat	LT H2	20	100	0.00	1.00	1000	800
Low temp heat	LT DH Elec	20	100	0.00	1.00	1000	800
Final gas	Gas Egas	20	100	0.12	1.00	1000	800
Hydrogen	H2 Elec6000	20	100	0.00	1.00	6000	3600
Hydrogen	H2 Elec2000	20	100	0.00	1.00	2000	1600
Hydrogen	H2 Elec500	20	100	0.00	1.00	500	800

5.3 Parameters of the model describing the interconnectivity

From all the scenario dimensions, this one is composed by the most straightforward parameters arrange. As the name suggest it, the parameters used here are the interconnection capacities of the Netherlands with the five foreign interconnected countries Belgium (BE), Germany (DE), Denmark (DK), Great Britain (GB), and Norway. There are two assumed scenarios, also named low and high interconnectivity, T_L, and T_H respectively. The low interconnectivity scenario is sourced from the almost certain evolution until 2030 of the North Western European Network (ECN, 2017b, ENTSO, 2018), and the interconnection developments are kept frozen after 2030. The high interconnectivity scenario follows the same development path until 2030, and onwards expand at the rate perceived between 2025 and 2030 for Belgium and Germany, and in 2035 double its trading capacity with the other countries. All the cross-border capacities are assumed symmetric[2], and their development path can be appreciated in the table 5.6.

TABLE 5.6: Interconnectivity input parameters varying in the scenarios

Parameter	Units	Scenario	2010	2015	2020	2025	2030	2040	2050
BE Interconnection	[GW]	T_L	1.4	1.4	1.4	3.4	3.4	3.4	3.4
		T_H	1.4	1.4	1.4	3.4	3.8	4.6	5.4
DE Interconnection	[GW]	T_L	2.5	2.5	4.3	5.0	5.0	5.0	5.0
		T_H	2.5	2.5	4.3	5.0	5.4	6.2	7.0
DK Interconnection	[GW]	T_L	0.0	0.0	0.7	0.7	0.7	0.7	0.7
		T_H	0.0	0.0	0.7	0.7	0.7	1.4	1.4
GB Interconnection	[GW]	T_L	0.0	1.0	1.0	1.0	1.0	1.0	1.0
		T_H	0.0	1.0	1.0	1.0	1.0	2.0	2.0
NO Interconnection	[GW]	T_L	0.7	0.7	0.7	0.7	0.7	0.7	0.7
		T_H	0.7	0.7	0.7	0.7	0.7	1.4	1.4

The tables above describe the differences between the two scenarios that are considered for each of the three defined dimensions, use of renewable energies, R, decentralized demand-side flexibility, F, and cross-border interconnectivity, T. The eight scenarios resulting from the combination of those scenarios are explored and reported in the next chapter.

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[2] The same transmission capacity for both directions.

Chapter 6

Results

In this chapter, the results obtained by using ENSYSI to explore the eight scenarios described in the previous section, are reported. These scenarios are going to be referenced during the text in accordance with table 6.1:

TABLE 6.1: Identification of the explored scenarios

Scenario		Description of the Dimensions		
No	Tag	RES	Decentralized DSR	Cross-border Interconnection
1	$R_L F_L T_L$	low development	low development	frozen development after 2030
2	$R_L F_L T_H$	low development	low development	high development after 2030
3	$R_L F_H T_L$	low development	high development	frozen development after 2030
4	$R_L F_H T_H$	low development	high development	high development after 2030
5	$R_H F_L T_L$	high development	low development	frozen development after 2030
6	$R_H F_L T_H$	high development	low development	high development after 2030
7	$R_H F_H T_L$	high development	high development	frozen development after 2030
8	$R_H F_H T_H$	high development	high development	high development after 2030

For every scenario the reported indicators cover all the three impact categories (these are: economic, environmental, and technical). Moreover, to provide a continuous and connected follow-up of the results, these will be shown from a general to a more detailed perspective. This means that first, the impacts of each scenario on the whole energy system will be reported, followed by the impacts on the power sector, and ending with a general perspective on all the different sectors.

6.1 Net impacts on the Netherlands' energy system

The first set of results presented in this report correspond to the development of the scenarios at a national scale. These scenario developments are monitored at environmental, economic and technical dimensions. For the environmental dimension the system emissions in comparison with the ambitious self-established emission abatement targets of 49% emission reductions as of 1990 before 2030 and of 95% before 2050 are reported (*Coalition Agreement 'Confidence in the Future'* 2017, EZK, 2017). The economic dimension is reported using the total system costs and its decomposition as capital, fuel, and operational costs as indicators, but also with the total system investments and its composition as an investment in new stock and stock transfer investments (e.g., efficiency improvements or CCS expansions). However, to report the technical dimension on a national scale, it is required to use a general indicator, as each sector of the system presents certain peculiarities. The indicators selected for this dimension are the share of inland electricity consumption within the gross inland energy consumption, and the share of renewable energy present in the system.

6.1.1 Environmental impact. National scale.

Perhaps the most significant result shown in figure 6.1 is that none of the eight explored scenarios is possible to get close to the self-established 2050 emission reduction target. It is important to remember from chapter 5, that despite the global technological stock developments, and the actor's decision making parameters, the most important differences between the low and the RES scenarios are driven by policy regulations. Particularly from the continuation of the three billion euros annual budget for the SDE+ subsidies after 2030, and the expected emission prices for the ETS and non-ETS sectors. The main relevant finding is that without the continuation of the SDE+ subsidies, it will be almost impossible to compel with the EU mitigation targets of 40% before 2030, and 80% before 2050 (*Climate strategies and targets*, European Commission, 2011), let alone the aforementioned national targets. Another obvious observation is that even with the high CO_2 emitting prices used for the high RES scenario, the 2050 target is still far from what is predicted by ENSYSI for these four scenarios. Therefore to achieve such targets further technological innovation is still required, and more intense environmentally-driven social postures towards a consumption reducing behavior and low-carbon sources investments, whose integration in ENSYSI is still limited.

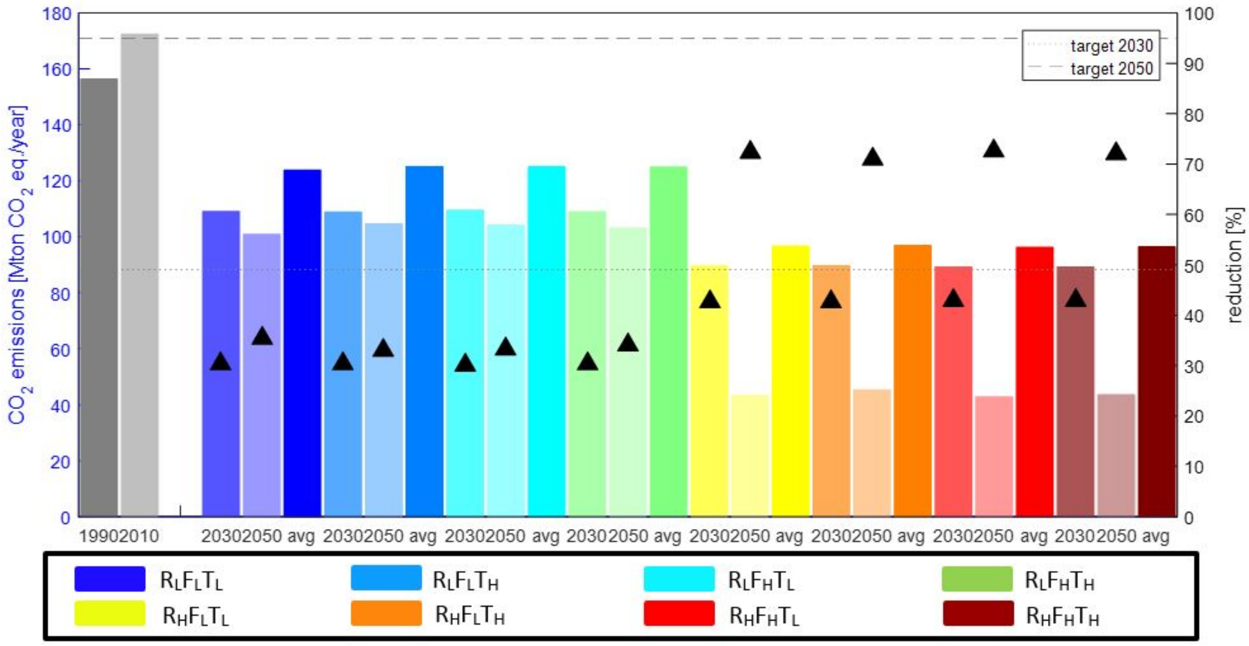

FIGURE 6.1: Energy system emissions. The left axis reports the net energy system national emissions. In grey: historical reference emissions in 1990 and 2010. In colors: predicted emissions for each scenario in 2030, 2050, and the average of the 2010-2050 period. The right axis reports the 1990 emission reduction. The dotted and dashed lines represent the 2030 and 2050 reduction targets. The black triangles correspond to the achieved reductions in 2030 and 2050 for each scenario.

6.1.2 Economic impact. National scale.

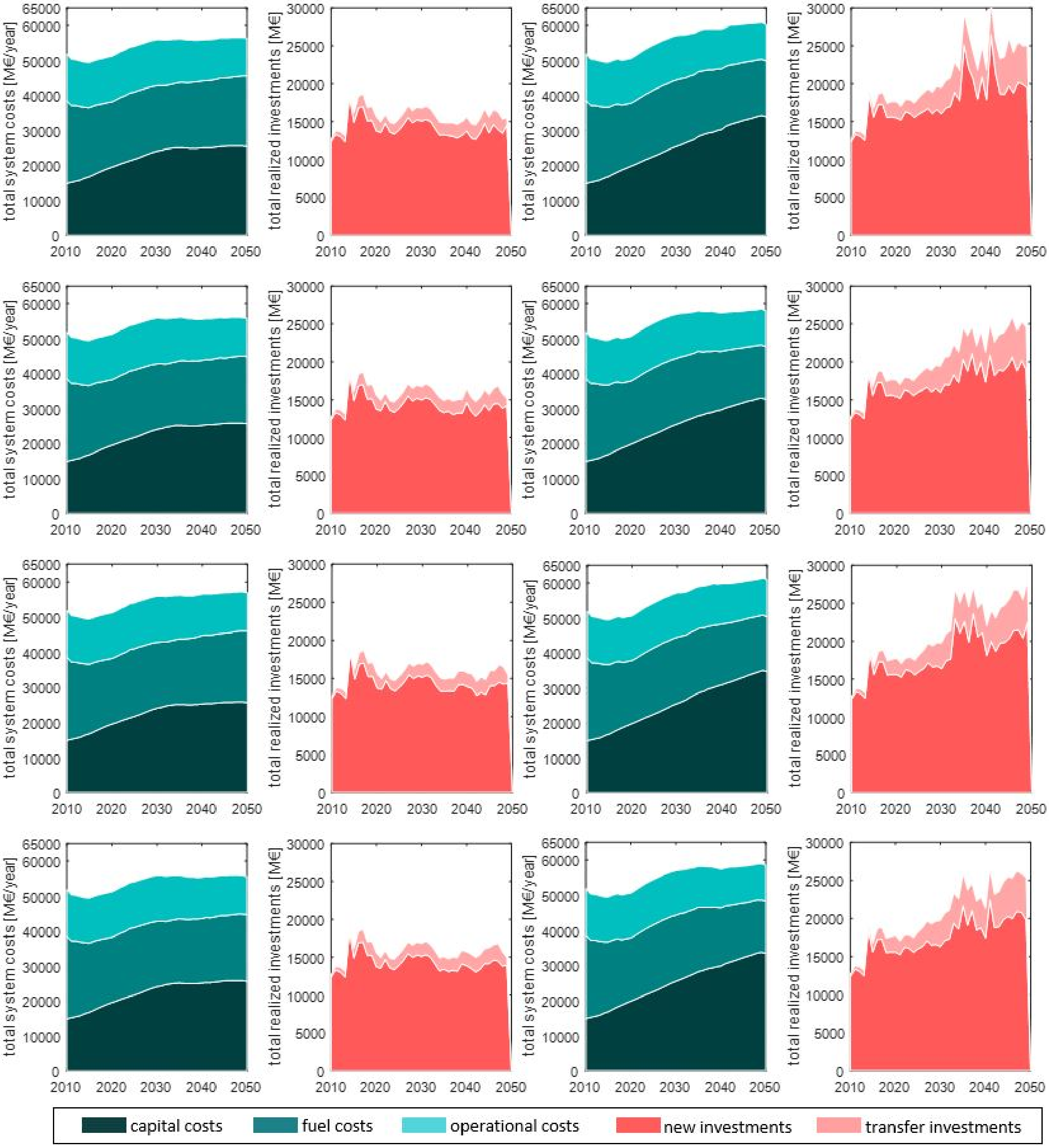

FIGURE 6.2: Energy system costs and investments. The reported costs (in green), are decomposed in the capital, fuel, and operational costs. The total investments (in red), are decomposed in investments in new stocks, and investments in stock adaptations such as carbon capture or efficiency improvements (stock transfers). The left column reports results for the low RES scenarios and the right column reports results for the high RES scenarios. From top to bottom the results respectively correspond to low flexibility and interconnection, low flexibility and high interconnection, high flexibility and low interconnection, and high flexibility and interconnection.

Again, in this dimension, the most striking results are found in the contrast between low and high RES scenarios, as can be derived from figure 6.2. The first one and more relevant is that in all the four different combinations of the flexibility and interconnection degrees, it is possible to appreciate that the total costs difference between the low and high RES scenarios is of roughly 5 billion euros per year, which is in line with existing reports (McKinsey & Company, 2016). The second one is that in the high RES scenarios show a swift from operational costs, but mainly from fuel costs to capital costs in relation to the low RES scenarios. This is mainly due to the substitution of many fossil-fueled processes to free and renewable available energy sources, which simultaneously decrease the amount of money spend in burning fuels, while increases the necessary capital due to the presence of more investment-intensive RES technologies. Figure 6.2 illustrates the general differences between the low and high RES renewable scenarios. It allows to see that the technology transfer investments of the high RES scenarios increased by roughly 4 billion euros per year. This explained by the higher emission costs of the high RES scenarios, which increases the cost-effectiveness of CCS and some other energy efficiency measures in all the carbon-intensive energy system sectors.

When focusing on the relative differences in the scenarios with different degrees of flexibility and cross-border interconnection, there are two main observations to highlight. The first one is that higher interconnectivity lowers the total costs for both low and high RES scenarios regardless of the degree of flexibility present in the system. This is even more notorious in the high RES scenarios, where the total costs of the transition were a higher degree of interconnection present resemble more to the original costs of the low RES scenarios. This indicates that the interconnection capacity has the potential to decrease the costs of the transition considerably.

Another finding is that the interconnection capacity has the potential to soften the predicted investments irregularities, as it can be observed in the high RES scenarios investment figures, where the peaks present in the $R_H F_L T_L$ and the $R_H F_H T_L$ scenarios are almost eliminated in the $R_H F_L T_H$ and the $R_H F_H T_H$ scenarios. Of course these irregularities originate mainly due to the way in which the model predicts investments, so in reality, this phenomena may not be so relevant. But this concept is meaningful given that investments in the model are mainly triggered by activity deficits in the available stocks. Therefore it is an indicator that transmission capacity has the potential to dilute these deficits providing a greater system resilience to changes in activities and stocks.

6.1.3 Technological impact. National scale.

The energy system is so broad and diverse that in order to describe the technical development of the transition, it is required to increase the insight in the different sectors of the system, which is done in the subsequent chapters 6.2 and 6.3. However, a good initial overview for the whole system is provided by the two following indicators, the level of electrification of activities, and the degree of penetration of renewable energy sources into the system.

The first indicator is reported in figure 6.3, where three system features are exposed for each scenario: the gross inland energy consumption (GIEC), the inland electricity consumption (IEC), and the level of activities electrification expressed as the share of the IEC in the GIEC. In the previously mentioned figures, the first peculiarity can be explained by the fact that in the low RES scenarios, the initial decreasing trend on the GIEC is reversed after the suspension of the SDE+ program assumed for those scenarios. This results in an approximate 12% GIEC reduction after the 2010-2050 period, while in the high RES scenarios the achieved reductions are of about 42%. The main driver behind this phenomena is that after the suspension of the SDE+ program, investments in natural gas consuming technologies reappear in the system. The use of natural

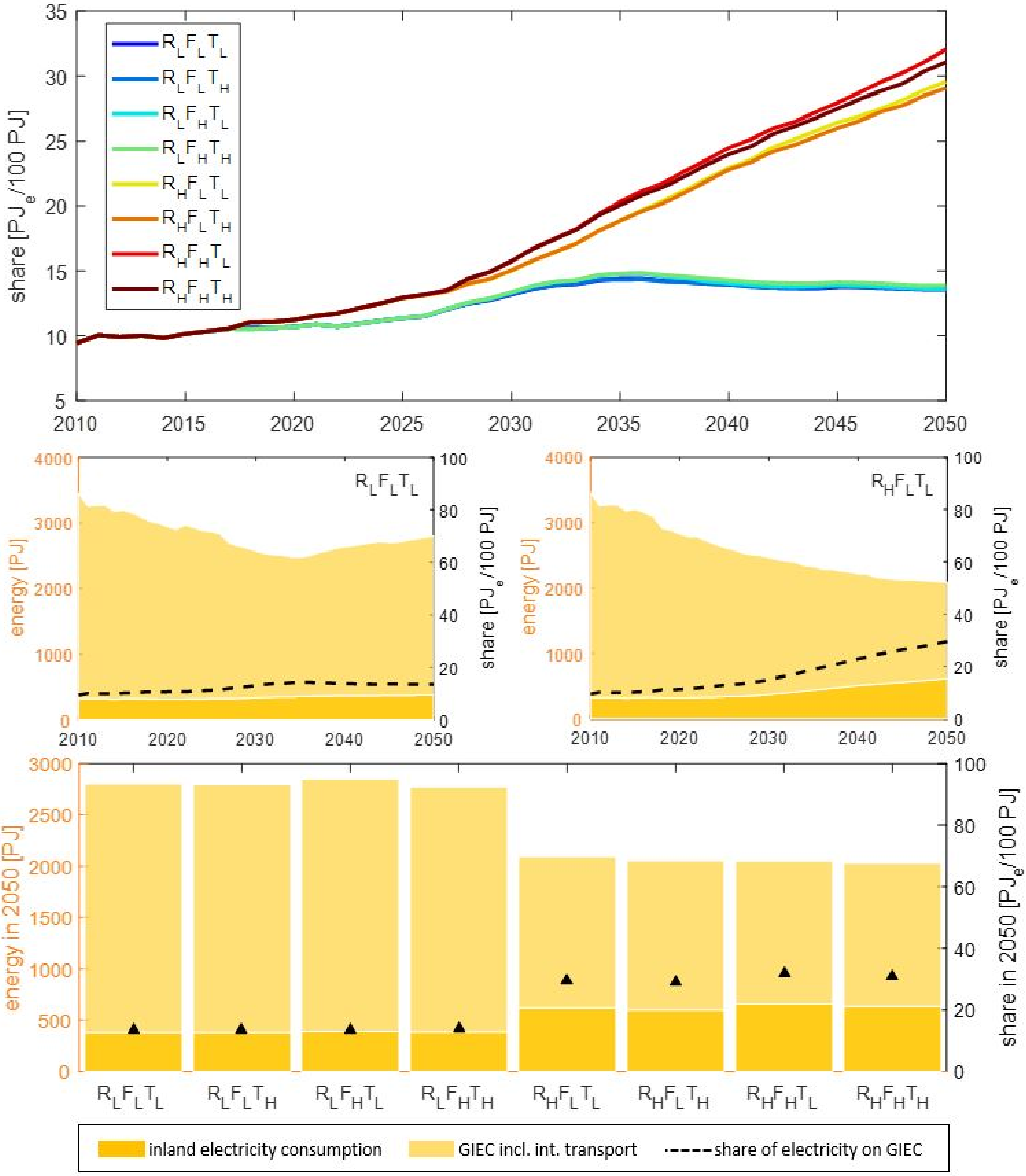

FIGURE 6.3: Energy consumption and system electrification.Top: Electrification trend of the eight scenarios. Mid: Energy consumption and system electrification development (Left:low RES. Right: high RES). Bottom: The same than above for all the scenarios in 2050.

gas to produce electricity is accompanied by its inherent exergetic inefficiency[1], thus increasing the amount of primary energy required to deliver final energy forms.

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[1] The process of converting chemically stored energy, into heat, and then into work to finally be converted into electricity, induces a high change in entropy. This means that only a relatively small fraction of the primary energy of the natural gas will be used as electricity.

On the other hand, the expansion of electricity intensive technologies also occurs slower in the low RES scenarios in comparison with the high RES scenarios. This means that in the low RES scenarios the electricity consumption is stacked somewhere below the 4 EJ/year, wherein the high RES scenarios this accounts for roughly 6 EJ/year. Both effects combined result in a final degree of electrification of activities in the high RES scenarios of 30%, which doubles the low RES scenarios of just 15%. The electricity consumption gap mainly occurs because of a lower adoption of electric-powered transportation options and heat sources in the low RES scenarios. These particular effects are analyzed more in detail in sub-chapter 6.3.

Given the broadness as an indicator of the level of electrification of activities, the consequences of the degree of decentralized flexibility and cross-border interconnections are not as perceivable as in the previously explored results. However, it becomes apparent that in the high RES scenarios, when a more decentralized demand side response is present in the system, the level of electrification increases. This is due to the adoption of more electricity-intensive technologies in some flexible industrial sectors, as it is further explained in this chapter. As a contrast, the level of interconnection does not present any significant impact in this category.

The other indicator that is explored in this category corresponds to the share of renewable energy in the gross final energy mix, and is illustrated in figure 6.4. In line with the previous observations a clear decrease on the share of renewable energy forms in the low RES scenarios after 2030 is noticeable due to the SDE+ discontinuation. Here it is also evident to state that after 2017 the presence of renewables in the high RES scenarios start to diverge from the low RES scenarios, but even with such differences the model predicts that in all the scenarios the EU 2020 target of 14% is reached (*DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*). When looking to the reported state of the renewables' share of 8.6% in 2018 CBS, the optimism of the model is exhibited as for 2018 the predictions almost double what happens in reality.

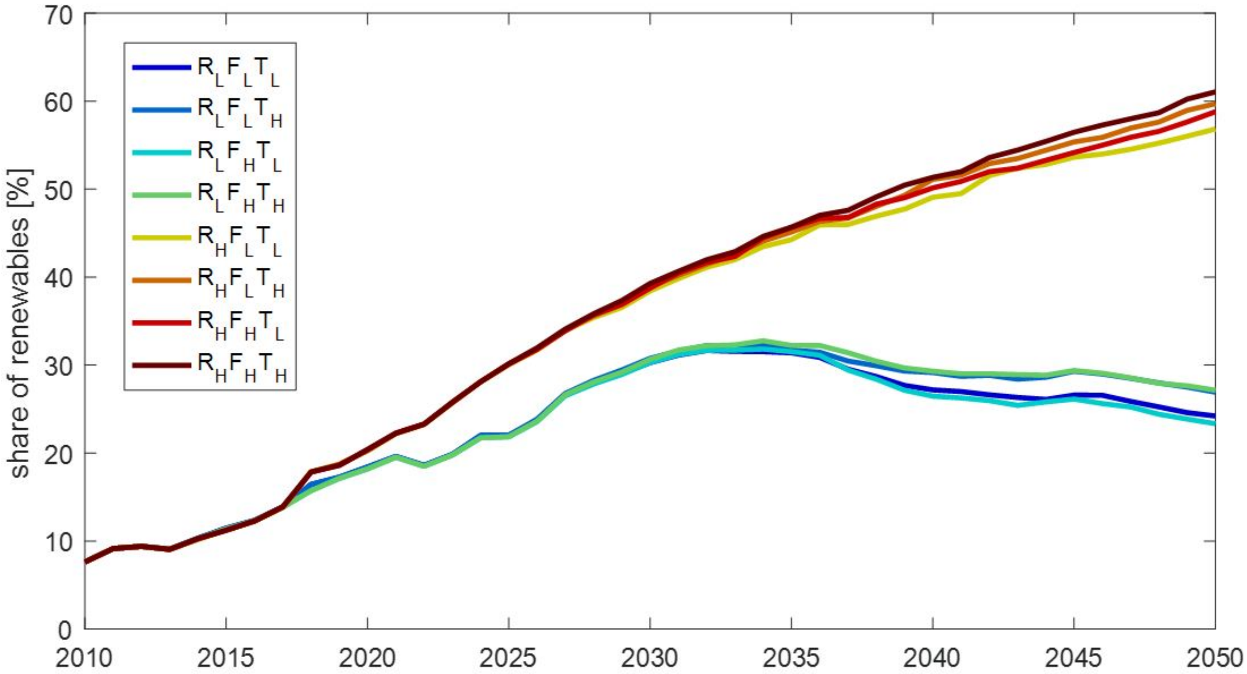

FIGURE 6.4: Share of renewable energy in the gross final energy consumption.

6.2 Impacts on the Netherlands' power sector

The next step to understand how the different scenarios influence the energy system is to dive more into detail on each sector. As the most direct impact of both decentralized demand-side response and cross-border interconnection lays on the balancing of electricity demand and supply together to the technologies driving this balance, this sub-chapter specifically focuses on describing the different scenario developments within the power sector.

Again, the three previously mentioned impact categories are used to provide these descriptions, such as using the sectoral emissions path as an indicator for the environmental impact. The economic and technical dimensions of this sector are influenced in many different ways, and that is why there are several elements reported for each. In the economic dimension the costs, investments, and electricity prices are used to provide the required insight. As for the technical dimensions, the generation stocks, the load profiles, the curtailed renewable energy, and the import and export flows are used for the purpose.

6.2.1 Environmental impact. Power sector scale.

Perhaps the most remarkable results are the ones shown in figure 6.5, as they are key to understand the results presented in figure 6.1. In this figure, the development of the yearly greenhouse gas emissions from the power sector is illustrated, and besides the expected lower emissions in the high RES scenarios, there are two main behaviors to be understood.

On the low RES scenarios, the development of the emissions follows two paths, the one followed by the scenario with low decentralized flexibility and no further interconnection expansions, and the path followed by the other three scenarios. It is remarkable that the other three scenarios report almost the same level of emissions after 2035, which is the year where the decentralized flexibility and the interconnection scenario's input begin to differ considerably. This is explained by two phenomena; the first one is that in the four low RES scenarios, the generation stock develops almost equally, providing an almost exact generation mix. To explain the second phenomena it is important to keep in mind that there is still a meaningful amount of gas present in the mix in the low RES scenarios. Moreover, this technology often ends up being the marginal generator. Therefore for the scenarios which expand the interconnection capacity, the increase in the load due to exports is mainly sourced by less curtailed wind, but also by the otherwise unused remaining capacity of the marginal generator. Whereas for the scenario where only the demand side response is increased, a big share of the load is redistributed to hours with a lower presence of renewables as appreciated in figure 6.9 (e.g., nighttime). Therefore using the remaining capacity of the non-renewables marginal generators in the hour. It is striking that even when the three scenarios use different mechanisms and end up having different net loads, and different amounts of curtailed energy (figure 6.10), they end up in a state with almost the same emissions due to the "physical barrier" that the marginal generators represent.

For all of the high RES scenarios the emissions follow almost the same path. This is partly due to the same reason exposed above for the low RES scenarios, only that for the high RES scenarios the differences are less perceptible as the stock of gas-fueled generators is the same in the four scenarios and represent less than 15% of the total stocks (figure C.1). However, it is important to mention that in the scenario with low decentralized flexibility and frozen interconnection expansions, there is a higher share of gas generators capturing their emissions due to the higher carbon prices assumed for those scenarios. The latter is a key reason of why in scenario $R_H F_L T_L$ the emissions are not higher than in the other R_H scenarios as occurred for the $R_L F_L T_L$ scenario.

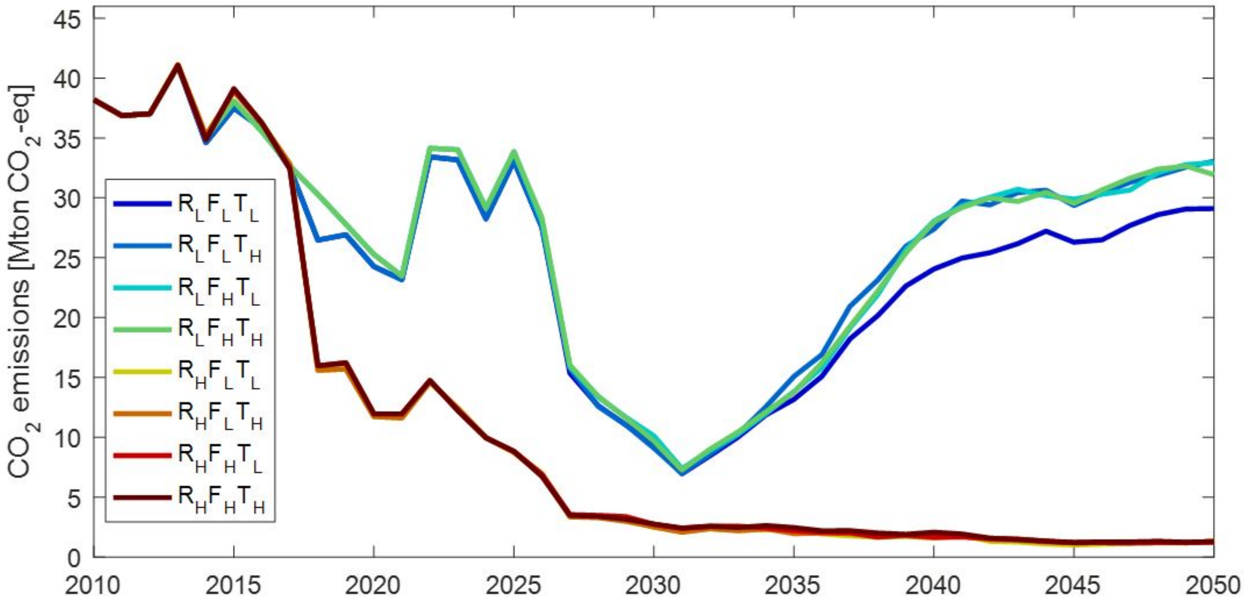

FIGURE 6.5: Power sector GHG emissions.

6.2.2 Economic impact. Power sector scale.

So far, in all the reported results the most visible differences in all the analyses have been found between the low RES and high RES scenarios, and the other scenario dimensions have echoed subtly in the results. However, is in the economic aspects of the power sector that the most significant impacts are perceived between the different decentralized flexibility and interconnection scenarios. To start unraveling these impacts, a visualization of the developments of the cost components of the sector is provided in figure 6.6.

When analyzing the differences between the high RES and low RES scenarios, some trends can be easily observed. The high RES scenarios predict higher new capacity investments, and technology transfer investments, thus resulting in higher capital costs. The shift towards renewable technologies results in a simultaneous increase in the operational costs due to the capacity increase, and a decrease in the fuel costs (reported in the figure including the revenues of the electricity sold as negative costs) due to the costless nature of the renewable energy resources. Observations are in line with the behavior found for the complete energy system reported in figure 6.2. Also in line with the general observations is the fact that the low RES scenarios end up with lower total sector costs in 2050 that the high RES scenarios, not before revering a trend in which the high RES scenarios were showing lower sectoral costs. However, these differences and the tipping point are more influenced by the degree of decentralized flexibility and cross-border interconnection present in the system, as it is described below.

When analyzing the effects of the interconnectivity, it is possible to observe that a higher presence of it under a high RES scenario has the ability to lower the required investments and therefore the capital costs. A relatively more accentuated behavior in the same direction than in the capital costs is present in the operational costs. Curiously under a low RES scenario these effects are no longer visible, and they even present slighter opposite effects. Furthermore findings indicate that when the cross-border capacity is still expanded after 2030, in both the low and high RES scenarios, the fuel costs drop considerably. All this is resulting in a net lowering effect on the sector costs of the interconnection capacity regardless of the RES scenario.

For the degree of decentralized demand-side response, less pronounced but similar results were

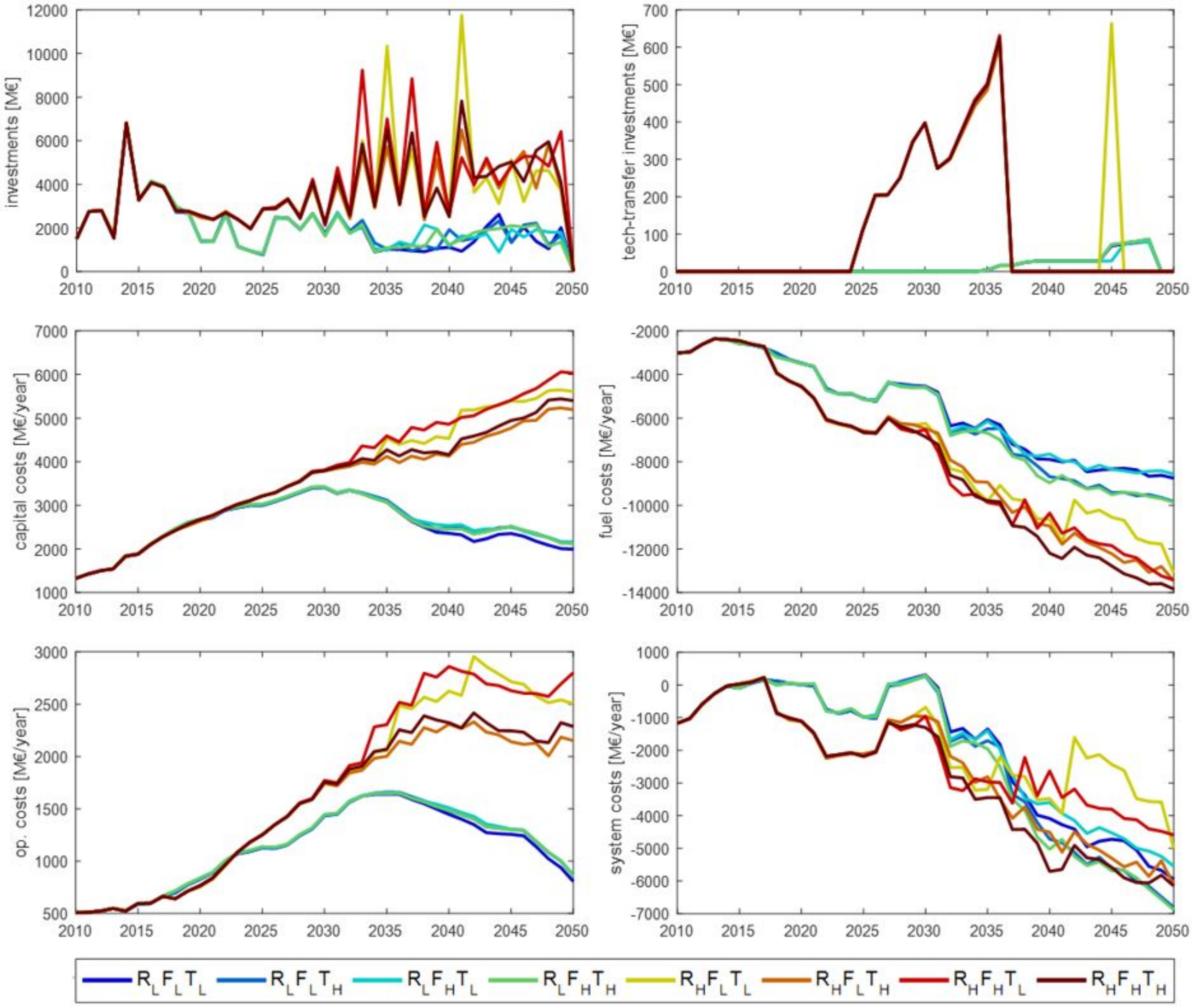

FIGURE 6.6: Power sector costs. Top left: New investments in the power sector from 2010 to 2050. Top right: Technology transfer investments in the power sector from 2010 to 2050. Mid left: Capital costs in the power sector from 2010 to 2050. Mid right: Fuel costs in the power sector from 2010 to 2050. Bottom left: Operational costs in the power sector from 2010 to 2050. Bottom right: Total costs in the power sector from 2010 to 2050.

found within the high RES scenarios. A higher decentralized flexibility results in higher investments, and capital and operational costs, with a simultaneous decrease in the fuel costs, resulting in a net lower sector costs. For the low RES scenarios, the degree of implementation of this flexibility dimension results in imperceptible impacts for the sectoral costs. A final overall observation is that without any flexibility implementation, the low RES scenario presents overall sectoral costs more than 1 billion euros lower than for the high RES scenario in 2050 (from 2040 to 2048 more than 2 billion euros lower). But with higher adoption of the two analyzed flexibility dimensions, the sectoral costs in the low RES scenario are roughly half billion euros lower than in the high RES scenario in 2050 (and the same costs or lower until 2048).

Another aspect in which interconnection and demand-side response show having an enormous impact on the system is the distribution events of the electricity prices. It is via their impact on this element of the system through which both dimensions have repercussions in the technological development of other sectors of the system. Figure 6.7 shows the distribution of the 2050 electricity price events for the eight scenarios. Is important to mention that the obtained results are in line with the expectations reported in the 2017 Netherlands' energy outlook (ECN, 2017b), which for the year 2035 reports an expected electricity price of roughly 50 €/MWh (within a range of 30 to 90 €/MWh), while in this study the average electricity prices predicted for the year 2035 are between 47.9 and 50.6 €/MWh for the low RES scenarios, and 60.5 and 67.9 €/MWh for the high RES scenarios.

Surprisingly, there is not a big difference between the average electricity price of the low and high RES scenarios (as can be appreciated in appendix C, the differences used to be higher in previous years). However, there is a big difference in the wideness of the domain in which these price events occur, as it can more clearly contrasted between the $R_LF_LT_L$ and the $R_HF_LT_L$ scenarios. For all the four combinations of decentralized flexibility and interconnectivity, it is possible to detect a wider spread of the events in the high RES scenarios. And for both the low and high RES scenarios it can be noted that both flexibility dimensions can effectively decrease the spread of the electricity price events, being the interconnectivity the dimension with a higher impact on this variable. It is important to keep this results in mind as they are a key explanation of the results that will be presented later on.

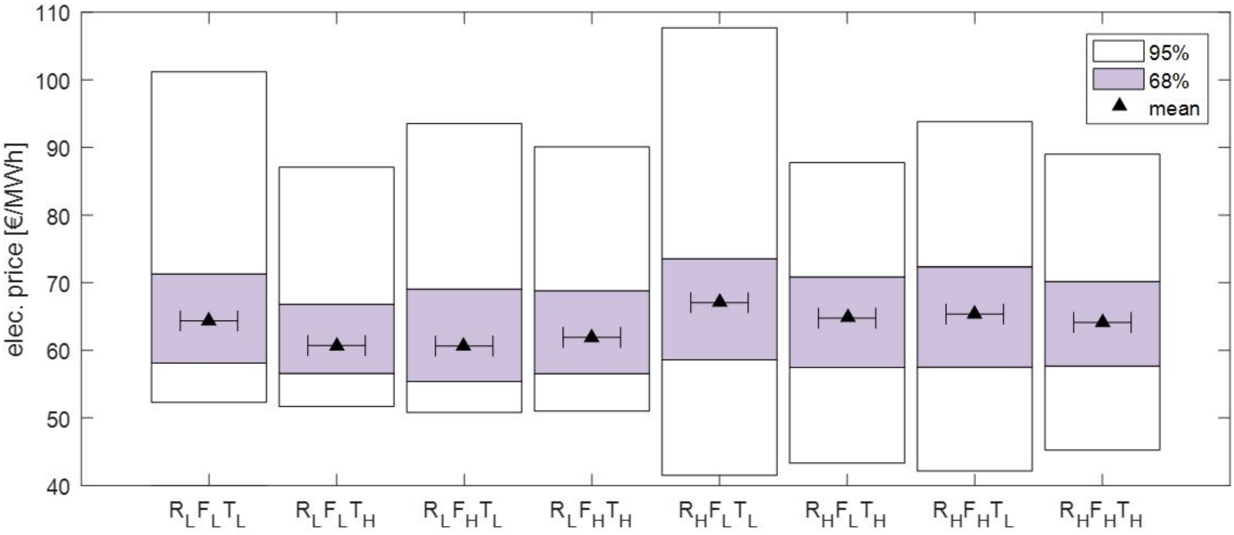

FIGURE 6.7: Wholesale market electricity price events distribution in 2050.

6.2.3 Technical impact. Power sector scale.

An obvious difference between the low and high RES scenarios is the development of the power generation stock. In figure C.1 a lower presence of fossil-fueled generators and a higher penetration of renewables in the high RES scenario can be observed. The latter scenarios, predicting an available generation stock of about 50 GW by 2035, are consistent with the 2017 Netherlands' energy outlook (ECN, 2017b). However, although similar predictions for the fossil-fueled generators with a bit more than 10 GW, and the RES generators with 40 GW of installed capacity, the national energy outlook expects a faster development of solar PV and slower development of offshore wind than reported in the high RES scenarios. For the low RES scenarios, it is possible to notice that after the suspension of the SDE+ subsidies, natural gas generators take an active role in the stock development, which together with the imports of electricity, decrease the total stock to 30 GW by 2050 (more than 70 GW for that year in the high RES scenarios).

There are no major differences in the flexibility dimensions within the low RES scenarios, at

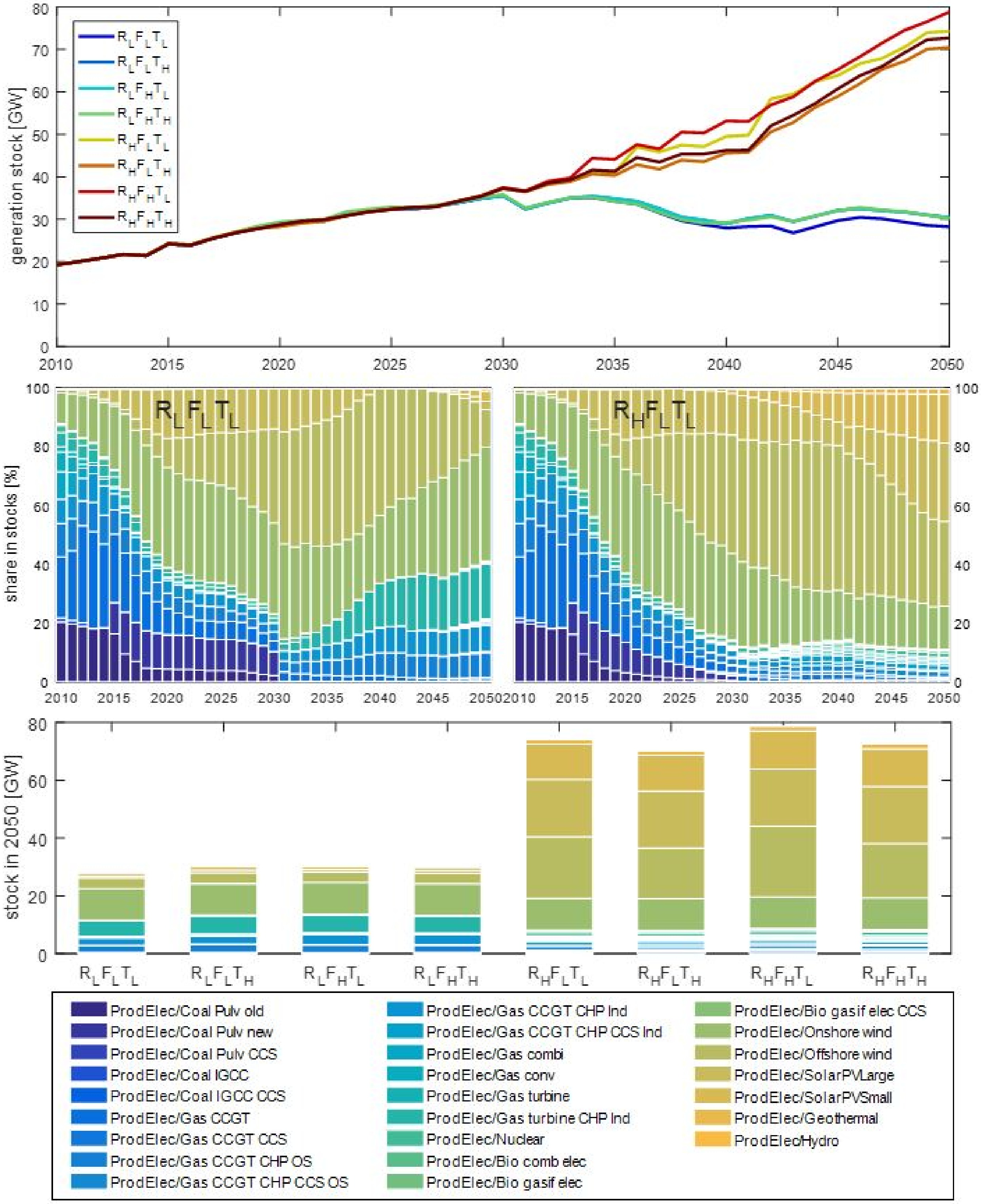

FIGURE 6.8: Power sector stock development. Top: Development of the net available electricity generation stock in the Netherlands for the eight scenarios. Mid: Characteristic stock composition development for the low and high RES scenario sets (the four scenarios of each set show a very similar composition). Low: The electricity generation stock available in 2050 for each of the generation technologies in the eight scenarios.

least not as strong as in the high RES scenarios. Findings indicate here that cross-border interconnection capacity tends to slightly decrease the total available installed capacity at expenses of offshore wind. Oppositely, decentralized demand side response tends to increase the available stock also at expenses of offshore wind. The impact of the interconnectivity increase is mainly explained by a higher trading capacity together with a lower curtailment rate, which decreases the need for local capacity while increasing its exploitation. In the case of the decentralized demand-side response, the increase in stock is mainly explained due to the higher electrification present in this scenario as described above.

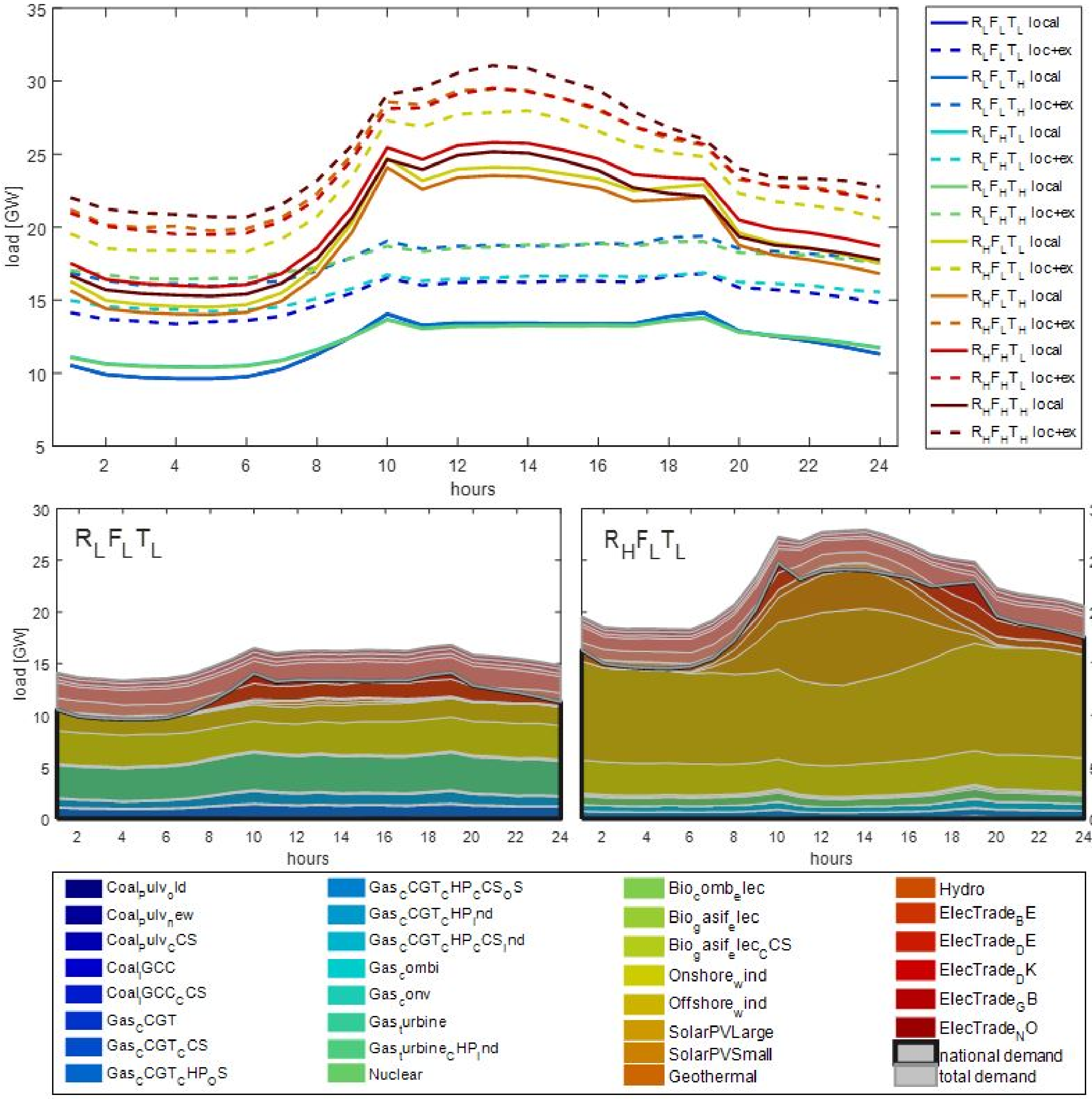

FIGURE 6.9: Demand and supply profiles. Top: Average local demand and net demand hourly profiles in the year 2050 for the eight scenarios. Mid: Characteristic stock composition development for the low and high RES scenario sets (the four scenarios of each set show a very similar composition). Low: The electricity generation stock available in 2050 for each of the generation technologies in the eight scenarios.

Next to the stock development, it is also important to understand which technologies are used and at what times to satisfy both the local and the foreign power demand. In figure 6.9 the yearly hourly load and generation profiles for the $R_L F_L T_L$ and $R_H F_L T_L$, are shown. The same figure illustrates the redistribution effects of the flexibility dimensions in the local and foreign loads hourly profiles.

The main observations besides the evident generation mix composition between the low and high RES scenarios lay in the impact of the flexibility dimensions. First, two peaks are observable around 10:00 and 19:00 hours, these are due to the presence of electric vehicles and their particular reference charging profiles. Curiously, despite electric vehicles following a lower development in the low RES scenarios, it is still possible to note the peaks, this due to lower relative electrification, so the remaining load is not sufficient to hide the effect of their charging profiles. Also, around the peaks it is possible to see that interconnection has a flattening effect in the net load profile, while decentralized demand side response present this flattening effect it in both the local and the net load profiles.

In the low RES scenarios it can be remarked that, as the flattening effect operates with the same local demand in the four scenarios, the load is redistributed under a more flattening pattern. However, in the high RES scenarios, the flattening is not so visible due to the higher relative electrification of the system in the high decentralized flexibility scenarios. And in both the low and high RES scenarios, it is apparent that even with the presence of decentralized demand-side response, the characteristic load peaks due to electric vehicles charging, are not possible to disappear from the profile. It is important to mention that this could be a consequence of the algorithm used to redistribute the charging of the electric vehicles, and it would be recommended not to draw strong conclusions from this observation. At least not until a study focusing on this particular topic is used to strengthen the model considerations.

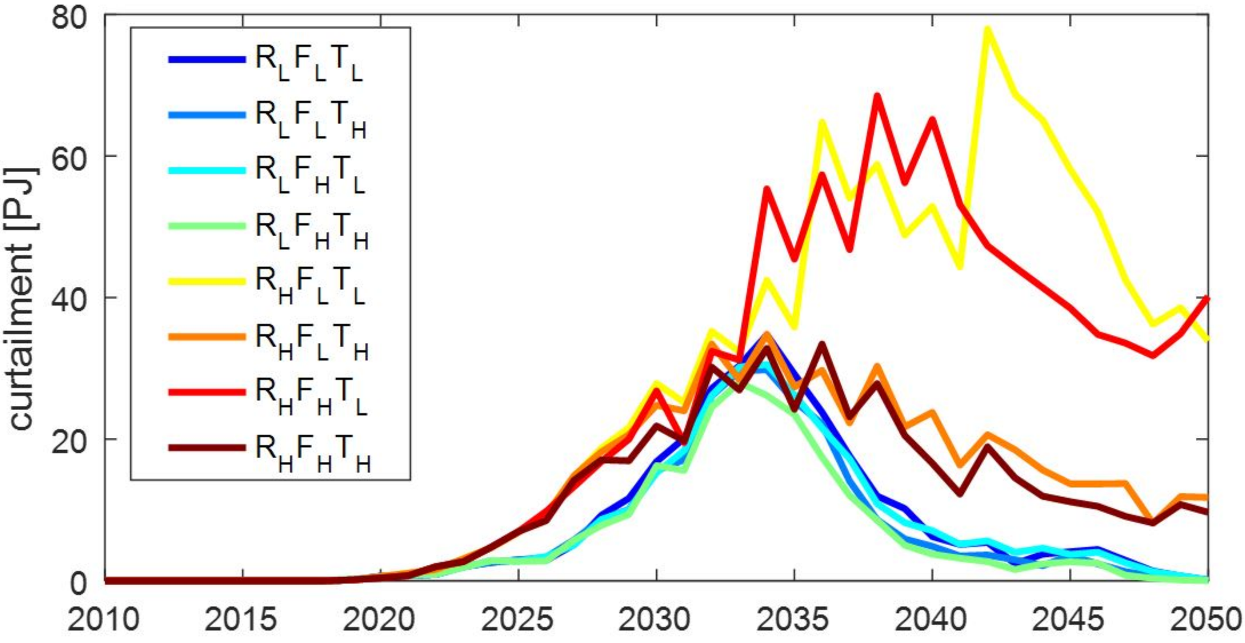

FIGURE 6.10: Renewable electricity curtailed.

Curtailment is understood as an undesired form of grid flexibility, as it contributes to decrease network congestions by paying the opportunity cost of producing clean, renewable electricity, thus negatively impacting the emission factor of the power system, and the business case of intermittent renewable generation. In figure 6.10 the RES curtailment for the eight scenarios is reported, and the observations are straightforward. Increasing cross-border interconnectivity boosts curtailment reductions in a much more efficient way than decentralized demand-side response, and such reductions are more significant with a higher presence of renewables in the system. This impact helps to explain many of the above results for the $R_H F_L T_H$ and $R_H F_H T_H$ scenarios, such as the relatively lower fuel, operational and capital cost requirements, and the lower stock requirement with higher net load outputs.

The total imports and export flows are also an interesting result of this study as reported in figure 6.11. A main difference between the low and high RES scenarios is that in the low RES scenarios the Netherlands become a net electricity exporter after 2020, while in the second ones the opposite behavior is perceived. Furthermore, besides the indicated higher import and exports flows in the scenarios with higher interconnectivity, it is possible to derive that demand-side response has a much less significant impact on these flows.

Between 2018 and 2027 a contrasting behavior can be noticed between the low and high RES scenarios. In the low RES scenarios, the system tends to behave as a net electricity exporter, whereas in the latter the system has a counter behavior. This is due to the relative slightly higher presence of dispatchable capacity in the low RES scenarios, and due to the assumed higher development of renewables in the foreign countries for the high RES scenarios.

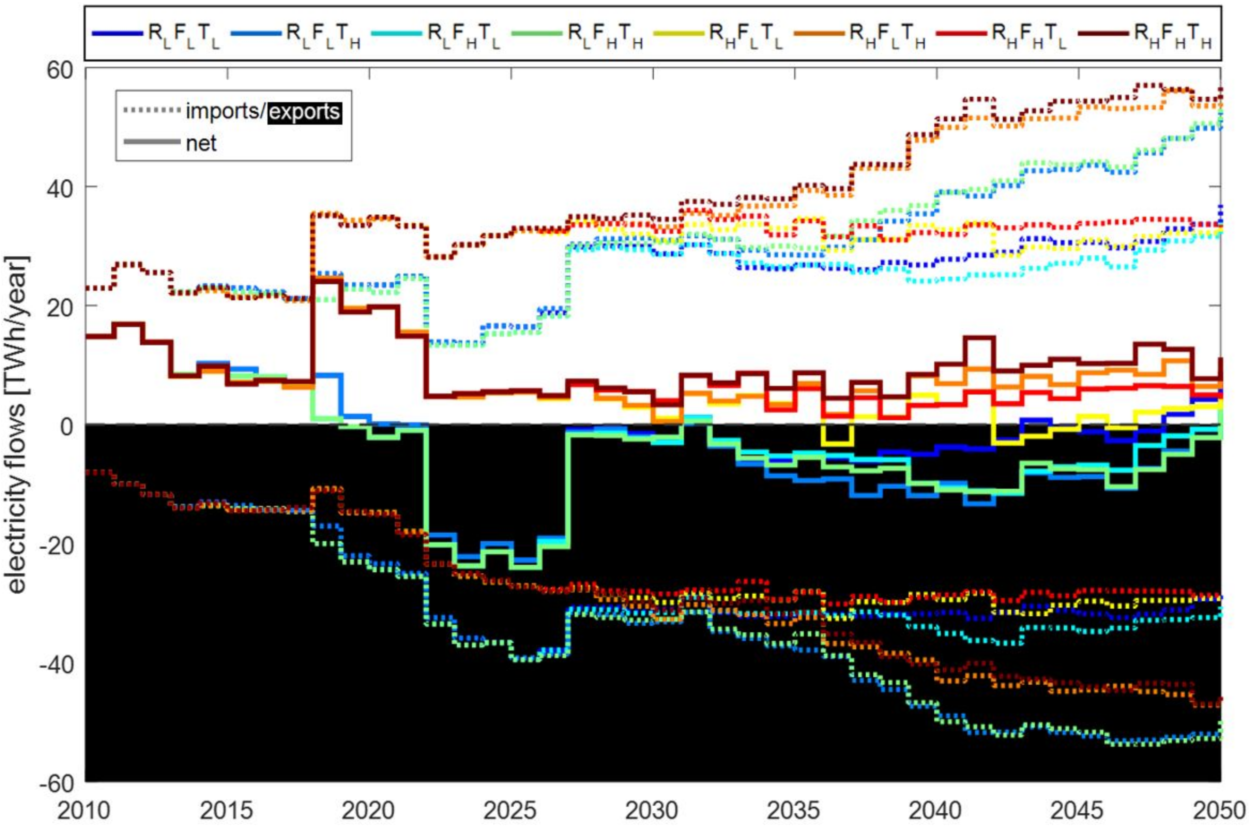

FIGURE 6.11: Cross-border electricity flows. The white background area represents positive flows; this is import flows. The black background area represents positive flows; this is export flows. The dashed lines represent the gross electricity flows. The continuous lines represent the net electricity flows; this is the difference between the imports and the export flows.

6.3 Impacts on different sectors of the energy system

When analyzing the impact of system developments that happen in the power sector, the changes in other sectors are often ignored, but one of the goals of this study is to expose the impact of these changes in all the different sectors of the energy system. Nevertheless, measuring those impacts is already a challenge, reporting them in a compiled way requires a framework in which general comparable characteristics are combined. In this study, a visualization framework is used to report such results using one indicator for each of the three impact categories of interest: the sectoral emissions for the environmental one, the total sector costs for the economic one, and the level of sectoral electrification for the technical one (also expressed as units of consumed electricity per hundred units of consumed energy). This framework is used to expose the impact of cross-border interconnection and decentralized demand-side response. Therefore it is applied two times, one for each low and high RES scenarios sets.

6.3.1 Sectoral impact of flexibility in the low RES scenarios

For each of the twenty-two sectors of the national energy system, the emissions, costs, and level of electrification of the $R_L F_L T_L$ scenario are reported in figure 6.12. Next to these in the same figure, the relative changes of the other three low RES scenarios towards the $R_L F_L T_L$ scenario are also shown. This figure indicates that demand-side response and interconnectivity differently affect the development of the sector.

For instance, one of the most interesting observations of the low RES scenarios is that the transport sector is not affected by flexibility other than in the decrease of the system costs of the highly electrified rail transport sector due to the decrease in the electricity prices.

The hydrogen production sector reveals another interesting result: here higher decentralized flexibility decreases both sector costs and emissions due to a shift in production from the traditional methane reformation to electrolysis. The opposite effect in the sector is produced by higher interconnectivity, when by decreasing the spread of the electricity price events also decreases the number of hours with cheap electricity, therefore hampering the deployment of the hydrogen production via electrolysis of water. However, although these results seem logical, it is recommended to expand the modeling considerations of this sector as current simplifications may be limiting the predictions.

Furthermore, a potential future industrial heat generation landscape making use of hybrid heat pumps provides another set of results similar to the hydrogen production sector ones. In this sector, the system costs increases with interconnectivity, but decreases with decentralized flexibility in such a way that when both are combined, the net effect of both mechanisms results in a lowering of the sectoral costs.

6.3.2 Sectoral impact of flexibility in the high RES scenarios

The sectoral results of the high RES scenarios are reported following the same structure than for the low RES scenarios and are reported in figure 6.13. Here it can be noticed that these scenarios report lower emissions, higher costs, and higher electrification than the low RES scenarios, which is in line with the results reported at the beginning of the chapter.

Similarly than to the low RES scenarios, the hydrogen production sector tends to increase the degree of electrification with higher decentralized flexibility, and decrease it with higher interconnectivity. In this case a higher electrification results in lower emissions, and lower sector costs due to carbon pricing.

It is worth pointing out that the industrial heat sector has developed a higher technology mix,

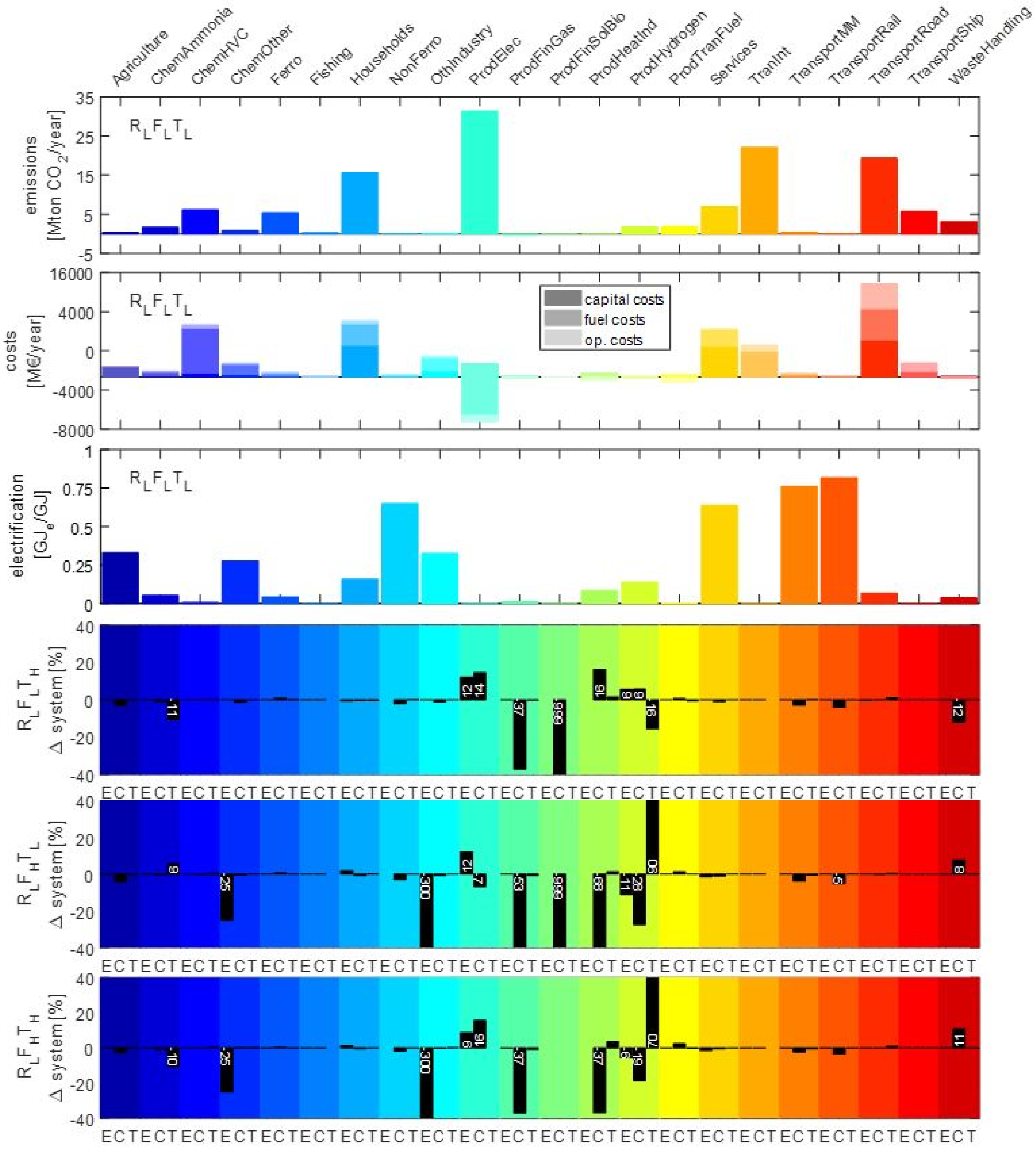

FIGURE 6.12: Sectoral impact of flexibility in the low RES scenarios. From top to bottom. First graph: 2050 carbon emissions for all the sectors in the scenario $R_LF_LT_L$. Second graph: 2050 total costs for all the sectors in the scenario $R_LF_LT_L$. Third graph: 2050 level of electrification of all the sectors in the scenario $R_LF_LT_L$. Fourth to sixth graphs: Relative change of each indicator within each sector for scenarios $R_LF_LT_H$, $R_LF_HT_L$, and $R_LF_HT_H$ respectively. Each color represent the same sector than the visualized in above graphs, and over each color it is plotted with a black bar the net sectoral change for: (E) emissions, (C) total costs, and (T) level of electrification.

and is more resilient to changes in flexibility, with the difference that in these scenarios both the costs and the degree of electrification tends to slightly decrease with an increase of any form of flexibility.

A new sector is now strongly influenced by flexibility on the high RES scenarios. The produc-

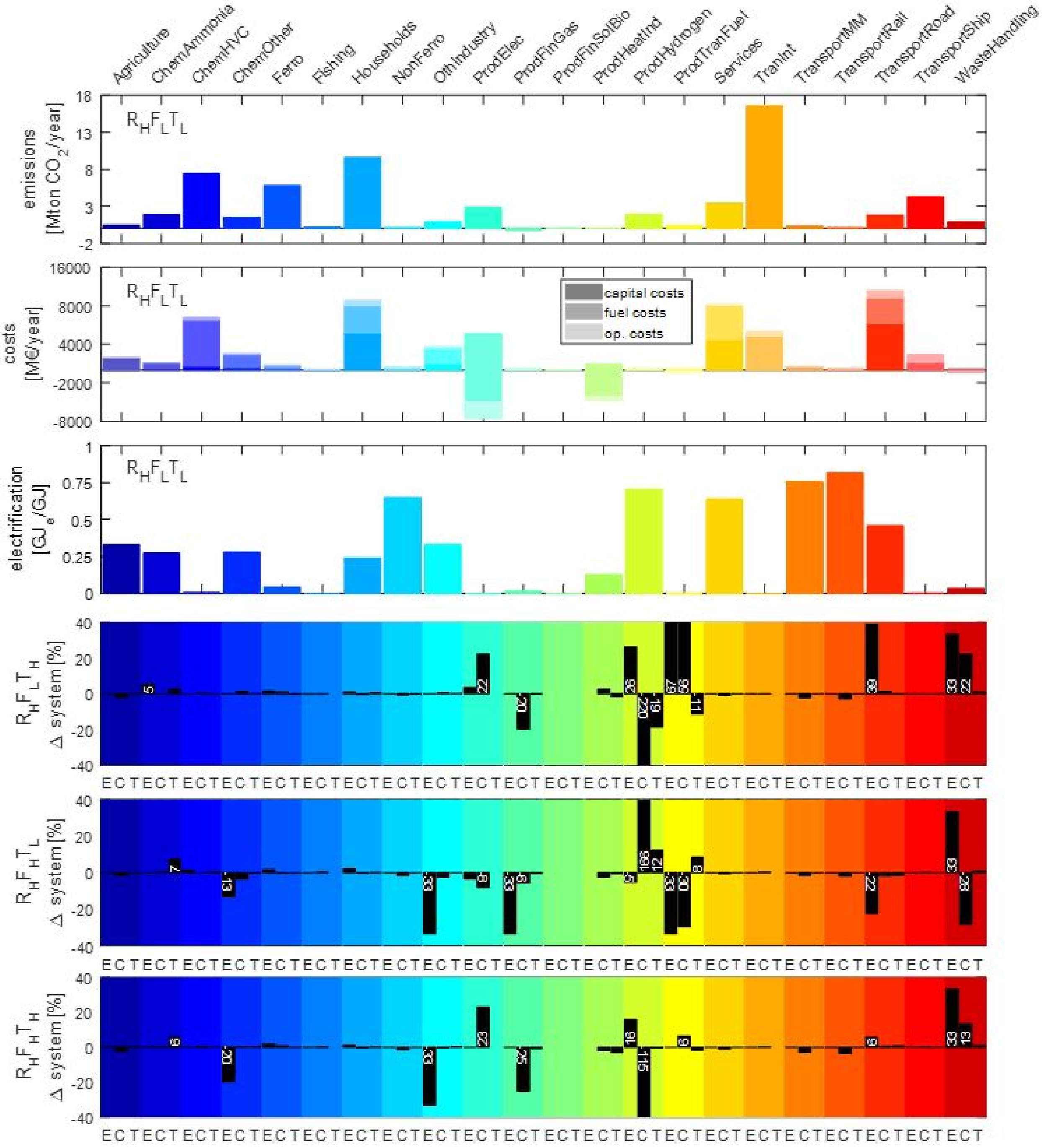

FIGURE 6.13: Sectoral impact of flexibility in the high RES scenarios. From top to bottom. First graph: 2050 carbon emissions for all the sectors in the scenario $R_H F_L T_L$. Second graph: 2050 total costs for all the sectors in the scenario $R_H F_L T_L$. Third graph: 2050 level of electrification of all the sectors in the scenario $R_H F_L T_L$. Fourth to sixth graphs: Relative change of each indicator within each sector for scenarios $R_H F_L T_H$, $R_H F_H T_L$, and $R_H F_H T_H$ respectively. Each color represent the same sector than the visualized in above graphs, and over each color it is plotted with a black bar the net sectoral change for: (E) emissions, (C) total costs, and (T) level of electrification.

tion of transport fuel sector has a higher electrification[2], and thus its development is strongly influenced by the number of cheap electricity hours in a year. Therefore higher interconnectivity tends to lower the electrification of the sector and the share of bio-sourced oil while increasing sectoral costs and emissions. Remarkably higher decentralized flexibility has the exact opposite effect.

The transport sector suffers a massive transformation driven by the higher electrification of the road transport. However, its most significant impact is due to a curious indirect effect which occurs in the system. As explained just above, higher interconnectivity increases the emission factor of the fuel mix, while higher decentralized flexibility decreases it. This is why the observed sectoral emissions tend to increase with higher interconnectivity and to decrease with a higher decentralized demand-side response.

Appendix B includes the detailed developments of the technologies stocks for some selected sub-systems under all the eight analyzed scenarios.

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[2] In figure 6.13 is not perceived as is opaqued by the enormous amount of oil input and fuel output

Chapter 7

Interaction between the two flexibility dimensions

Among the previously reported results, there is one category that stands out from the rest: the power sector costs. It has been demonstrated that the power sector costs respond to cross-border interconnectivity (XBIC), and decentralized demand-side response (DDSR), where both alternatives present themselves as an opportunity to decrease system costs. As shown in figure 6.6, in some years the difference between the scenarios without any flexibility implementation, and any of the others could exceed the three and one billion euros per year in the high RES scenarios and low RES scenarios respectively. Thus it is important to explore and analyze such opportunities. As figure 6.12[1] illustrates, the results for the low scenarios show that in 2050 the $R_L F_L T_H$ scenario and the $R_L F_H T_H$ scenario has a decrease in costs of 14% and 16% respectively in relation to the $R_L F_L T_L$ scenario, while the $R_L F_H T_L$ scenario has a cost increase of 7%. Similarly in the high RES scenarios it can be observed that for the same year (figure 6.13), the $R_H F_L T_H$ scenario and the $R_H F_H T_H$ scenario has a decrease in costs of 22% and 23% respectively in relation to the $R_H F_L T_L$ scenario, while the $R_H F_H T_L$ scenario has a cost increase of 8%.

From this could be concluded that interconnectivity helps to decrease power system costs while DDSR increases the costs unless interconnectivity is also applied as a flexibility measure of the system. However, this would not be an adequate conclusion, since - as it can be observed in figure 6.6 - in some years the $R_H F_H T_L$ scenario the power sector costs were lower than in the $R_H F_L T_L$ scenario. Therefore to make such a conclusion, it would require more scenarios consider the average sector costs in the period, instead of only the 2050 costs. That is why another experiment was performed in the form of a sensitivity analysis to further test the impact and the interaction of both flexibility dimensions.

7.1 Sensitivity of interconnection and flexibility on 2050 power sector costs

A small exercise was performed in order to gain a better understanding of the simultaneous impact of XBIC and DDSR. In this exercise seven different scenarios increasing in interconnectivity (each scenario has a quicker development of the transmission capacities than the previous one for every country), were combined with eleven different scenarios increasing in decentralized demand-side response (each scenario present a higher DSR in households and electric vehicles, and a higher industry flexibility than the previous one). This resulted in a bi-dimensional mesh of 77 scenarios distributed among two axes, the 7 XBIC scenarios, and the 11 DDSR scenarios, as shown below where $T_i \; \forall \, i \in [1, 2 ... 7]$ represents an interconnectivity scenario, and

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[1] Remember that the costs in the power sector are negative as they include the revenues from selling electricity. Therefore when the costs of a sector in this figure has a negative value, and $\Delta > 0$, means that there is a profits increase, or in other words, costs decrease.

$F_j \, \forall j \in [1, 2...11]$ a decentralized demand side response scenario:

$$\begin{matrix} (T_1, F_1) & (T_1, F_2) & \cdots & (T_1, F_{11}) \\ (T_2, F_1) & (T_2, F_2) & \cdots & (T_2, F_{11}) \\ \vdots & \vdots & \ddots & \vdots \\ (T_7, F_1) & (T_7, F_2) & \cdots & (T_7, F_{11}) \end{matrix}$$

The results obtained within this experiment for the the average yearly costs of the power sector between the period 2010 to 2050, are reported in the bi-dimensional visualization contained in figure 7.1. It can be observed that the sectoral costs decrease sharply for the XBIC dimension, and decrease more modestly for the DDSR. Furthermore it can be noticed that in the DDSR dimension some spikes appear which does not happen in the case of the XBIC. Besides, the steepness of the slope points towards the cost mitigation potential of DDSR, which is lower when more interconnectivity is present in the system.

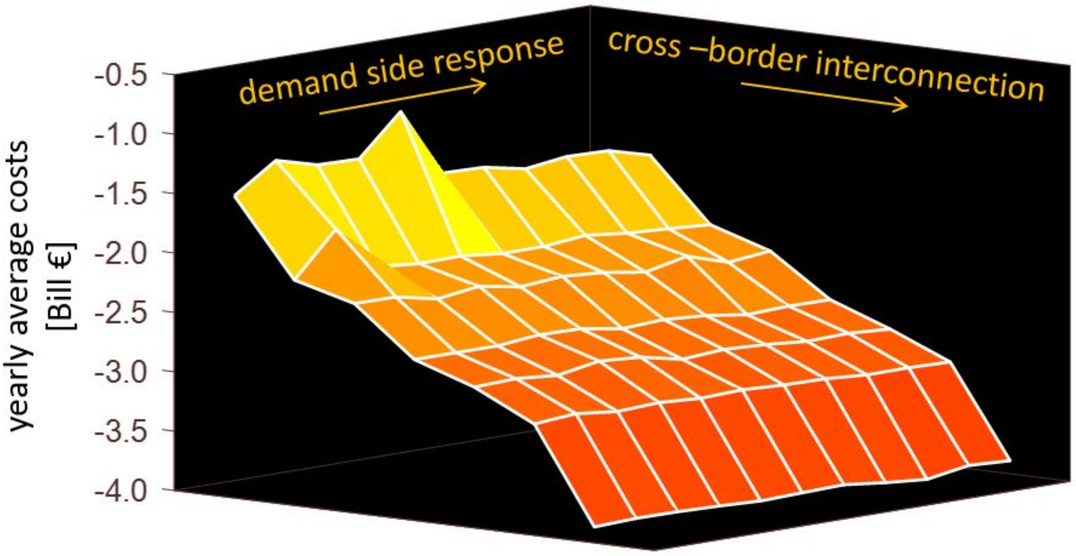

FIGURE 7.1: Power sector costs from bi-dimensional sensitivity analysis. 3-D representation of the power sector yearly average costs for the 77 scenarios of the bi-dimensional sensitivity analysis on DDSR and XBIC.

It is essential to keep in mind that the current modeling approach is not predicting the development of the generation technologies of the foreign markets, thus in some way works as a sink with an enormous generation capacity at a price predicted by ENSYSI. This means that the interconnection capacities assumed in the scenarios cannot be considered enormously high as reliability may decrease. In these scenarios, the total interconnectivity of the Netherlands varies from 8.1 to 26.5 GW for the year 2050 (roughly 40% and 130% of the local load in that year). Thus, the system costs for the last XBIC scenarios carry a higher uncertainty and may be underestimated.

Based on the above-presented information it can be concluded that under a likely upcoming scenario, both cross-border interconnectivity and decentralized demand side response present themselves as alternatives to alleviate the costs that the energy transition will represent for the society. Keeping in mind that the XBIC carries the more substantial benefits, then DDSR presents itself as a complementary solution. Nevertheless DDSR importance increases for sure under scenarios with moderated interconnectivity expansions, and likely under scenarios where interconnectivity cannot be considered a sink. However, for further conclusions it is necessary to understand why there are cost peaks in some scenarios with higher DDSR.

7.2 Explanation of DDSR behavior

To understand why the previously mentioned peak becomes visible, another small experiment was designed. In this experiment, a very simple power system was built, with PV, wind, nuclear, coal, NGCC, and gas turbine generators (4, 6, 0.5, 4.5, 8.5, and 1.5 GW of capacity respectively), and a fixed import flow of 0.5 GW. The supply is solved using a simplistic unconstrained economic dispatch approach based on the residual load (using the same profiles than ENSYSI), and the merit order curve of the generators (using the same 2010 marginal costs than ENSYSI). The interesting part of the experiment is that there was included a very similar demand-side response mechanism than the one used in ENSYSI, responding to the electricity price events, and considering the flexibility range and fraction of the redistributed load.

Based on this, two simulations were run one without using the DDSR mechanism(NO DSR scenario), and another using the DDSR mechanism (DSR scenario). The results of the simulations are reported in figure 7.2, where the impact of DDSR can be seen. The most prominent feature is that the top of the load hills are flatter when DSR is activated, and the difference of them with the valleys is lower. This behavior is an expected result, as it is the main concept of load redistribution and demand-side response. However, the most complex findings and the most remarkable observations are perceived in the figures reporting the electricity price profiles of the two scenarios. Here it can be seen, that two out of the three electricity price peaks of the NO DSR scenario disappear in the DSR scenario. Furthermore, there are many other hours in which the high electricity price events also decreases in the DSR scenario (cf., just before the hour 150), which remains intuitive. Most surprising is that there are many hours in which the opposite effect is perceived (cf., around the hours 40, 70, and 100), where there are hours in which the electricity was cheaper in the NO DSR scenario which increased in price for the DSR scenario.

This can be explained by resorting to the merit order curve concept, where the electricity price is settled by the marginal technology. If the load redistribution shifting into that hour is larger than the residual capacity of the marginal generator, then the next generator in the order will provide electricity increasing the setup price. Similarly, if the load redistribution shifting from that hour is larger than the used capacity of the marginal generator, then this generator will not provide electricity, and the marginal generator will be the previous in the order, lowering the electricity price in that hour. In the mechanism analyzed, the electricity prices are the load redistribution, so the merit order curve is not taken into consideration. This means that sometimes the resulting net effect will be a lower average electricity price, and some other times a higher average electricity price.

Consequently, as mentioned in chapter 2, many other things are determining the hourly electricity prices in reality, such as the ramping constraints, the transmission and distribution constraints, etc. But it is relevant to learn from this exercise that the mechanism by which the decentralized demand side response is built in reality will impact on the social benefits of using DDSR. In other words, if the coordinating actors applying decentralized demand-side response (e.g., block-chain algorithms, or local aggregators), do not align their mechanism with the wholesale market it cannot be ensured that the resulting state will alleviate the costs of the energy transition.

The conclusion is possibly the most important contribution of this study, as it highlights the need of focusing efforts in studying potential DDSR redistribution mechanisms, other than the traditional ones responding to electricity price events or load profiles. The future developments of

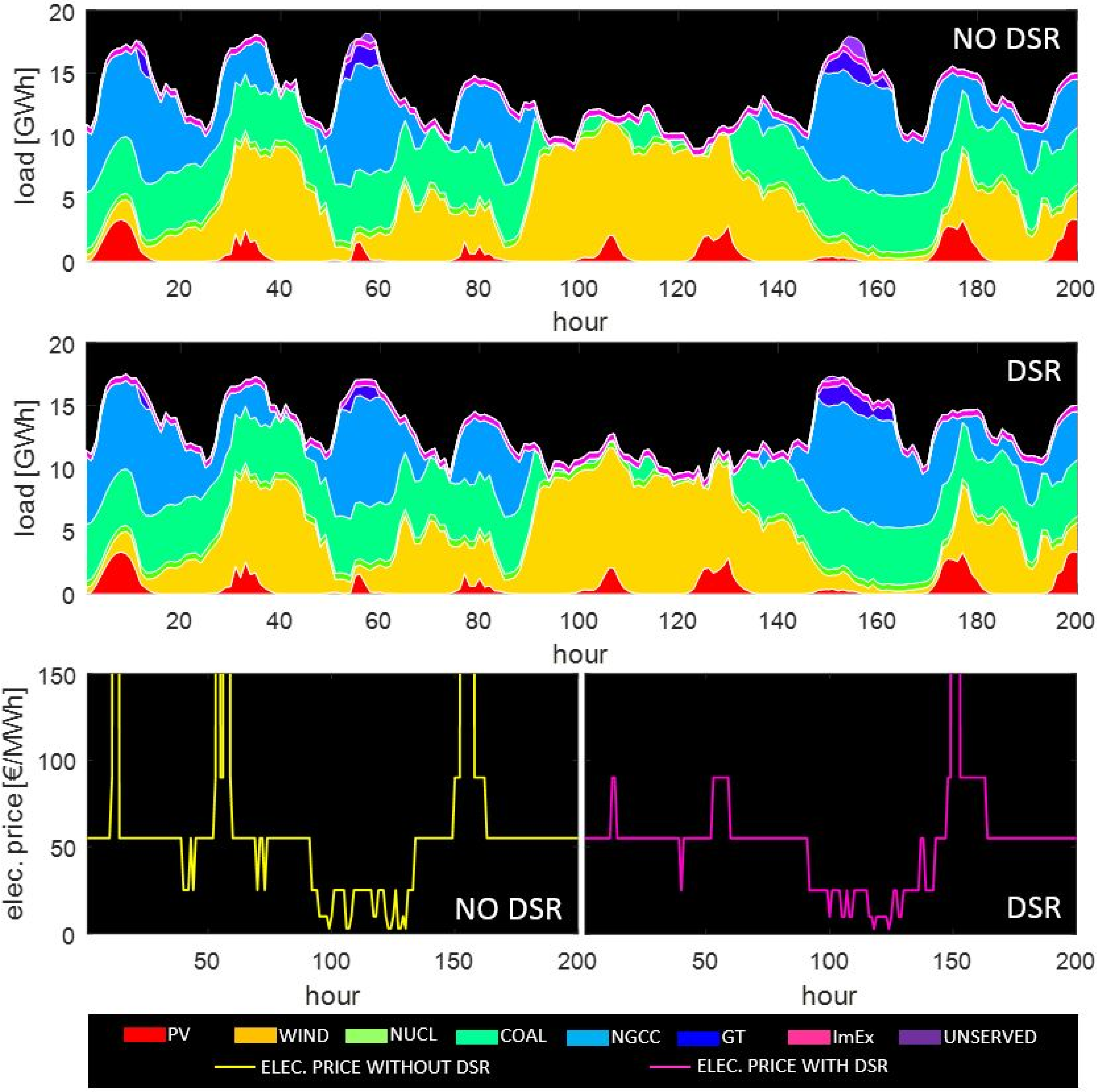

FIGURE 7.2: DDSR Mechanism. Top: Load and generation profiles in the NO DSR scenario. Mid: Load and generation profiles in the DSR scenario. Bottom-Left: Electricity price profile of the NO DSR scenario. Bottom-Right: Electricity price profile of the DSR scenario.

the technologies and structures behind DDSR are still uncertain, and therefore it is very important to have a better understanding of them and their interactions with other system elements such as cross-border interconnectivity. ENSYSI is a very suitable model to analyze these types of questions as it can easily include different actors using different DDSR mechanisms to reallocate the load, and then quantify the benefits for each actor and the whole system.

Chapter 8

Discussion

A crucial part of the outcome of this project is the gained insight into the potential development paths for the energy transition of the Netherlands. However, there are already many existing studies about possible future developments of the EU and the Netherlands power system. That is why this study was devised to expand the scope to the complete energy system of the Netherlands, and by doing so, those sectors (such as the gas and hydrogen production, the super-high heat generation, the transport sector, and others), that are vulnerable to considerable impacts brought by possible changes in the power sector, were exposed. Nevertheless, these vulnerable sectors were only exposed but not intensively analyzed, so it is recommended to perform further research on their specific implications, accompanied by some model improvements to allow for more profound observations. Moreover, next to the integrated energy system perspective provided in those scenario outcomes, there are two products of this project that are especially worth being highlighted.

The first one is the new methodology proposed and used to determine the electricity dispatch of a system. As observed in chapter 4, ENSYSI considerably increased its reliability by adapting the new dispatch approach without dramatically increasing the computational requirements[1]. And despite not being fully able to replicate COMPETES' predictions, it has now considerably brought results closer. This means that this "machine-learning" alike method can be further improved and adapted to different models providing them with a great agility/reliability ratio, arising two major consequences from this. First, a new functionality emerges for super detailed dispatch models, which can be used to teach other models how to replicate their predictions with way lower processing needs via a stochastic approach. Second, a new generation of super-agile models could bear, enabling them to perform a large number of simulations in the same time span in which a traditional model runs only one year. As a consequence of this, new serviceability horizons appear for these types of models, as now can be used to understand actor behaviors via the implementation of more complex Multi-Agent learning algorithms, or other approaches in which energy system modeling may merge with artificial intelligence. This would transfer the computational load to new uncertain areas of this field to deliver new broader perspectives to the scientific community.

The second contribution of this study is an insight in the XBIC-DDSR interaction, particularly in the relevance of the mechanisms behind the load redistribution of decentralized demand-side response. As previously discussed, this study predicts that interconnectivity has a larger potential than decentralized demand-side response to decreasing the costs of the transition. It is also shown that the reason of this occurring is due to the reallocation mechanism assumed by the model; in which flexible load tends to shift towards cheaper electricity price hours. As this process sometimes results in a cheaper state, and sometimes it does not, it highlights the importance of the mechanism used to redistribute the load. At the same time, how this flexibility may develop in the system is still something broad and uncertain, as it is not clear if some local clusters will emerge, if some companies will take the role of aggregators within the market, if

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[1] ENSYSI before required around 40 seconds to complete a 2010 to 2050 simulation. Now it does it in roughly 120 seconds.

block-chain technologies will decentralize the supply of demand-side flexibility, or if something different will happen. Therefore it is important to analyze multiple ways in which this processes may occur, to test how these can be linked with the wholesale market, possibly resulting in further social benefits, and a deepened understanding of the true meaning of DSR.

Simultaneously it is important to remember that ENSYSI is a model attempting to replicate an immense system, which means that there are several assumptions and sources of uncertainties in the model. Then it is important to critically analyze and identify which of these simplifications may be biasing the model predictions, and how these can be overcome in the future. In this study, there are mainly five issues that were detected as important which are worth to mention. First, ENSYSI is built in the context of current knowledge, and there are many technologies and structural changes that may emerge in the future as decarbonized alternatives, which opens the door to the unreached target shown in this study to be eventually reached due to unforeseeable changes. Secondly, the investment costs developments and future technological improvements are a key parameter that can strongly influence the energy system. Thus it would be convenient to perform risk analysis scenarios by assigning likelihood development ranges to those parameters. Third, many industrial sectors are underdescribed, leading to a very simplistic and limited approach in which industry can provide flexibility; it would be recommended to strengthen the key sectors highlighted in this research project in order to improve the reliability of the predictions[2]. Fourth, the charging profiles of the electric vehicles, and the decentralized demand side response mechanism used within this study are based on current understanding of those issues, and will most likely change in the future; integrating more potential development paths for those technologies can also lead to different results. Finally, as discussed during chapter 4, the new electricity dispatch approach is not considering ramping-ups and ramping-downs of the generators, and this can underestimate the need for dispatchable generation technologies in the system.

Despite that, ENSYSI is in a great position to further depth in the field of the future energy system, integrating the social dynamics together with the power generation intermittency, and key sources of flexibility such as cross-border interconnectivity, decentralized demand-side response, industry, households, and other emerging technologies. And it is advised to expand the research line in that direction as it could bring more value to society.

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[2] It would be extremely valuable to integrate in ENSYSI the knowledge gained by the MIDDEN project .

Chapter 9

Conclusion

In a context in which intermittent renewable electricity supply is expected to increase considerably, together with the electrification of human activities, the integration of the power sector with the remaining elements of the energy system is becoming a crucial component of the energy transition. Among the many different pieces of the transitory puzzle, the behavior of the electricity prices in both short and long timescales is considered to be one of the pivotal axes of the system integration analysis. In the current scientific sphere, there lies much attention on how international electricity trading and demand-side response could influence the development of the electricity price profiles, so studying them is placed within the scope of PBL's research. Because of this, the hereby presented research project aimed at increasing the understanding of the integrated energy system of the Netherlands. By means of the ENSYSI model, it was possible to retrieve an explicit quantification of total and multisectoral impact in a set of experiments that also enabled to expose the interaction of cross-border interconnectivity and decentralized demand-side response.

The research objective was achieved by first modifying ENSYSI to become a suitable model to fit such purpose, which requires the elaboration of an electricity dispatch proposal able to trustworthy include the cross-border electricity trading concept without compromising its agility. This modification was tested and proved to ameliorate the relative performance of ENSYSI's predictions. By doing this, not only ENSYSI was improved to an extent in which it can be used in this study, but also an original machine-learning-alike approach was proposed to the electricity dispatch problem, and new purpose to highly detailed traditional models. Nonetheless, it must be pointed out that this modification's reliability is constrained to operational domains similar to whose served as reference to obtain the data used to create the correlation matrices.

With the new version of ENSYSI, it was possible to explore eight scenarios with different levels of IRES presence, interconnectivity, and DDSR. The outcome of these scenarios allowed firstly to expose possible future system and sectoral states regarding GHG emissions, energy costs, and technological configurations, providing in this way a fresh perspective on the future energy system development of the Netherlands. Based on this, it should be highlighted that further efforts must be made if 2030, and 2050 prescribed targets are to be met, as none of the scenarios reported to get even close to them. Furthermore, the role of both cross-border interconnectivity and decentralized-demand side response were proven useful to lower the costs of the transition for both the total energy system and the power sector. Notwithstanding, the resonance of these impacts into a more detailed scope varies between industries and between scenarios, as was shown for the hydrogen and fuel production industries, and the heat sector among others. It can be concluded that system integration analysis can expose hidden intersectoral indirect effects, thus reasserting the need of maintaining efforts around these research line.

Beyond that, this project served to expose XBIC and DDSR interaction, by reaffirming the unparalleled advantage that the first brings to the system in relation to the latter; this conclusion is in line with conclusions of several similar reported studies. In addition, helped to break through the mechanisms by which this happens to explain the latter conclusion. This is: because XBIC can exploit the remainders of the marginal generators in both the supply and demand direction as it is occurring within the market's electricity dispatch. While the (here tested) DDSR approach only reacts to external stimulus to the dispatch, such as the load or electricity profiles. This observation proves relevant by exposing the potential contributions that DDSR could bring to the system if the algorithms and structures used to coordinate locally decentralized redistributions are linked to internal market dynamics instead to consequences of the market setting. Using ENSYSI to further explore this and other topics via multi-agent learning approaches could provide a novel approach to unraveling the development of these uncertain critical system components. Based on these findings it can be concluded that this study substantially contributed to shed more light on the fascinating energy transition challenge. Analogously to how in the real energy system a higher technological availability lowers the risk of a lock-up, in the research world, a higher diversity in perspectives increases society's ability to adapt to an unforeseeable denouement. It is hence crucial that future research continues to engage with this topic.

Appendix A

Model's Performance per Scenario

TABLE A.1: Performance evaluation for scenarios 1-5

Variable	Model	Units	C-10	C-15	M16-20	M16-25	$T16_1$-30
Av. Elec. Price	$ENSYSI_{new}$	%	97.3	93.5	85.9	96.8	99.6
	$ENSYSI_{old}$	%	99.7	96.1	92.6	85.9	82.4
Elec. Price Var.	$ENSYSI_{new}$	%	74.8	96.0	64.9	66.8	49.7
	$ENSYSI_{old}$	%	41.2	73.0	73.4	-48.6	53.2
Elec. Price profile	$ENSYSI_{new}$	%	75.6	64.5	71.2	61.4	76.8
	$ENSYSI_{old}$	%	57.2	30.6	41.4	10.0	28.2
Dispatchable Gen.	$ENSYSI_{new}$	%	98.5	88.3	96.6	80.2	75.4
	$ENSYSI_{old}$	%	98.3	97.7	93.9	92.7	93.9
IRES Gen.	$ENSYSI_{new}$	%	77.4	78.2	78.4	78.9	78.7
	$ENSYSI_{old}$	%	77.4	78.2	81.5	85.2	79.6
Elec. Imports	$ENSYSI_{new}$	%	96.8	80.7	96.4	71.0	85.0
Elec. Exports	$ENSYSI_{new}$	%	77.0	70.5	66.5	92.8	82.2
Elec. Net Imports	$ENSYSI_{new}$	%	88.8	75.9	83.8	82.8	83.9

TABLE A.2: Performance evaluation for scenarios 6-10

Variable	Model	Units	$T16_2$-30	$T16_3$-30	$T16_4$-30	M17-20	M17-25
Av. Elec. Price	$ENSYSI_{new}$	%	95.1	90.2	90.1	88.1	99.5
	$ENSYSI_{old}$	%	82.5	90.8	93.7	92.1	86.4
Elec. Price Var.	$ENSYSI_{new}$	%	43.1	54.1	79.8	60.9	60.9
	$ENSYSI_{old}$	%	62.6	-4.0	54.0	64.6	-47.5
Elec. Price profile	$ENSYSI_{new}$	%	73.3	63.0	55.5	68.9	58.6
	$ENSYSI_{old}$	%	24.6	26.2	53.2	40.5	11.2
Dispatchable Gen.	$ENSYSI_{new}$	%	80.7	68.2	71.9	98.7	77.7
	$ENSYSI_{old}$	%	93.8	93.4	92.8	93.1	91.4
IRES Gen.	$ENSYSI_{new}$	%	78.9	79.2	79.0	78.8	79.3
	$ENSYSI_{old}$	%	80.3	89.4	83.0	81.6	85.3
Elec. Imports	$ENSYSI_{new}$	%	80.5	57.0	60.3	94.4	65.2
Elec. Exports	$ENSYSI_{new}$	%	96.7	98.8	97.3	69.1	93.9
Elec. Net Imports	$ENSYSI_{new}$	%	86.4	80.7	78.4	82.9	82.4

TABLE A.3: Performance evaluation for scenarios 11-15

Variable	Model	Units	$T18_1$-30	$T18_1$-35	$T18_1$-40	$T18_2$-30	$T18_2$-35
Av. Elec. Price	$ENSYSI_{new}$	%	99.2	94.4	81.5	87.9	88.7
	$ENSYSI_{old}$	%	77.8	73.3	55.2	99.7	88.3
Elec. Price Var.	$ENSYSI_{new}$	%	79.3	99.6	83.2	82.9	89.6
	$ENSYSI_{old}$	%	32.0	76.7	93.5	39.3	97.1
Elec. Price profile	$ENSYSI_{new}$	%	78.6	77.7	73.8	78.3	57.7
	$ENSYSI_{old}$	%	37.9	43.2	34.4	44.3	34.6
Dispatchable Gen.	$ENSYSI_{new}$	%	99.2	90.0	92.4	56.7	63.4
	$ENSYSI_{old}$	%	97.4	92.2	84.0	93.4	98.4
IRES Gen.	$ENSYSI_{new}$	%	79.6	79.8	80.2	79.6	78.1
	$ENSYSI_{old}$	%	97.7	95.2	92.1	92.9	98.9
Elec. Imports	$ENSYSI_{new}$	%	88.9	97.9	99.5	49.8	77.5
Elec. Exports	$ENSYSI_{new}$	%	57.9	45.6	45.2	98.1	80.8
Elec. Net Imports	$ENSYSI_{new}$	%	72.6	72.2	74.3	78.0	79.0

TABLE A.4: Performance evaluation for scenarios 16-19

Variable	Model	Units	$T18_2$-40	$T18_3$-30	$T18_3$-35	$T18_3$-40
Av. Elec. Price	$ENSYSI_{new}$	%	82.7	90.5	99.8	92.2
	$ENSYSI_{old}$	%	69.1	91.3	85.8	84.1
Elec. Price Var.	$ENSYSI_{new}$	%	63.5	89.8	11.1	70.8
	$ENSYSI_{old}$	%	66.7	91.3	-33.2	-25.8
Elec. Price profile	$ENSYSI_{new}$	%	64.2	56.2	67.3	51.5
	$ENSYSI_{old}$	%	48.7	25.0	16.4	35.5
Dispatchable Gen.	$ENSYSI_{new}$	%	72.3	90.7	78.2	61.9
	$ENSYSI_{old}$	%	94.8	94.4	70.2	-14.2
IRES Gen.	$ENSYSI_{new}$	%	72.0	78.6	80.7	84.1
	$ENSYSI_{old}$	%	97.1	91.2	88.0	82.4
Elec. Imports	$ENSYSI_{new}$	%	96.1	90.8	91.2	95.0
Elec. Exports	$ENSYSI_{new}$	%	58.3	36.1	69.3	77.7
Elec. Net Imports	$ENSYSI_{new}$	%	82.6	71.5	79.7	84.6

Appendix B

Stock Development per Sector

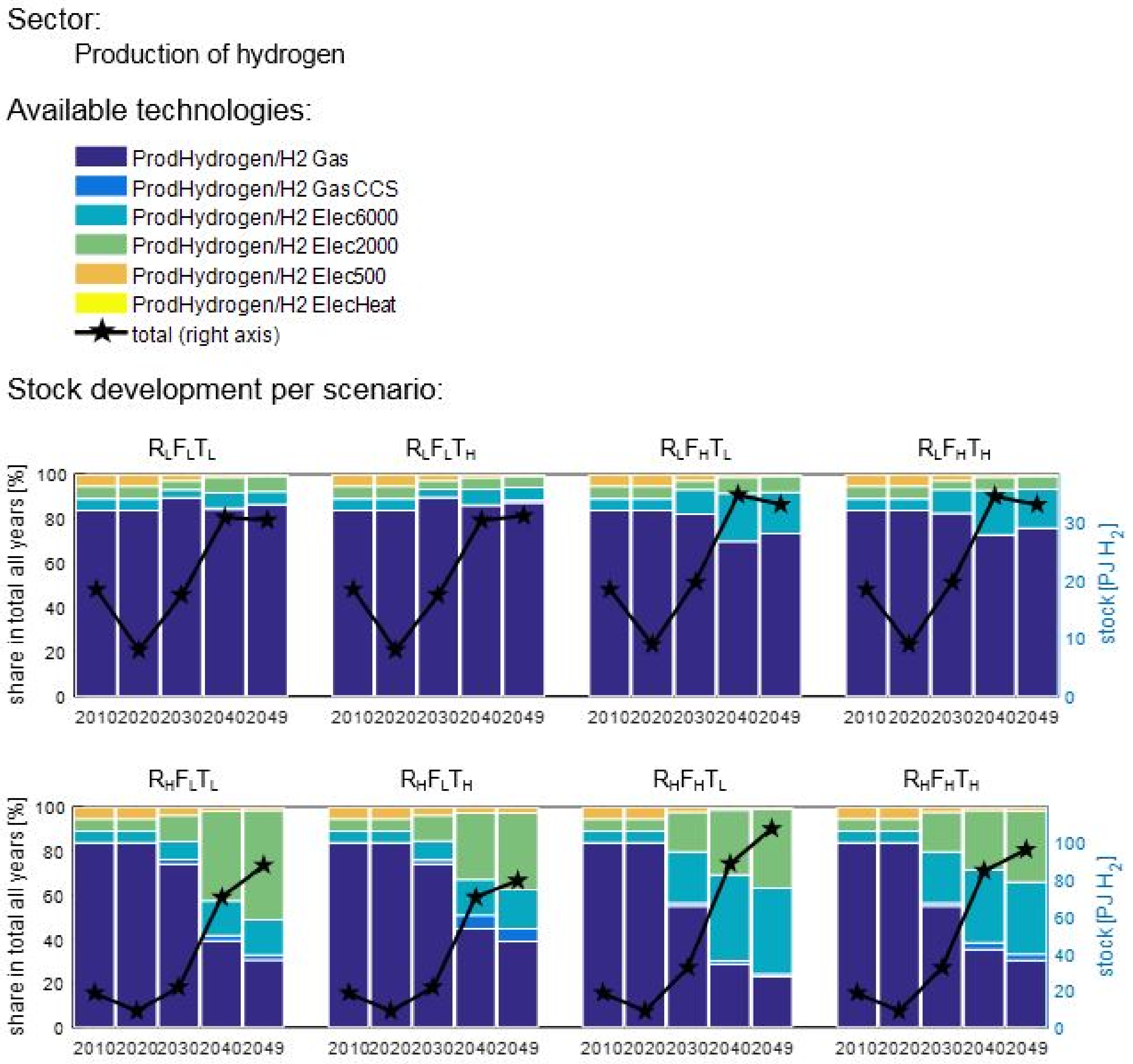

FIGURE B.1: Stock development for the production of hydrogen.

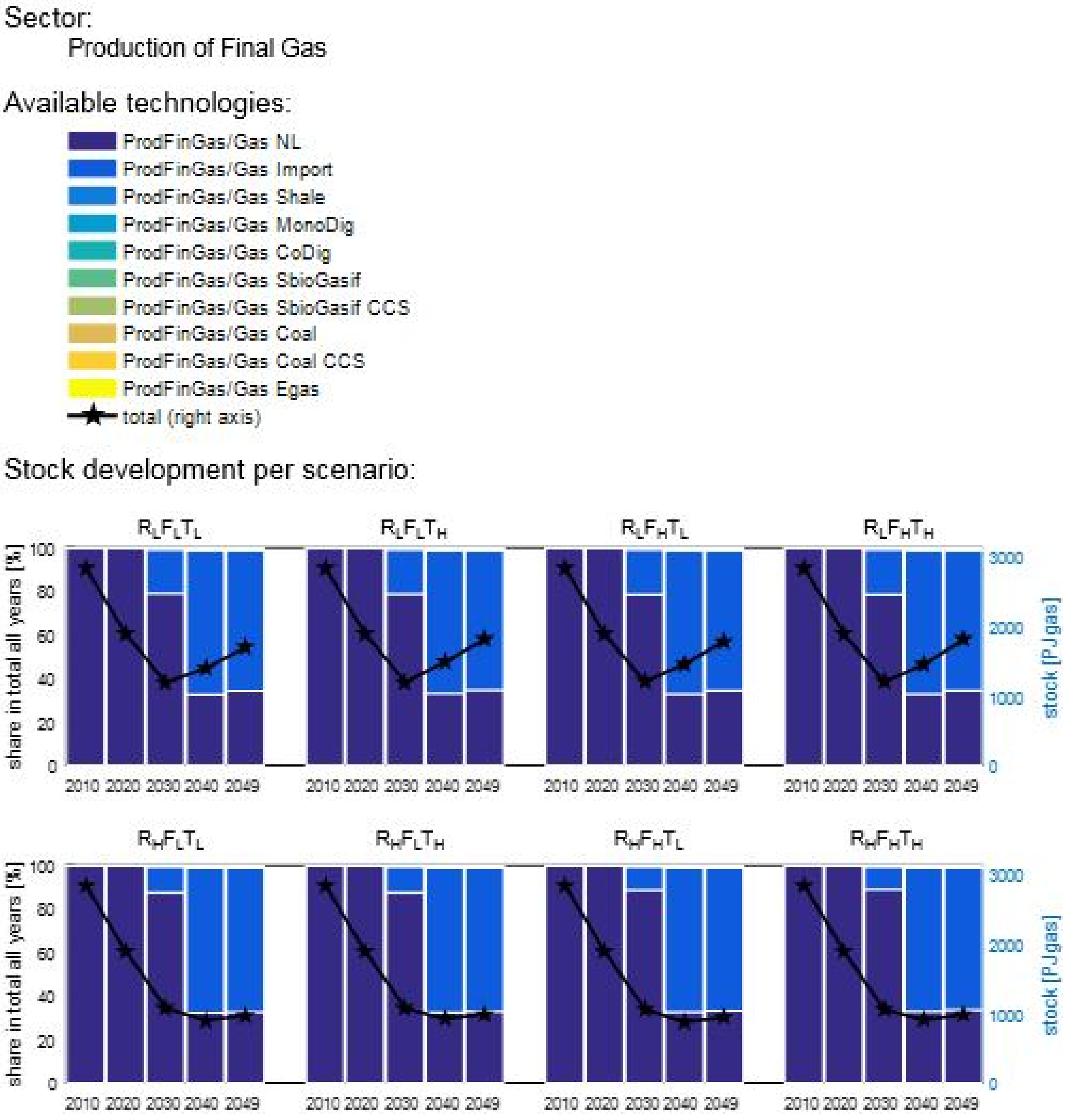

FIGURE B.2: Stock development for the production of final gas.

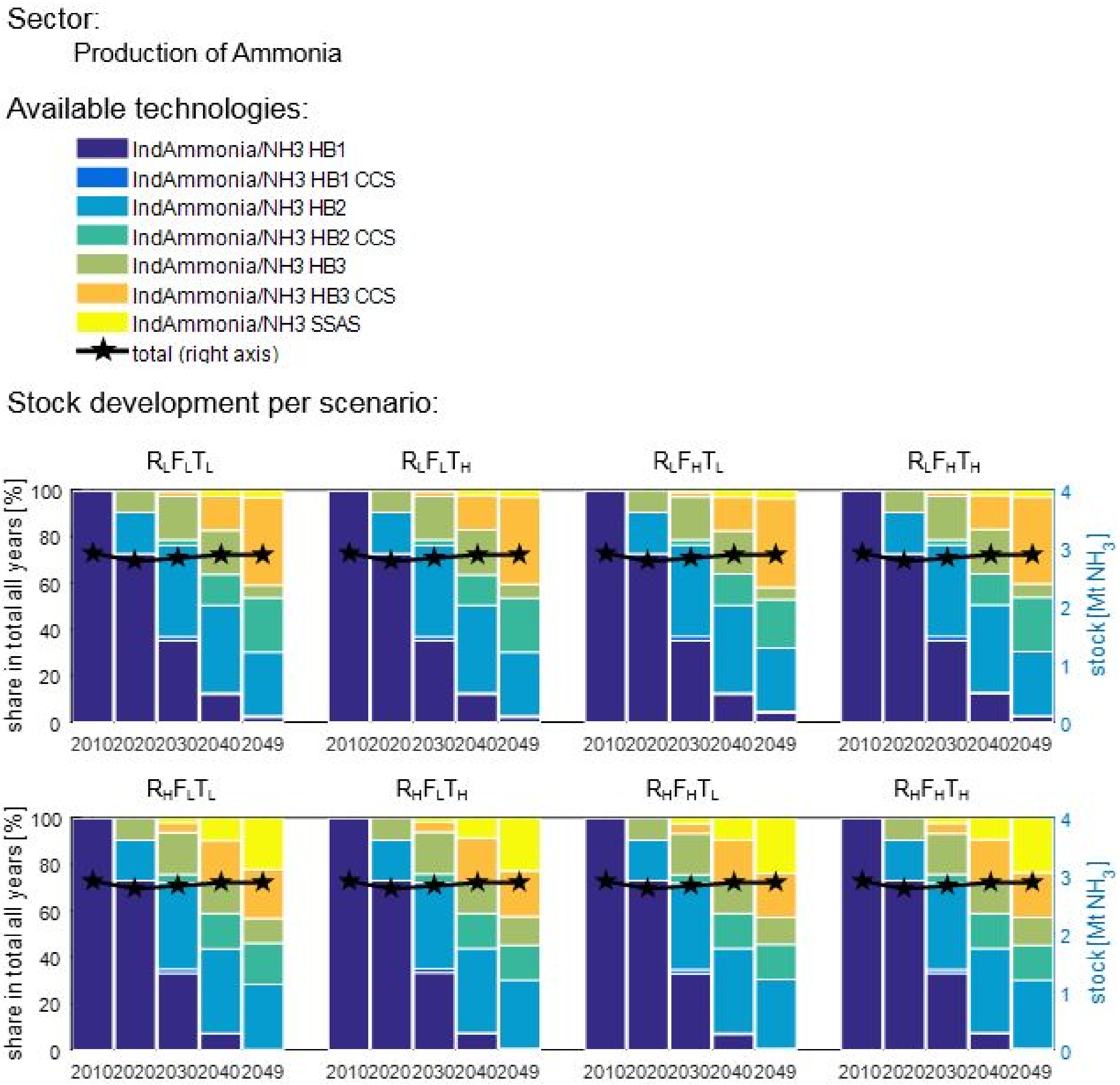

FIGURE B.3: Stock development for the production of ammonia.

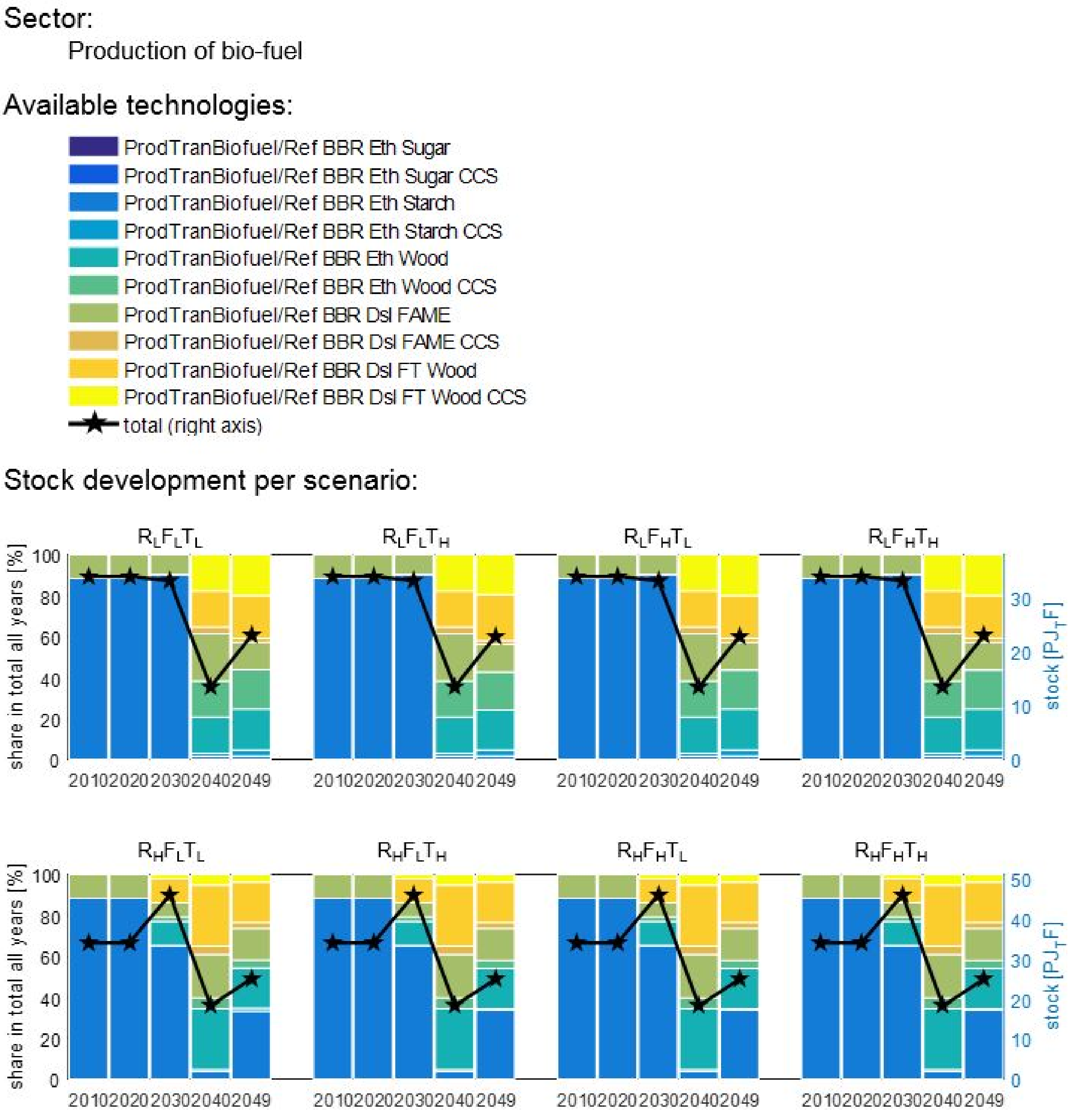

FIGURE B.4: Stock development for the production of bio-fuel.

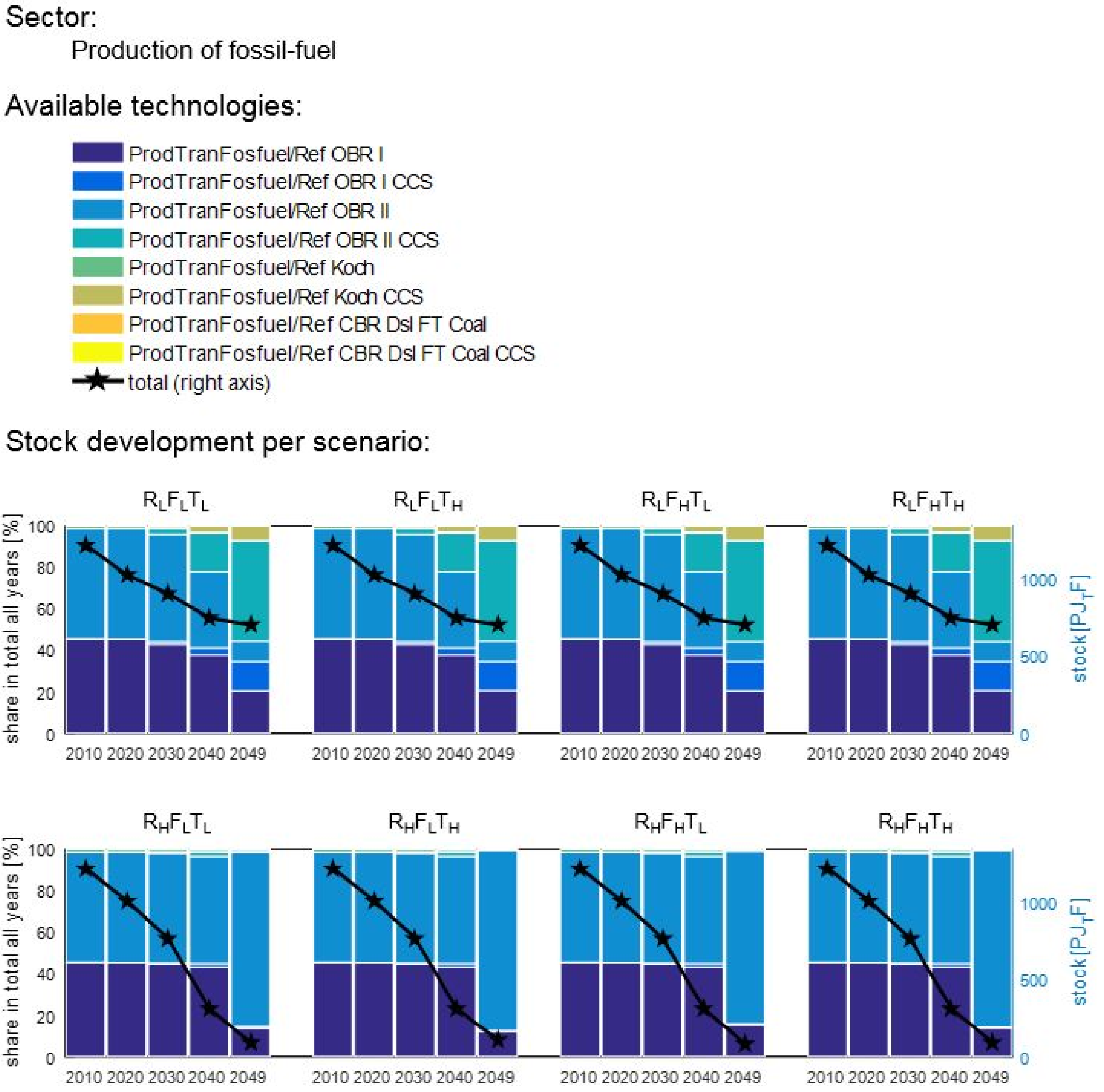

FIGURE B.5: Stock development for the production of fossil-fuel.

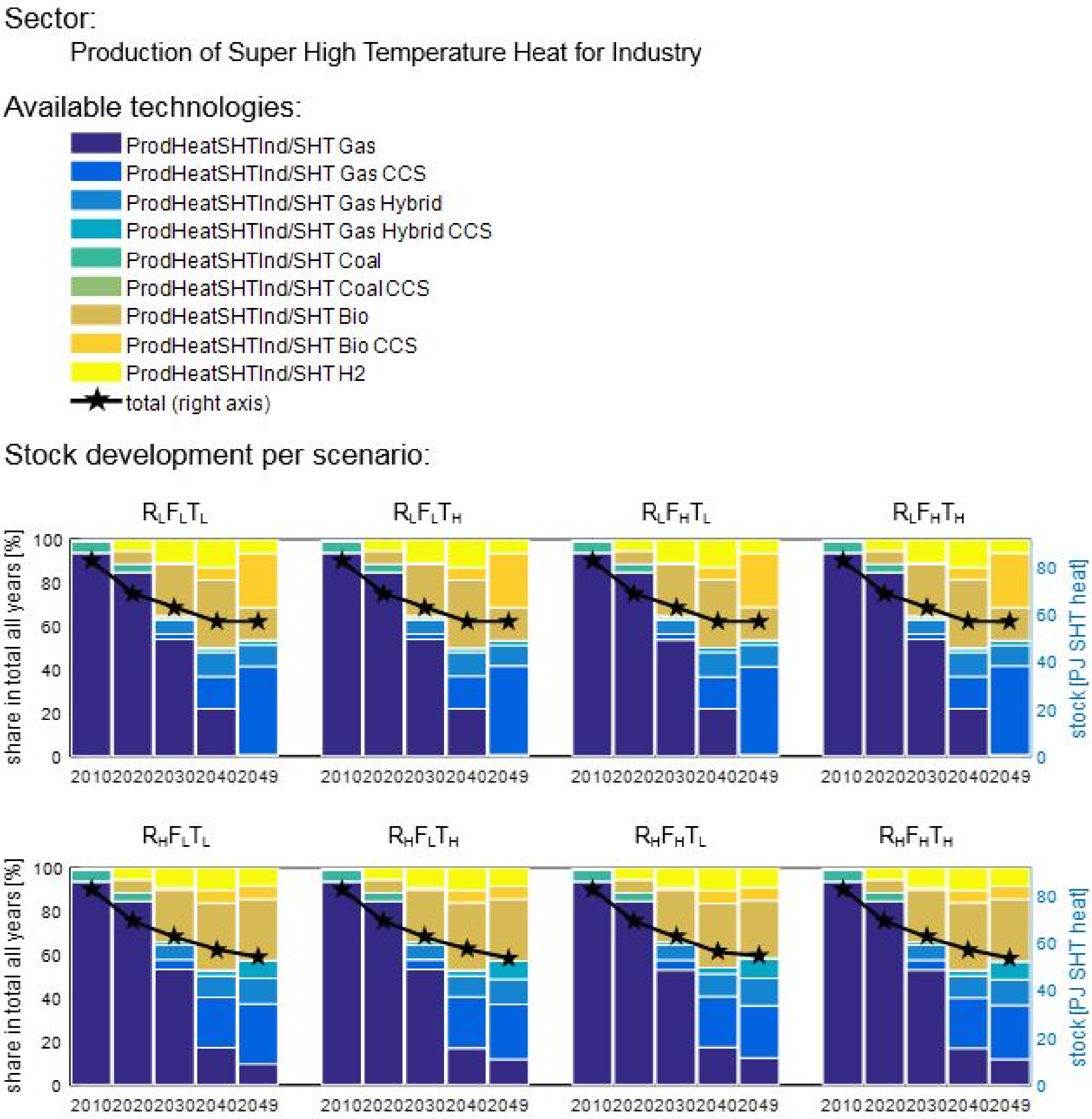

FIGURE B.6: Stock development for the production of super-high temperature heat for industry.

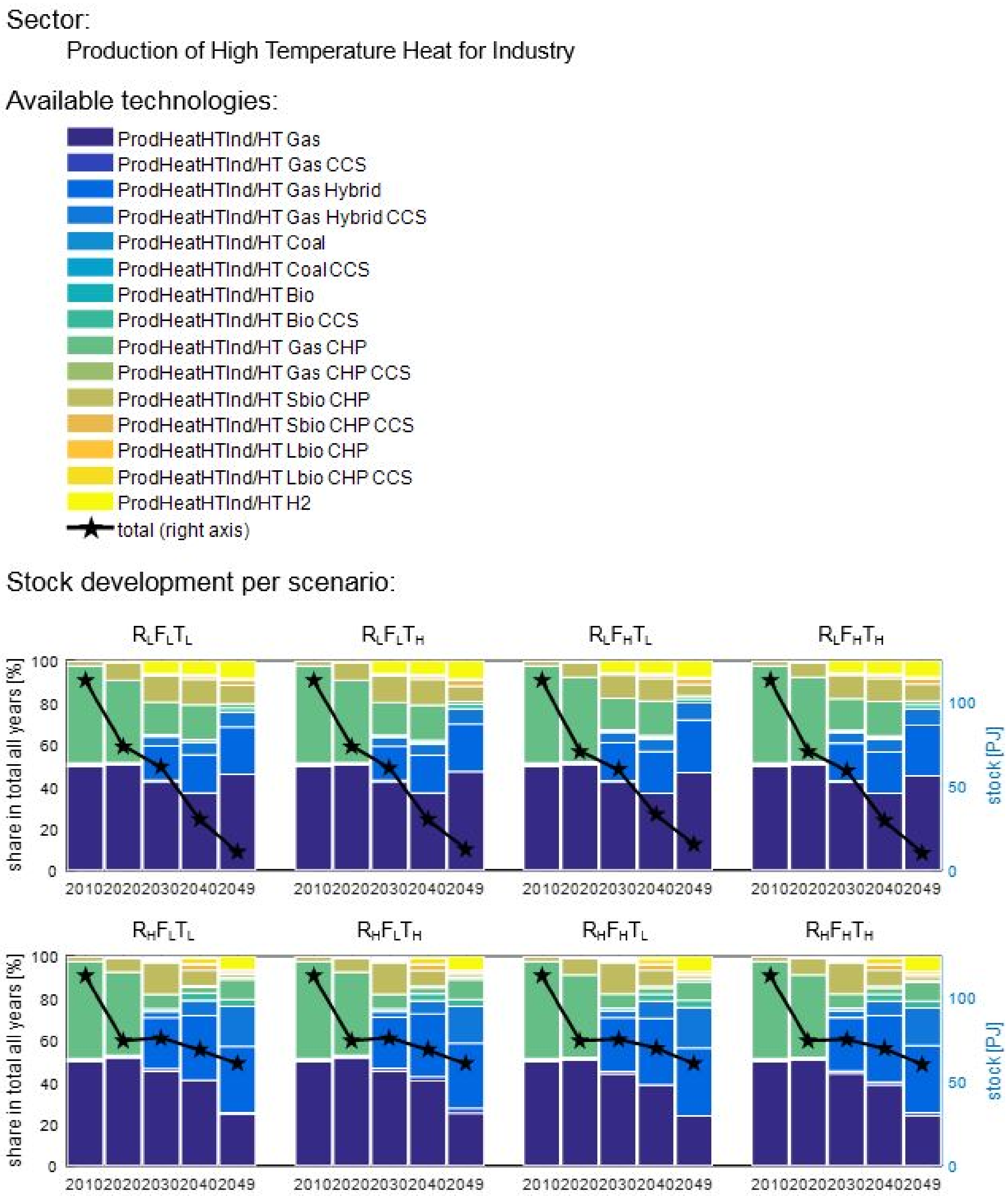

FIGURE B.7: Stock development for the production of high temperature heat for industry.

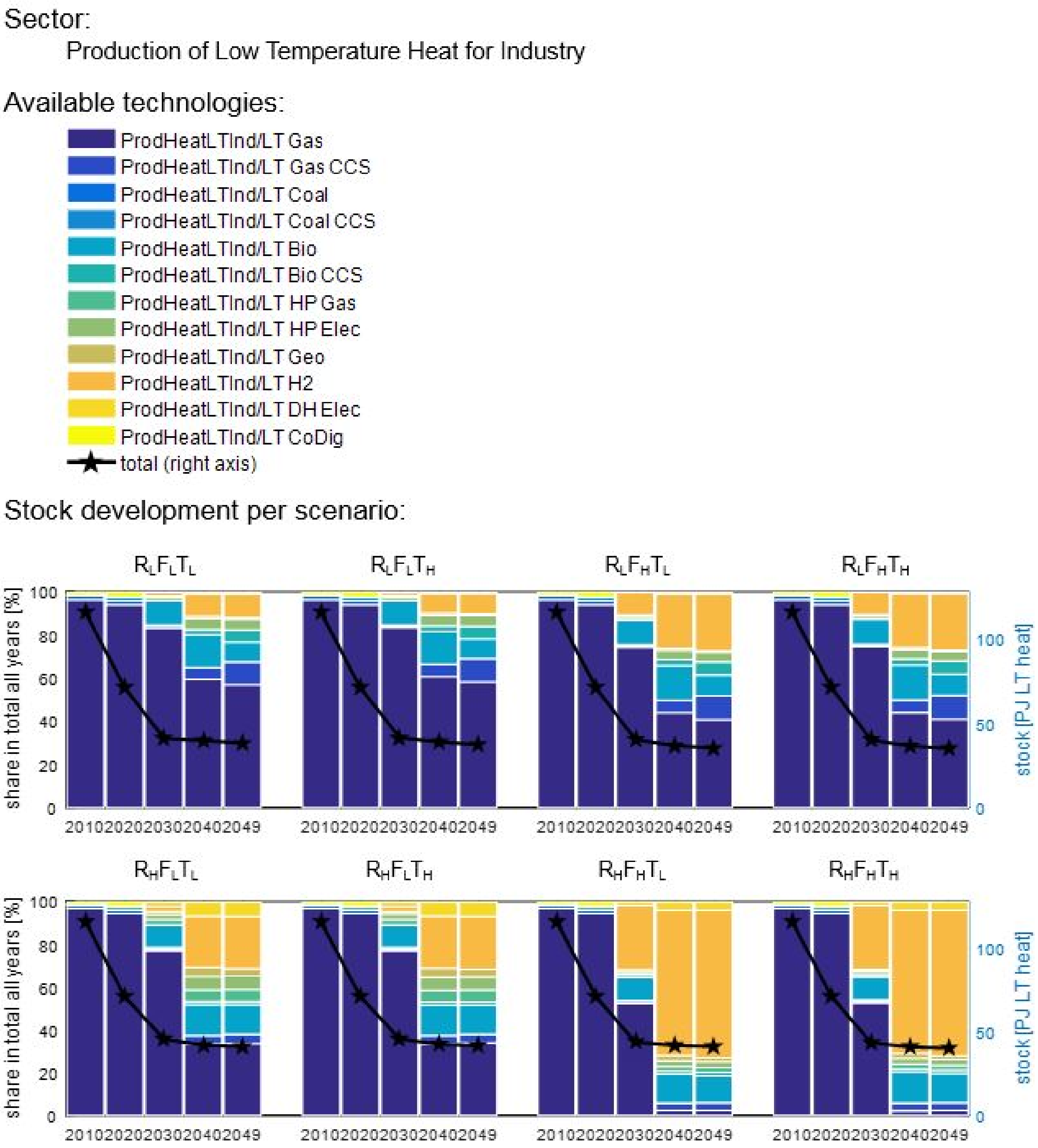

FIGURE B.8: Stock development for the production of low temperature heat for industry.

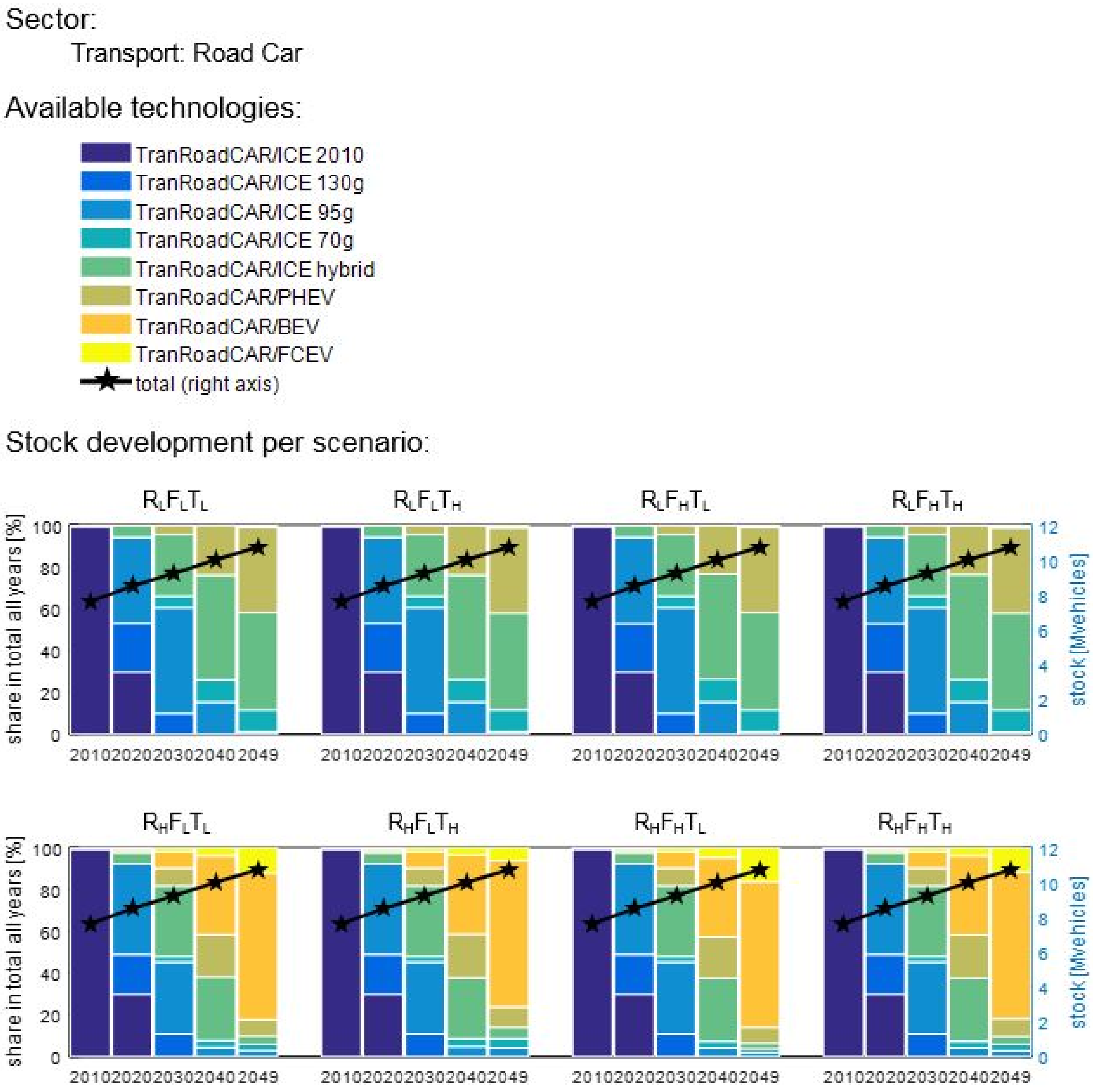

FIGURE B.9: Stock development of the car fleet.

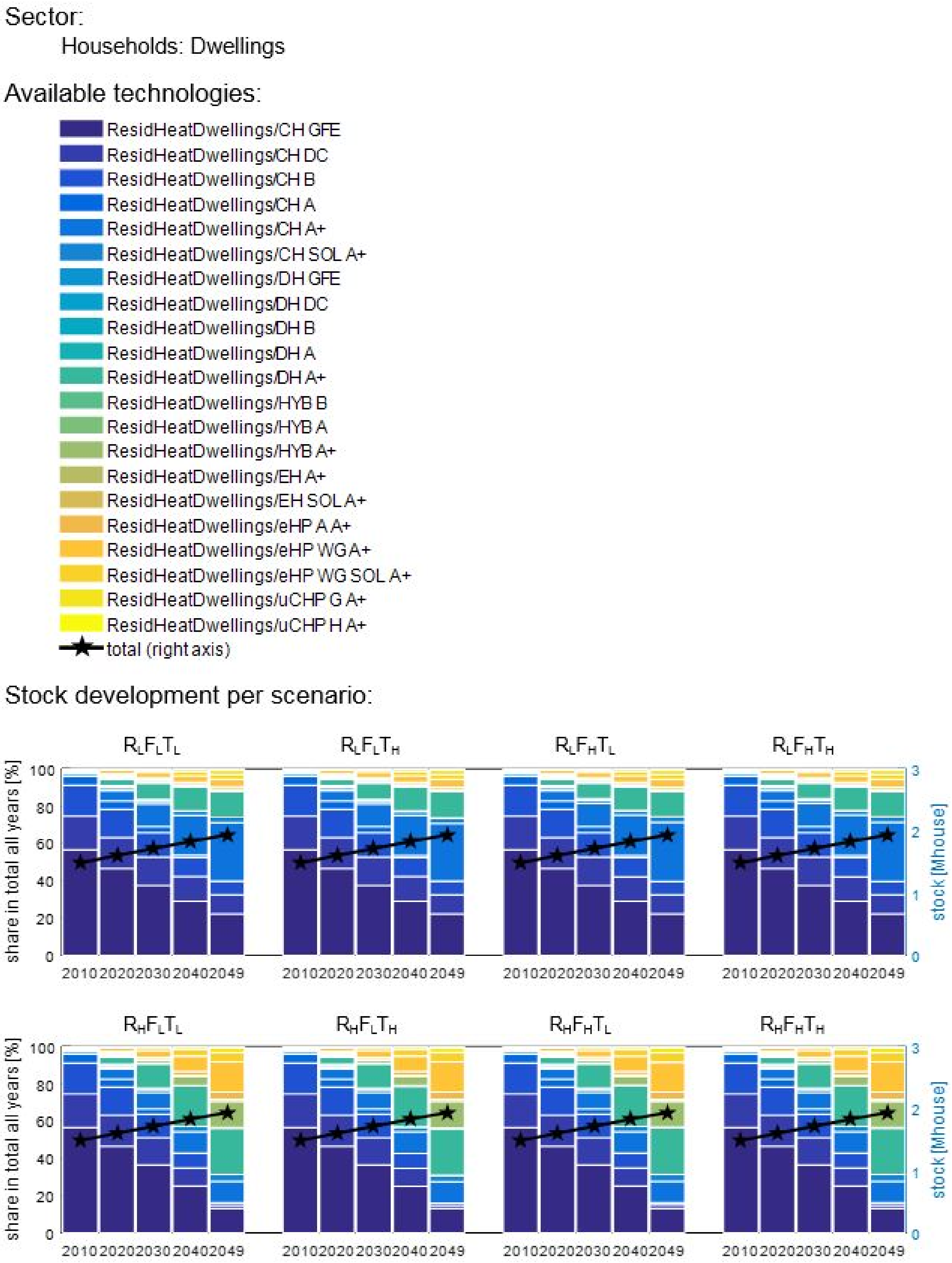

FIGURE B.10: Stock development of the dwellings' built environment.

Appendix C

Electricity Price

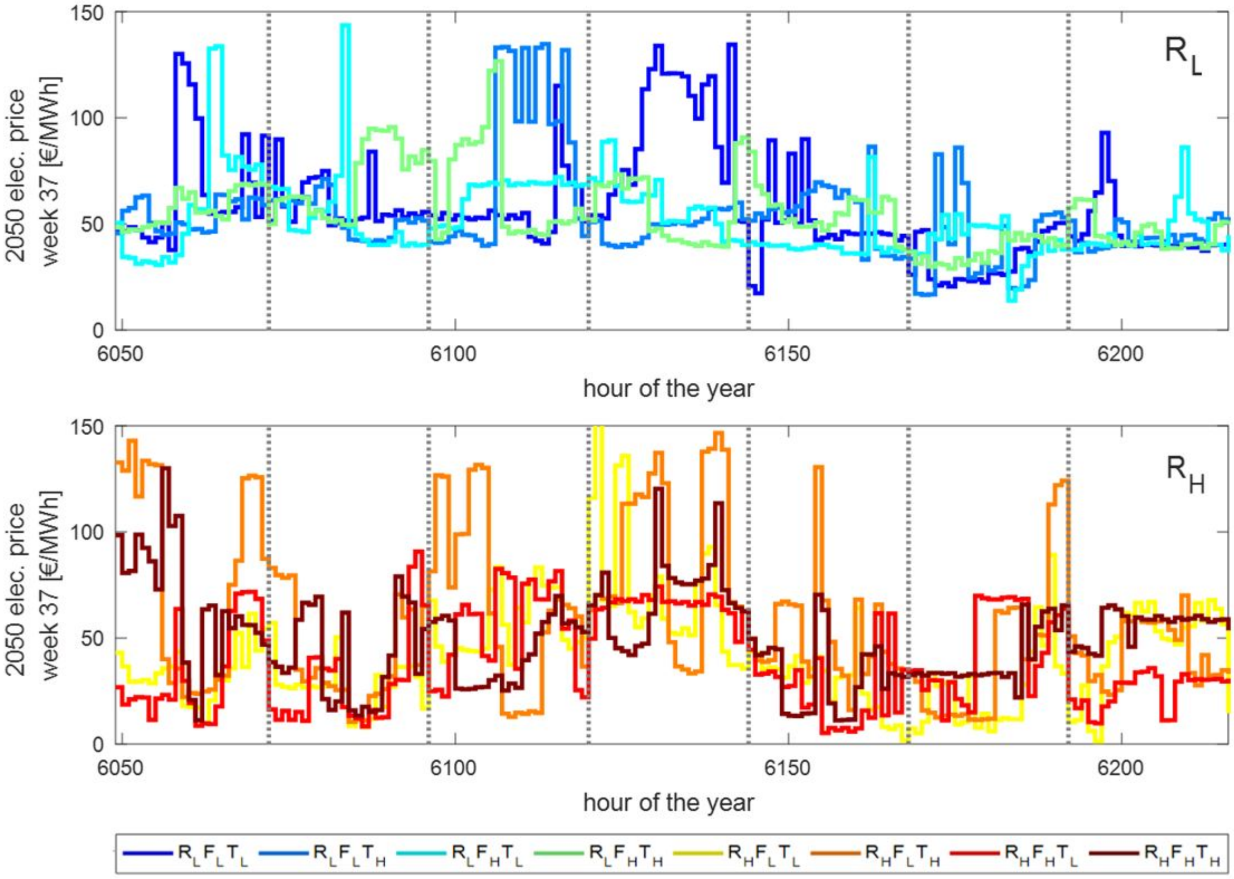

FIGURE C.1: Electricity prices in a week. Visualization of the impact of XBIC and DDSR on the electricity price fluctuations in the week 37 of the year 2050. Top: Low RES scenarios. Bottom: High RES scenarios. Is important to consider that the differences are not only due to the short term impact of the price redistributions but also from the long term impact of XBIC and DDSR in the development of the generation stocks.

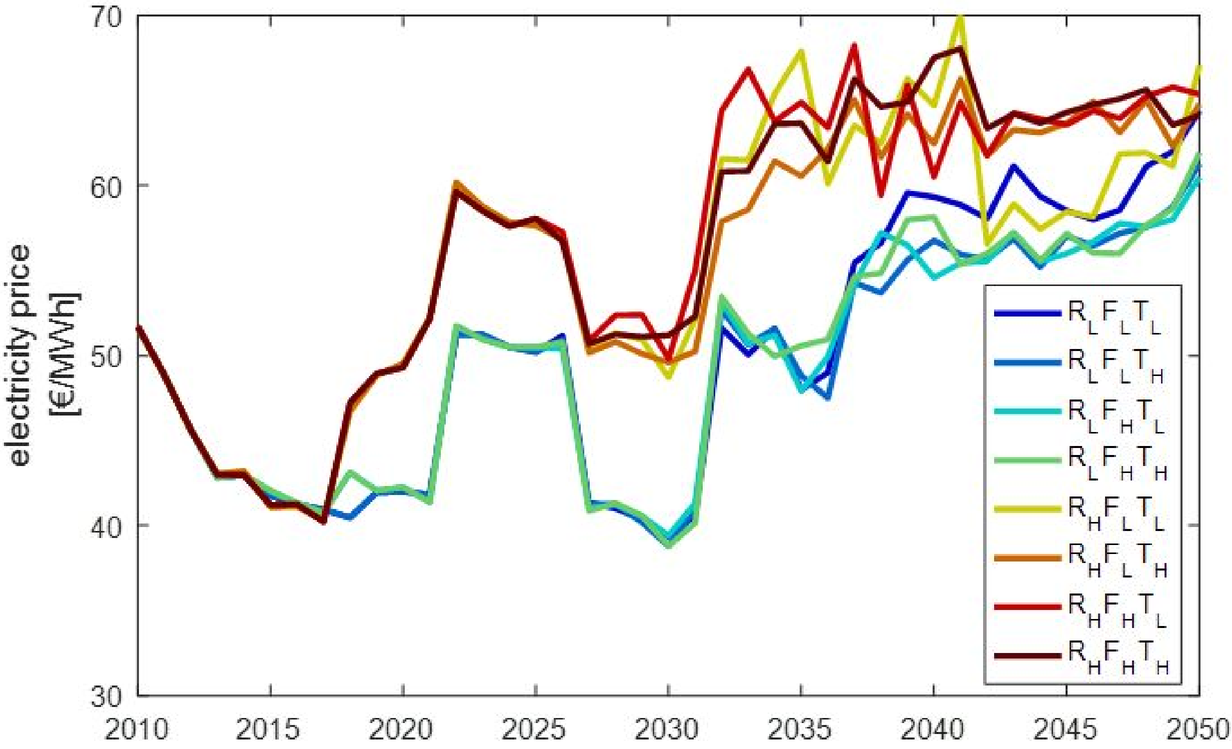

FIGURE C.2: Electricity price development. Visualization of the average electricity price per year of the eight scenarios.

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