Hybrid boiler systems in the Dutch industry

A techno-economic analysis of the potential of hybrid boiler systems to cost-effectively decarbonise steam generation in the Dutch industry.

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HYBRID BOILER SYSTEMS IN THE DUTCH INDUSTRY

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by
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PREFACE

This research is performed in view of the graduation from the master program Sustainable Energy Technology at the Delft University of Technology. The topic of this research arose during my internship at ECN part of TNO within the MIDDEN project. This project aims to develop a new knowledge network in order to gain practical knowledge about decarbonisation options for the Dutch industry looking into specific industries. During the collaboration with researchers and industries I realised that there was a lack of information about hybrid electrification solutions. Currently, the Dutch government is interested in hybrid electrification (Climate Agreement) due to its potential benefits for the energy transition.

This research was conducted between May 2019 and February 2020 in TU DELFT University under the supervision of two departments: Energy and Industry from TPM (Technology, Policy Management) faculty, and Intelligent Electrical Power Grids from Electrical Engineering. In addition, data and expertise were provided from PBL (Netherlands Environmental Agency) and ECN part of TNO.

This research focused on the potential of hybrid boiler systems to cost-effectively decarbonise part of the steam production in the industry for 2030. To this end, a techno-economic valuation of this technology is performed. This research showed that hybrid boilers can be a cost-effective decarbonisation strategy. However the potential strongly depends on the future prices of electricity, natural gas and CO2 which are uncertain.

This research would not have been possible without the support of the people around me. First, I thank my supervisors Andrea, Milos and Rob for their guidance and advice throughout this journey. Their complementary expertise enriched the focus of the research and elevated the quality of the work. They guided me into the hard process of research. I learnt how to work with honesty, transparency and be critical with every step. I also would like to thank my mentors Shantanu and Digvijay. They helped me through this process listening to my problems, guiding me and most important they encouraged me to enjoy my work.

Finally, I thank my family for their support and their infinite generosity. I also thank the family I created, Michela, Sofia, Keshav, Luna and my football team. They remind me who I am and where I want to be.

Yasmine Abdallas Chikri
Delft, February 2020

EXECUTIVE SUMMARY

Research Context

The Paris Agreement aims to combat climate change keeping the global temperature below 2 degrees Celsius above pre-industrial levels. In this context, The Netherlands has set national targets to reduce the greenhouse gas emissions for 2030 by 49% compared to 1990 levels. Moreover, the target for 2050 is a reduction of 95% of the emissions. To this end, the electricity sector and the industrial sector have been allocated a reduction of the emissions of 20.2 Mt and 19.4 Mt respectively, by 2030. The government aims to achieve these goals in the most cost-effective way to ensure that the transition is affordable.

A possible solution for reducing the emissions in the industry is the electrification of the heat generation through power-to-heat technology. However a strong electrification implies risks and costs. Therefore, a hybrid electrification could be a more cost-effective solution. Hybrid technologies can switch between natural gas and electricity. Hybrid electrification profits from the time-dependant prices of electricity and natural gas. As a result, these systems can provide cost advantages due to the volatility of the electricity prices. In addition, the use of power-to-heat technology, which couples heat demand with the electricity sector, can benefit the integration of electricity from renewable sources consuming electricity at low prices and avoiding the consumption during peak hours.

Research Objective

There is a lack of research on the potential of hybrid technologies to cost-effectively reduce the emissions in the industry. In addition, the introduction of the Climate Agreement might have changed the scenario for 2030 for which a higher share of renewable energy is expected as well as a higher CO2 price. This could influence the operation of hybrid electrification and therefore enhance its potential benefits. Hybrid electrification could play a role in the energy transition. An example of hybrid electrification are hybrid boilers and hybrid heat pumps. This thesis focuses on the hybrid electrification of steam generation in a production process using hybrid boilers. The main research question is:

"To what extent are hybrid boiler systems a cost-effective decarbonisation strategy for steam generation in the industry for 2030?"

In this research, the techno-economic performance of hybrid boiler systems in 2030 is evaluated. To this end, two configurations are considered: hybrid boiler (HB) and hybrid boiler with storage (HBS). The techno-economic analysis is set to answer three sub-research questions:

- ***"Q1: Which technical parameters are relevant to simulate the operation of hybrid boiler systems?"*** These parameters define the ability of the system to respond to the fluctuation of the prices.

- ***"Q2: What is the performance of hybrid boiler systems in terms of operation costs, efficiency, direct CO2 emissions and levelised costs of the steam produced in comparison with other alternatives?"*** This performance is compared to other alternative technologies: natural gas boiler, electric boiler and electric boiler with storage.

- ***"Q3: To what extent is the operation of hybrid boiler systems sensitive to the uncertainty of the electricity, natural gas and CO2 prices for 2030?"***

Methodology

In this research, the operation of hybrid boiler systems was simulated to evaluate its techno-economic performance. To this end a model was formulated in which the hybrid system seeks to minimise the operation costs. For the model, the hybrid system operation was simplified and technical parameters were selected. Furthermore, the operation costs related to its operation were defined. Then, performance indicators to evaluate the performance of the hybrid boiler were defined. These performance indicators result from the simulation of the hybrid systems. Finally, the model formulated was adapted to simulate the operation of alternative options: natural gas boiler, electric boiler and electric boiler with storage.

In order to evaluate the performance of the hybrid systems in a production process in 2030, a case study was presented. The hybrid boiler was assumed to participate in the wholesale market (Day-ahead market). The models were simulated for the scenario presented for which the performance indicators were obtained. The following analysis were performed using the models developed:

- The relevance of the technical parameters was analysed by means of a sensitivity analysis. In addition, the hybrid boiler was simulated considering a shorter period of forecast (information available for optimisation) to analyse the impact on the performance of the hybrid systems.

- The indirect emissions from the electricity consumption were estimated. The estimation was performed assuming different emission factors for three ranges of electricity prices.

- The network tariffs of electricity were included as additional investment costs.

- The impact on the hybrid systems operation of the uncertainty of the electricity prices, the natural gas prices and the CO2 price for 2030 was analysed. This was performed by means of a sensitivity analysis in which 26 alternative scenarios for 2030 were presented.

- The uncertainty was also analysed considering two different measures to reduce the emissions. A Tax scenario in which it was assumed a high CO2 price for 2030 and a Cap scenario in which a maximum amount of emissions was assigned to the industry.

Results

The results from the analysis were presented to answer the sub-research questions proposed in the research objective section.

- **Q1**: The relevant technical parameters to simulate the operation of the hybrid boilers in the case study presented were the capacity of the boilers and the efficiencies. The hybrid boiler was able to respond to the hourly fluctuations of the electricity prices.
- **Q2**: The share of electricity consumed was 17% for the HB conguration and 19% adding the storage. The natural gas was substituted with electricity during approximately 1752 hours, 20% of the year. As a result, the hybrid systems reduced almost 20% of the CO_2 emissions respect to the natural gas boiler. The results showed that the hybrid configurations saved costs by consuming electricity at low prices. Although the investment costs of the hybrid congurations were considerably higher than the alternative technologies, the price of the steam produced was lower due to the operation costs saved. Therefore it was concluded that the hybrid boiler (HB) reduced the emissions cost-effectively. However, in the case of hybrid boiler with storage (HBS) the electricity consumption did not increase significantly respect to the HB system, while the investment costs increased considerably. Therefore, the hybrid boiler with storage would not be a cost-effective solution.

  In order to have a broader picture of the results, the indirect emissions were estimated. The indirect emissions represented only 8% of the total emissions.

  The network tariffs were included to evaluate the impact on the case study presented. The network tariffs had a negative effect increasing the levelised cost of the steam produced. The levelised cost was more expensive than the steam produced in natural gas boilers.

  Finally, it was observed that hybrid systems could optimise it operation for 1 day with a prediction horizon of 2 days (available information of future electricity prices). The error between this optimisation and the optimisation in the base case study (prediction horizon of 1 year) was negligible.

- **Q3**: The increase of natural gas price had the largest impact on the performance of the boiler in terms of operation costs and emissions reduction. The extreme scenarios for 2030 occurred when the hybrid systems worked almost entirely with electricity or natural gas. In this case, the hybrid configurations are not a cost-effective solution as they were used as an electric boiler or a natural gas boiler. Furthermore, in this analysis it was observed that the impact of the carbon tax strongly depended on the difference between the natural gas price and the electricity price. For the same CO_2 price the emissions were reduced by only 5% in case of a relative high difference between natural gas and electricity prices. Conversely, with low differences the emissions were reduced by 88%

respect to the base case study.

Deep decarbonisation measures were analysed for the hybrid configurations. From this analysis it was concluded that for the same amount of CO_2 emissions reduction the Cap scenario incurred in lower operation costs.

Limitation of the research

In this research several limitations to the results were discussed. These limitations could be explored in future research.

- In this thesis it was assumed that the industry participated in the Day-ahead market. The models used for the analysis considered perfect foresight of the prices. In reality the industry would have to pay for forecast of prices. In addition a bid strategy would be required to participate in the market. Demand response programs could be a better option to exploit the potential benefits of the hybrid boiler.
- Taxes and levies were excluded in this research. Taxes could influence the operation of the hybrid boiler.
- Transmission tariffs were added as an additional investment, however these tariffs depend on the number of hours in which the electricity was used and the capacity consumed. This would affect the operation of the boiler.
- The scenario for 2030 presented in this research presented hours with electricity prices close to zero. In case of smaller and less frequent fluctuations the performance of the hybrid boiler would be affected.

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1 INTRODUCTION

1.1 RESEARCH CONTEXT

In 2018, the primary energy consumption worldwide increased at 2.3% rate of growth. This rise is due to a strong global economy and the increasing demand of cooling and heating in different parts of the world. Consequently, the energy-related CO_2 emissions raised by 1.7% growth rate [IEA, 2019b]. In this context, the energy sector represents two-third of total greenhouse gas emissions including 80% of worldwide CO_2 emissions [IEA, 2019a]. Therefore, climate change has become a decisive aspect for energy analysis, planning and policy making.

In 2015, the Paris Climate Agreement was set to enhance a global response to the climate change and to limit the increase of the global temperature. The Netherlands ratified the Paris Climate Agreement committing to an ambitious climate policy which would result on a reduction of greenhouse gas emissions. The global objectives in the Paris Agreement had to be translated into concrete goals for the Netherlands. The targets set in the Netherlands is a reduction in greenhouse gas emissions for 2030 by 49% compared to 1990 levels. In addition, the goal for 2050 is a reduction of 95% of the emissions. To this end, a National Climate Agreement has been elaborated. This document contains agreements with the different sectors to achieve the greenhouse gas emissions targets [Dutch Government, 2019b]. In the Climate Agreement an estimation of the CO_2 allocation by sector was presented. The industry is allocated 19.4 Mt of carbon dioxide while the electricity sector is allocated 20.2 Mt [Dutch Government, 2019a]. The government aims to achieve these targets in the most cost-effective way to ensure that the transition is affordable. For instance, the industry has to become more sustainable while maintaining its competitive position [Ministry of Economic Affairs and Climate Policy, 2019].

Renewable energy has an important role in this transition. The Netherlands aims to increase the share of Renewable energy in the electricity production accelerating the growth in offshore wind power, onshore wind and solar energy. In addition, the electrification of other sectors and the ambition to phase out coal-fired electricity generation by 2030 requires an important growth in the share of electricity from renewable sources [Dutch Government, 2019a]. A higher share of VRE (variable renewable energy) in the electricity generation, in particular from solar and wind energy will increase the fluctuation in the power production. This fluctuation or volatility results in large changes in the supply from one hour to the other [Van Hout et al., 2014].

A possible long-term decarbonisation option is a large-scale electrification where the electricity would be the main source for the energy used in buildings, transport and heating in the industry. A scenario with a large-scale electrification implies risks and costs, moreover it requires an important flexibility capacity in the power system [European Parliament, 2018]. The share of VRE and a higher electricity consumption is expected to lead to a significant increase in the volatility of the power system between 2015 and 2050. Consequently, the demand of flexibility sources which can cope with the fluctuations in the power system will also increase. It was estimated that the flexibility demand doubles between 2015 and 2030 [Sijm et al., 2017].

Different definitions for flexibility were mentioned in [Sijm et al., 2017]. In this master thesis flexibility is defined as : *"... the ability of the energy system to respond to the variability and uncertainty of the residual power load within the limits of the electricity grid"* [Sijm et al., 2017]. According to this definition, among the causes of flexibility demand is the hourly variations of the load demand and the renewable energy generation. Scenarios for 2030 and 2050 indicate that with a larger electrification (heat pumps, electric vehicles and other electrification) the hourly variation in the demand will increase significantly [Sijm et al., 2017]. Moreover, for these scenarios it can be observed that hours with VRE surplus (i.e. hours in which the generation from VRE is larger than the demand) will increase as well as the amount of the surplus.

The demand of flexibility caused by the first category is related to the hourly variations of the residual load. Scenarios for 2030 and 2050 indicate that with a larger electrification (heat pumps, electric vehicles and other electrification) the hourly variation in the demand will increase significantly [Sijm et al., 2017]. Moreover, for these scenarios it can be observed that hours with VRE surplus (i.e. hours in which the generation from VRE is larger than the demand) will increase as well as the amount of the surplus.

In this context, sector coupling is becoming a strategy to provide flexibility. The idea of sector coupling was developed in Germany and it referred to the electrification of the heat and transport sectors (end-use sectors) with the goal of increasing the Renewable energy share in these sectors (assuming that a large part of the electricity can be from renewable sources) [European Parliament, 2018]. In addition, these sectors would be able to provide balancing services [1] to the power system.

Recently the concept of sector coupling was broadened including the supply-side sector (electricity and gas) coupling. The European Commission has defined the concept of sector coupling as: *a strategy to provide greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way* [European Parliament, 2018]. The sector coupling can be applied in different ways. For instance, power-to-heat technology, which transforms electrical energy into heat, combined with storage can shift heat generation to hours with cheap electricity supply [European Parliament, 2018].

As mentioned previously a strong electrification implies risks and costs [European Parliament, 2018]. Therefore, this solution can be complemented with sector coupling. For instance, the energy from electricity can be complemented with other energy sources such as biogas, biomethane or hydrogen. These gas-based energy sources can be used where the electrification is difficult to implement or when a hybrid solution would provide benefits.

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[1] Electricity balancing means all actions and processes to ensure the maintenance of the power system frequency in a stable range.

1.2 LITERATURE REVIEW

Researches have used models to analyse sector coupling in future scenarios. In [Schaber, 2013] it was concluded that there is a strong coupling between the heat and power sector with the increase of VRE share. Moreover, the power which replaced the natural gas came from oversupply of VRE generation. In [Brown et al., 2018] it was concluded that the cost-optimal use of technologies for sector coupling can reduce total system costs up to 28%. These flexibility options provide greater benefits than the flexibility provided by cross-border transmission. [Schaber, 2013] showed that the heat sector plays a major role as a sink of temporary excess of electricity from VRES which made it economically attractive. In conclusion, coupling of heat and power is relevant for the energy transition.

Coupling of power and heat relies on the integration of power-to-heat technology. In particular, hybrid solutions can provide benefits as they take advantage of fluctuations of electricity prices and can help balance power supply and demand absorbing VRE generation [IRENA, 2019; den Ouden et al., 2017; Van Kranenburg et al., 2016; Jansen et al., 2019].

Hybrid technologies for heat generation are systems that can switch between gas and electricity to satisfy a heat demand. These systems can also include a thermal storage so that the system can operate with more flexibility. Hybrid systems can be applied in decentralise heat demand (e.g. households, industries) or in centralise heat demand (e.g. district heating). According to [den Ouden et al., 2017] hybrid systems can provide cost advantages due to the volatility of electricity prices.

This literature review is focused on the following points:

- Whether hybrid solutions have been considered for power and heat coupling in the models used to analyse sector coupling from a system perspective (e.g. coupling energy system). In case hybrid systems are considered, in what sectors (e.g. residential, industry) these technologies have been implemented.
- Whether these technologies have been analysed at a local level (e.g. households, industry, district heating). Whether these technologies have been modelled with technical depth.

1.2.1 System Level Research

Sector coupling has been analysed from a system perspective in [Schaber, 2013]. This research provides an insight into the integration of VRE in the European power system through sector coupling. To this end, an energy system model based on cost-optimization was used. The cost-optimisation simulation for Germany in 2050 revealed that heat production from natural gas is substituted by electricity using electric heaters. The heat demand considered was space heating, warm water and process heat demand (excluding high temperature process heat) in households, industry and the service sector. In Figure 1.1 shows the technologies used and commodities coupled in the model.

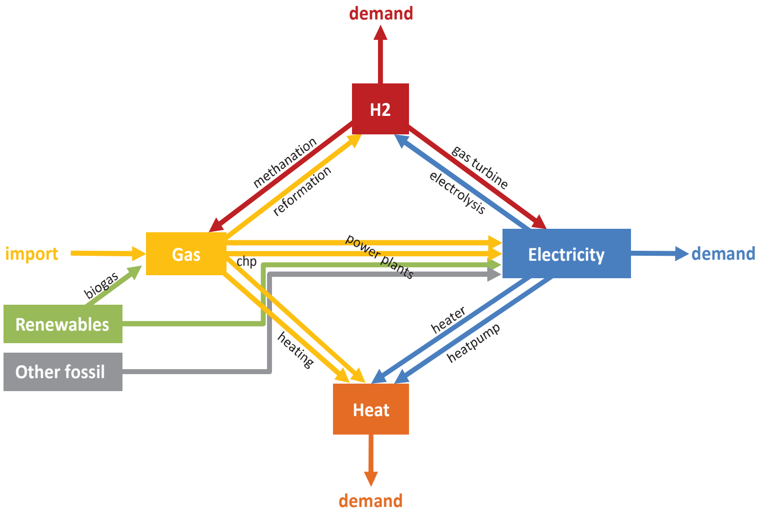

Figure 1.1: Energy sector coupling: technologies and commodities [Schaber, 2013]

The technologies considered for the heat production are natural gas heating, CHP, electric heating and heat pumps. The model optimised the capacity installed to satisfy the local demand. This model did not consider hybrid solutions, therefore, the demand is not flexible. Each local generation (electric heater, natural gas, CHP) must follow the hourly load.

In another study, sector coupling has been analysed modelling the energy sectors for Europe in the case of a 95% reduction of CO_2 emissions [Brown et al., 2018]. The model minimised the operational and investment costs considering technological and spatial restrictions. The heat demand considered is only from space and water heating in the residential and service sector excluding the industry. The decentralised heat demand is satisfied by individual technologies (electric boiler, CHP, gas boiler, heat pumps, storage) and for centralised heat demand (district heating) different technologies work together to satisfy the demand. In this model hybrid solutions are not considered for decentralised heating. However, in the case of centralised heating, district heating can be considered a hybrid system as different technologies (boilers, storage, CHP) work together to satisfy a heat demand (district heat demand). The technical constraints considered for the technologies were the efficiency and the capacity. However, more technical restrictions (e.g. ramping, cold start-ups, etc) might be relevant as different technologies work together to satisfy the demand similar to generators in a power system.

The Imperial College London developed a model to assess the performance of low-carbon heating in 2050 for three decarbonisation scenarios [Strbac et al., 2018]. The decarbonisation scenarios analysed are electric pathway, hydrogen pathway and hybrid pathway. The hybrid pathway used hybrid technologies [2] (hybrid heat pumps and hybrid resistive heating) to supply the heat demand. The heat demand included residential heating and industrial process heat. The model optimised the capacities of the heating appliances for the different scenarios. In this analysis the model identified the hybrid scenario as the most cost-effective decarbonisation strategy [Strbac et al., 2018].The model only considered the efficiencies of the technologies as technical constraints. This simplification of the hybrid system might change from a local perspective in which the technical constraints can affect its hourly operation.

According to [Härtel and Sandau, 2017] neglecting the interaction of coupling technologies (CHP systems, heat pumps, immersion heater) with the power system will make the large-scale power models insufficient. In [Härtel and Sandau, 2017] the research was focused on the integration of the power and the heat sector. In this case hybrid boilers are included in the analysis and the sectors considered are residential, tertiary sector and different temperature levels of process heat. Again the operation of hybrid boilers is restricted by the maximum capacity and the efficiency neglecting other possible restrictions that might affect its hourly operation.

Sector coupling in the Netherlands was analysed in [RVO, 2015]. The integration of different energy carrier networks is a strategy to enhance flexibility and an optimal utilisation of the resources. The valuation in this paper is technical, economical, institutional and social. In this study a hybrid system (heat pump, gas fired boiler and CHP-unit) is only analysed for district heating. These systems enable the switching between different energy sources depending only on the commodities prices (electricity, gas). Hybrid heating networks provided a large flexibility to the power and gas infrastructure.

From the literature review, it can be concluded that electric boilers and heat pumps are usually considered, however hybrid systems (e.g. hybrid boilers) are usually excluded from the models. In addition, the models [Schaber, 2013; Brown et al., 2018; Strbac et al., 2018; Härtel and Sandau, 2017] tended to exclude heat demand in the industry and to simplify the technical limits of the technologies included.

1.2.2 Local Level Research

Hybrid systems relies on the integration of power-to-heat technology. At a local level, power-to-heat technologies have been analysed in the residential sector. There are studies that analysed the demand response of power-to-heat in the residential sector [van Etten, 2017; Bruninx et al., 2013]. Other researches into power-to-heat in the residential sector are collected in the literature review ”Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials” [Bloess et al., 2018]. This literature review presents an extended list of different models and simulations for power-to-heat options in the residential sector.

From these papers it can be concluded that power-to-heat technology was broadly analysed from a local level in residential heating. These papers accurately simulated the technical

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[2] Combinations of electric and gas-based heating appliances such as hybrid heat pumps and hybrid heating.

restrictions. In this analysis it was concluded that the use of power-to-heat technology in households can reduce the use of fossil fuels, reduce the need for costly power storage and peak load, as well as reduce VRE curtailment. Therefore power-to-heat could cost-effectively benefit Renewable energy integration.

Power-to-heat technologies within hybrid systems were analysed for residential heating in [Nielsen et al., 2016; Lund et al., 2010; Ehrlich et al., 2015; Heinen et al., 2016; Pensini et al., 2014; RVO, 2015] . In [Nielsen et al., 2016] hybrid systems were analysed for district heating. In this paper an economic valuation of a hybrid system was performed. The model considered the technical constraints of the technologies and the daily operation was simulated optimizing the operating costs.

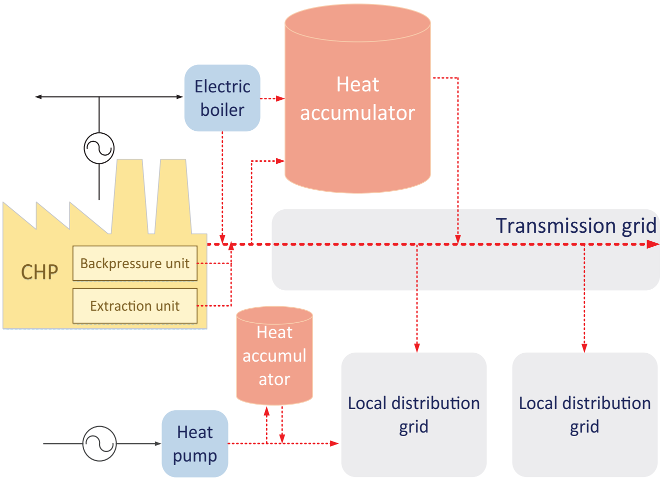

Figure 1.2: Hybrid system condensing gas boiler, electric rod and thermal storage [Nielsen et al., 2016]

Research papers which analysed hybrid systems in the residential sector showed that hybrid systems could be cost-effective and provide flexibility to the power and gas infrastructure [RVO, 2015]. However, these systems are not analysed for the industrial sector.

There are studies from the industry [Akzo Nobel, 2018; Verschuur, 2019] and [Jansen et al., 2019] in which hybrid boilers were analysed for steam production. In [Akzo Nobel, 2018] a technical report elaborated by DNV GL analysed the performance of power-to-heat in the industry to integrate offshore wind. This study was performed for industries located near offshore wind areas to support the system by reducing the strain in the transport network. To this end a hybrid system that can switch between electricity and gas to supply heat is presented. In this study [Akzo Nobel, 2018] it is assumed that an electric boiler is installed next to an already existing natural gas boiler and the operation is optimised for different cases. The operation of the boilers in the case of the market optimisation scenario is based on hourly prices of electricity and gas (including CO_2 price). The hybrid boiler was analysed for different business cases. The study concluded that the none of the operating options analysed are economically viable. The transport tariff is constant independently of the number of hours that the hybrid boiler worked electrically which make it a significant barrier for the business case. In addition, it was concluded that almost 70% of the total costs are due to the commodity costs.

Finally, a more recent study was published [Jansen et al., 2019] in which different hybrid boilers for steam generation in the industry were analysed for different business cases. This study made an analysis for the electrification of a gas boiler by means of a retrofit of 1 MW of electrical power in an existing 7 MW gas boiler. The retrofitting was compared with the installation of a parallel resistance boiler for the same capacity. The business cases were negative for both variants. It was concluded that this outcome can change if the capacity tariffs, electricity price or gas price change. [Jansen et al., 2019].

1.3 KNOWLEDGE GAP

In the literature review it was concluded that coupling of heat and power is expected to provide benefits in terms of flexibility which would result in a higher integration of renewable energy [Schaber, 2013; Brown et al., 2018]. In addition, coupling of power and heat is presented as a low cost option to reduce the emissions through the substitution of natural gas use in the heat sector [Schaber, 2013]. In [Strbac et al., 2018], the hybrid pathway is identified as the most cost-effective decarbonisation strategy. These scenarios, in which heat and power is coupled, rely on the integration of power-to-heat technology at a local level. This technology has been analysed for the residential sector in which it was concluded that it can cost-effectively benefit renewable energy and reduce the use of fossil fuels [Bloess et al., 2018]. However, in contrast with the residential heating, significantly less research has been done into the coupling of the power and heat sectors within the industry. The electrification of the heat in the industry has a high potential to contribute to the targets established in the Climate Agreement. According to the Climate Agreement, hybrid electrification will be considered in the expanded SDE+ scheme to ensure the electification of heat [Dutch Government, 2019a].

Hybrid systems for steam generation in the industry can be implemented with heat pumps or electric boilers. Currently, heat pumps have a limited temperature application in comparison with electric boilers which can provide steam up to 350 °C [den Ouden et al., 2017; TNO, 2019]. High temperature heat pumps are currently not available for industrial (MW) application [den Ouden et al., 2017]. In these master thesis we focus on hybrid boilers which are already commercially available. The scenarios in which hybrid boilers were analysed in [Akzo Nobel, 2018] and [Jansen et al., 2019] revealed that the economic business of this technology is not positive. In these studies the hybrid boiler is presented as a retrofitting of an already existing gas boiler which constrains the lifetime of the hybrid boiler to the remaining lifetime of the gas boiler [Jansen et al., 2019]. In addition, in this configuration thermal storage was not considered. Furthermore, the Climate Agreement might have changed the scenario expected for 2030 which influences the operation of the hybrid boiler systems.

Analysing the operation of hybrid boiler systems (hybrid boilers with and without storage) can provide insight into the uncertainties related to the operation of this technology in 2030 and its potential as a cost-effective decarbonisation strategy for heat in the industry.

1.4 RESEARCH OBJECTIVE

Hybrid electrification 'profits' from the time-dependent price of electricity and conventional energy carriers, for instance natural gas. This thesis focuses on electrification of steam generation in the Dutch industry. In the Netherlands, the steam generation is traditionally provided by natural gas boilers. The flexible electrification can be achieved with hybrid boilers which can switch between natural gas and electricity.

The research objective is to perform a techno-economic evaluation of hybrid boiler systems as a potential cost-effective decarbonisation strategy for steam generation in a production process. As a result of the literature review and the literature gap the main research question is proposed:

"To what extent are hybrid boiler systems a cost-effective decarbonisation strategy for steam generation in the industry for 2030?"

To this end, the techno-economic performance is assessed by simulating the operation of the hybrid systems. This method is supported with literature review and expert interviews. In addition, in order to answer the main research question, sub-research questions are formulated.

- Hybrid boiler systems profit from the fluctuation of the electricity prices which are expected to be more volatile in 2030 due to a higher share of Renewable energy. A flexible electrification can accommodate the variability of Renewable energy sources. The operation of hybrid boiler systems is determined by the ability to respond to the fluctuations of the electricity prices (demand response). In practice, the responsiveness of the system is defined by the technical restrictions (ramp up/down, start-up costs, minimum down time, etc). In the studies mentioned, the hybrid boiler was assumed to switch hourly depending on the commodities prices and the efficiency, however more restrictions might be relevant for the operation of the boiler. Therefore, to analyse the operation of the boiler the following sub-research question Q1 is formulated:

  "Q1: Which technical parameters are relevant to simulate the operation of hybrid boiler systems?"

- In order to analyse if hybrid boiler systems are a cost-effective decarbonisation strategy for steam generation in the industry, the performance of the systems must be defined. The performance is defined by means of technical indicators and economic indicators. The technical indicators are direct CO_2 emissions and efficiency of the system. While, the economic indicators are the operation costs and the levelised cost of the steam produced. These indicators are used to analyse the operation of the hybrid boiler configuration. In addition, the performance indicators are used to compare the performance of the hybrid configurations to alternative technologies: natural gas boiler, electric boiler and electric boiler with storage. Accordingly, the sub-research question Q2 is formulated:

Q2:" What is the performance of hybrid boiler systems in terms of operation costs, efficiency, direct CO_2 emissions and levelised costs of the steam produced in comparison with other alternatives?"

- The performance of the hybrid boiler systems is analysed for 2030 which is subjected to uncertainties. Accordingly, the sub-research question Q3 is formulated:

"Q3:" To what extent is the operation of hybrid boiler systems sensitive to the uncertainty of the electricity, natural gas and CO_2 prices for 2030?"

1.5 SCIENTIFIC AND SOCIETAL RELEVANCE

Investigating the potential of hybrid boilers to cost-effectively decarbonise the steam generation in a production processes can provide insight into an alternative strategy to support the energy transition in the industrial sector and the electricity sector. Cost-effective solutions for the energy transition are relevant, in addition this research can provide insight into the uncertainties of this technology.

- Scientific relevance: models that simulate the energy system tend to simplify the operation technology included, in this case hybrid boilers. The benefits of hybrid electrification and sector coupling from these models could be overestimated due to the simplifications assumed. Modelling the operation of hybrid boilers in a production process can close the gap between high level models and local level models providing insight into the errors. This is relevant as high level models (energy system) can be used for future planning in the complex scenario of energy transition.
- Society relevance: evaluate potential cost-effective options for the energy transition of the industry. Assess the relevance of hybrid boilers in the decarbonisation process of the industry and the uncertainty of its potential to cost-effectively reduce the emissions.

2 RESEARCH METHODOLOGY

In this chapter we explain the methodology used to answer the sub-research questions proposed and thus, the main research question derived from the literature review. This master thesis aims to assess the techno-economic performance of a hybrid boiler system in a production process. To this end, a model is developed to simulate the operation of the hybrid boiler system to satisfy a particular steam demand in a production process.

2.1 PHASE 1: MODEL FRAMEWORK

In this thesis models are developed to assess the techno-economic performance of hybrid boiler systems as well as alternative technologies (natural gas boiler, electric boiler, electric boiler with storage) in a production process. Prior to formulate the models, the concept of a hybrid boiler systems is defined as well as the main parameters to characterise their operation. This phase aims to present the decisions made to simplify the hybrid boiler. The following activities are performed in this phase (see Figure 2.2):

1. The heat demand in the industry is described. The heat in the industry is classified as well as the steam demand. This classification provides insight into the potential of hybrid boiler systems for heat generation (see Section 3.1) .
2. The possible configurations of hybrid boilers are described from literature review. From these configurations one is selected for the model (see Section 3.2).
3. The technologies included in the hybrid systems selected are described. The technical and economic parameters to characterise the hybrid boiler systems are defined (see Section 3.3).
4. The operation of the hybrid boiler systems is simplified into three modes: cold start-up, online operation and shutdown (see Section 3.4).
5. The operation costs considered in the model are defined (see Section 3.5).

In Figure 2.2 the research steps followed, the research methods as well as the outcome for each step are presented. The legend presented in this figure is used for the diagrams included in this chapter.

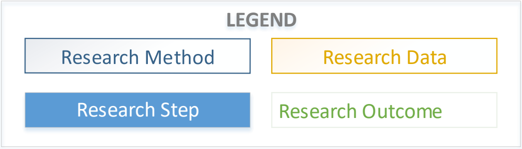

Figure 2.1: Legend of the methodology diagrams.

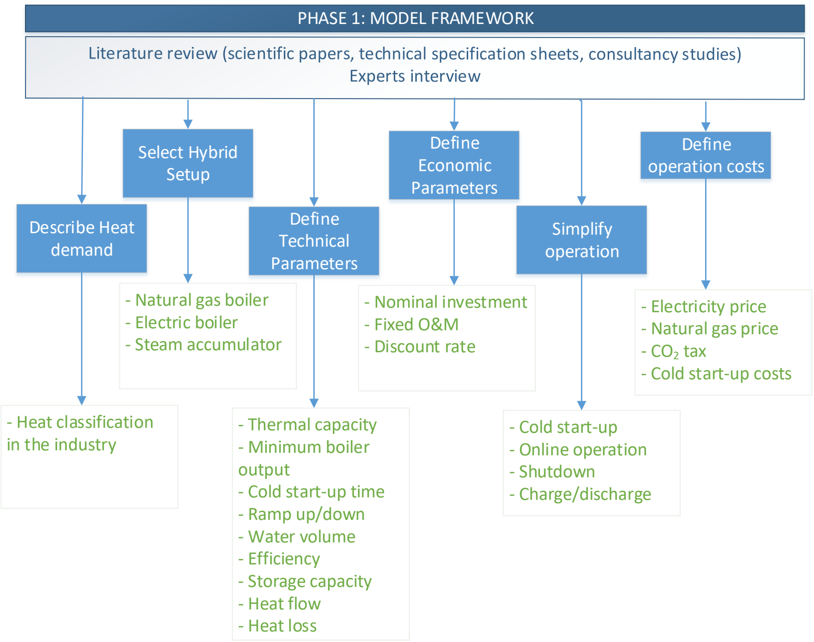

Figure 2.2: Methodology in Phase 1.

2.2 PHASE 2: FORMULATION AND IMPLEMENTATION OF THE MODELS

In this section the methodology for Phase 2 is explained. The main research steps in Phase 2 are: (1) performance indicators are selected and described, (2) the models to calculate the performance indicators for every technology are mathematically formulated, (3) the models are implemented to obtain the performance indicators.

2.2.1 Performance indicators

Performance indicators are selected to evaluate the technical and economic performance of the boilers operation throughout one year. In this section the technical and economic indicators are described.

1. **Technical Indicators**
   a) Total system efficiency is the total energy entering (fuel, electricity) the boiler system divided by the energy output (heat). The efficiency of the system indicates the energy saved in comparison with other boilers. The efficiency in hybrid boiler systems depends on the share of electricity and natural gas consumed as the con-

version of electricity to heat is more efficient than natural gas. The energy input is calculated simulating the operation of the boiler throughout one year, while the energy output is data retrieved from the case study analysed.

b) CO_2 emissions are the direct CO_2 emissions released from the natural gas combustion during the boilers operation. This indicator provides insight into the emissions reduced in comparison with alternative boilers. This indicator is calculated simulating the operation of the boiler throughout one year. In this thesis also the indirect emissions are analysed, however this analysis is presented in a separate section (see Chapter 7.3) due to the uncertainty of the methodology used for the estimation of the emissions.

2. **Economic Indicators**

   a) Total operation costs are the costs incurred during the operation of the hybrid system. These costs include the start-up costs and the fuel costs (natural gas and electricity). The operation costs are calculated simulating the operation of the boiler throughout one year.

   b) The levelised cost of product (LCOP) is the analogous performance economic indicator of the LCOE (levelised price of electricity) which is commonly used for electricity generation [U.S. Energy Information Administration, 2019]. The LCOP is a measure of the revenue per unit of product generated that the plant needs to receive to recover the costs of 'building' and operating the generation unit (boiler) [Fernández-Dacosta et al., 2017]. This indicator includes the cash flows into and out of the project which are levelised over the lifetime of the system. The cash flows are normalised over the amount of steam produced during that period. This indicator is calculated using the operation costs (calculated), the investment costs [1] (data), steam production (data), lifetime of the system (data) and the discount rate (data).

2.2.2 Mathematical formulation

The Phase 2 aims to formulate the model that minimises the operation costs of the hybrid boiler defined in Phase 1 (see Figure 2.4). In the hybrid boiler system there are different generation units that have to satisfy a demand, this is very similar to the working principle of the power system. The hybrid boiler have to decide at each time step (i.e. hourly) which technology (conversion) to use for the steam production: electricity to steam or natural gas to steam. Each source is subjected to different efficiency, technical restrictions and costs. Similarly, in the power system, different technologies produce electricity to satisfy the demand at every time step. In this case the system has to decide which technology will deliver the electricity to the demand at the minimum operational costs. In the power sector this problem is called the Unit Commitment problem which seeks to determine the optimal schedule of a set of power

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[1] Investment costs are the nominal investment costs and the fixed operation and maintenance costs of the boiler. The investment costs are retrieved from literature review.

plants (in this case boilers) to meet the electricity demand (in this case heat demand) [Van Den Bergh et al., 2014]. To this end, mathematical formulations to solve the Unit Commitment (UC) problem are reviewed [Abdou and Tkiouat, 2018]. From the different possibilities the Mixed Integer Linear Programming (MILP) is selected. The MILP approach is an efficient methodology to solve the (UC) [Abdou and Tkiouat, 2018]. The hybrid boiler have to decide whether to use electricity or natural gas at every time step, the decision can be represented with binary variables and therefore linear programming is not able to solve the problem. The MILP formulation can indicate the ON/OFF status of the boilers which can be modelled with binary variables. Similarly, the start-up and the shutdown status of the boilers can be modelled with binary variables. The heat output from the boiler is represented with continuous variables. The formulation seeks to minimise the operational cost of the system. This is a powerful modelling tool which can reach a global optimal solution [Abdou and Tkiouat, 2018].

In order to formulate the constraints (e.g. maximum capacity, ramp up/down, start-up time, etc) of the hybrid boiler operation (see Figure 2.4), which is simplified and described in Phase 1, the formulation for power thermal units (e.g. coal power plant) in the Unit Commitment problem is used. This is because thermal generation units use fuels to produce heat (which is further transformed in electricity). These units have similar constraints as a boiler in which thermal stress affects the start-up of the system. The MILP formulation for thermal units presented in [Morales-España et al., 2013] is used to formulate the constraints and to define the decision variables of the hybrid boiler system. In addition, in [Nielsen et al., 2016] a MILP formulation is presented to optimise the heat generation for a heat district in Denmark. This formulation is also used to formulate the model of the hybrid boiler system. The formulation for hybrid boilers is presented in Chapter 4.1.

2.2.3 Model implementation

The model is a Mixed Interger Linear Program which is solved with CPLEX solver in the modelling environment Matlab running on a computer with an Intel Core i5-8500 CPU processor at a clock-speed of 3 GHz and 16 GB of RAM memory.

The model developed is a deterministic model which aims to optimise the operation of the hybrid boiler systems during a year. The operation of the hybrid boiler depends on the variations of the electricity prices, the natural gas prices in addition to the operation costs. In this thesis we consider perfect foresight which assumes the correct prediction of future events (i.e. the future prices of electricity are assumed to be known).

Solving the optimisation problem for a whole year in one simulation is computationally challenging due to the large number of possible combinations of the state variables and the number of constraints. Therefore, the rolling horizon method is used to run the model for a whole year.

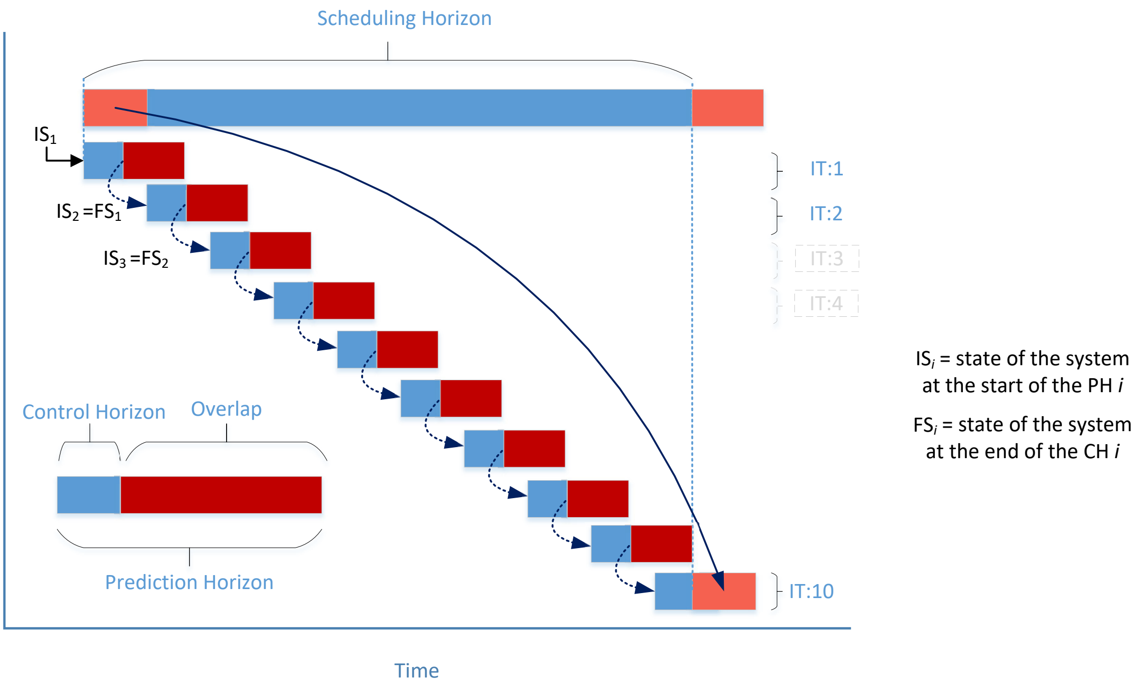

Figure 2.3: Rolling Horizon method

The rolling horizon method is used to divide a one-step simulation into shorter steps which are the iterations (see Figure 2.3). The rolling horizon is defined by the Scheduling Horizon, the Prediction Horizon and the Control Horizon:

- The Scheduling Horizon (SH) is the total period that is going to be optimised. This period is divided into equal-size intervals. In our case, the SH is one year and it is divided into hours.
- The Prediction Horizon (PH) corresponds with the information that the model has to optimise the problem at every iteration. If the model can predict prices for one month the results would be closer to the optimal solution than if it predicts the prices only for one week.
- The Control Horizon (CH) is the interval selected from the results of the PH interval simulation. The results selected are fixed as the final solution of the SH optimisation for that hours. The length of the CH horizon impact the results. With longer intervals selected the results will be affected by the fact that the model assumes that the end of the PH is the end of the simulation. This is especially relevant when a storage is included in the system. The storage would be fully discharge at the end of the PH. Choosing short intervals for the CH would reduce the deviation from the optimal solution due to the disruption of the simulation at the end of the PH interval.

Selecting longer PH intervals incurs into an increase in the number of variables and constraints for each iteration and consequently a higher simulation power and time are required. In the case CH intervals, if small periods are selected more iterations are required. Therefore the length selected should be a balance between accuracy and the computational power required.

In addition, the last conditions of the simulation has to be taken into account. If the simulation ends at the last hour of the year the model will optimise these hours as if the hybrid boiler system would stop at hour 8761 which does not correspond with reality. To avoid this disruption and simulate continuity at the end of the year, hourly electricity prices are added at the end of the year (See Figure 2.3). These prices correspond with the first hours of the year.

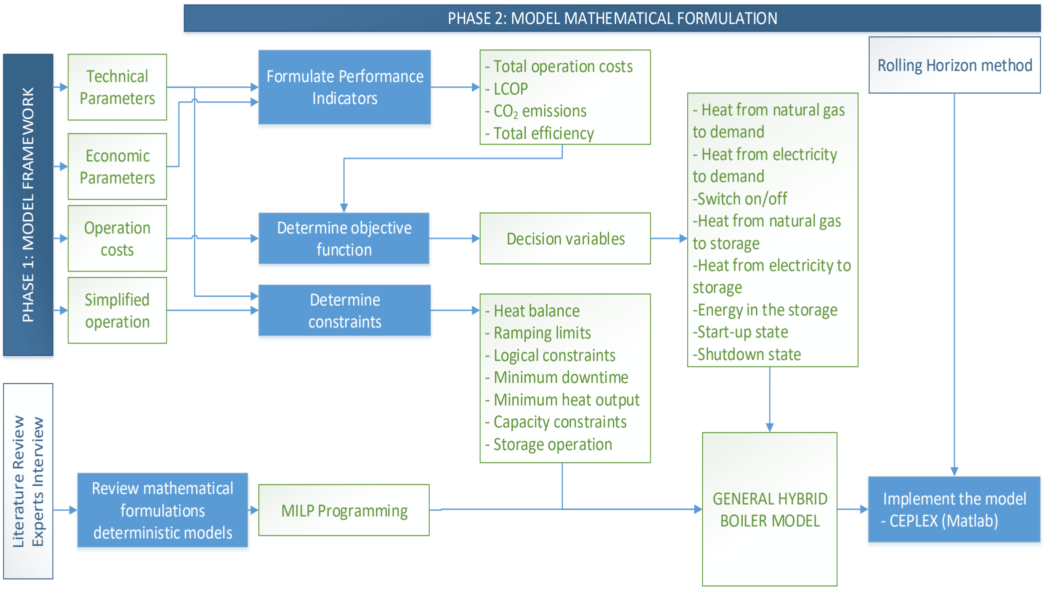

Figure 2.4: Methodology in Phase 2.

2.3 PHASE 3: CASE STUDY

In this phase the case study of a heat generation unit in a production process in 2030 is presented. The performance of the hybrid systems defined in the previous phases is assessed in the scenario presented in this section. First the demand and the parameters of the hybrid boiler systems are determined. The heat generation unit in the case study is selected from [Chikri et al., 2019] in which the production process of a tyre manufacturer is described and quantified in terms of energy and material balance (data available). This study is part of the MIDDEN project which aims to up-to-date information about the Dutch industry and propose possible decarbonisation options [PBL, 2019d]. In the production process a natural gas boiler is used to produce steam required to manufacture the tyre. This case study was selected as it is representative of the medium temperature heat generation in the industry (200^{o}C). Low and medium temperature steam represent 75% of the steam used in the industry [Arij van Berkel, 2018].

The parameters were estimated according to the demand (see Section 5.1). Subsequently the model is adapted to the scenario presented. This step is required because the model was formulated so that the hybrid boiler system can be simulated for different time steps[2] (Δt). Depending on the type of boiler and the time steps (i.e. frequency with which the hybrid boiler system has to make a decision) there are constraints that can be neglected. In addition to the hybrid configurations, this process is performed for alternative options to compare the results. These alternative technologies are: natural gas boiler, electric boiler and electric boiler with storage.

Hybrid boiler systems are technologies already available which can take advantage from the fluctuation of electricity prices. The case study is presented for 2030. As mentioned in the literature review the fluctuation of the prices is expected to increase by 2030 [Van Hout et al., 2014; Sijm et al., 2017]. This might create a higher opportunity for this technology. In addition, expected hourly electricity prices for 2030 were facilitated by PBL. These prices are used for the case study. The operation costs of the hybrid boiler are estimated according to the OKA scenario described in [PBL, 2019b] for 2030.

- Hourly electricity prices for 2030 were facilitated by PBL (Netherlands Environmental Assessment Agency). The hourly electricity prices resulted from the simulation of the OKA scenario in COMPETES. COMPETES is a model that simulates the European electricity market. The model is described in [Özdemir et al., 2008].
- From the OKA scenario the average natural gas price for 2030 is retrieved [PBL, 2019b]. Hourly prices of natural gas were not available. Therefore, in order to simulate the monthly fluctuations of the natural gas price throughout the year, prices of natural gas in Germany for 2018 were used due to the data availability. In addition, the difference between the natural gas price in Germany and Netherlands might be negligible for the analysis in this thesis.
- CO_2 prices are retrieved from the OKA scenario in [PBL, 2019b].
- Cold start-up costs are estimated as the energy required to bring the water volume in the boiler to the required operation conditions (temperature and pressures) (see Section 5). In addition the heat loss to the steel structure is also included (Section 3.5).

The model is run for the scenario described in Chapter 5 and the results of the model are presented in Chapter 6. The performance of the hybrid boiler systems is compared to alternative technologies: natural gas boiler, electric boiler and electric boiler with storage.

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[2] The time step change depending on the market analysed.

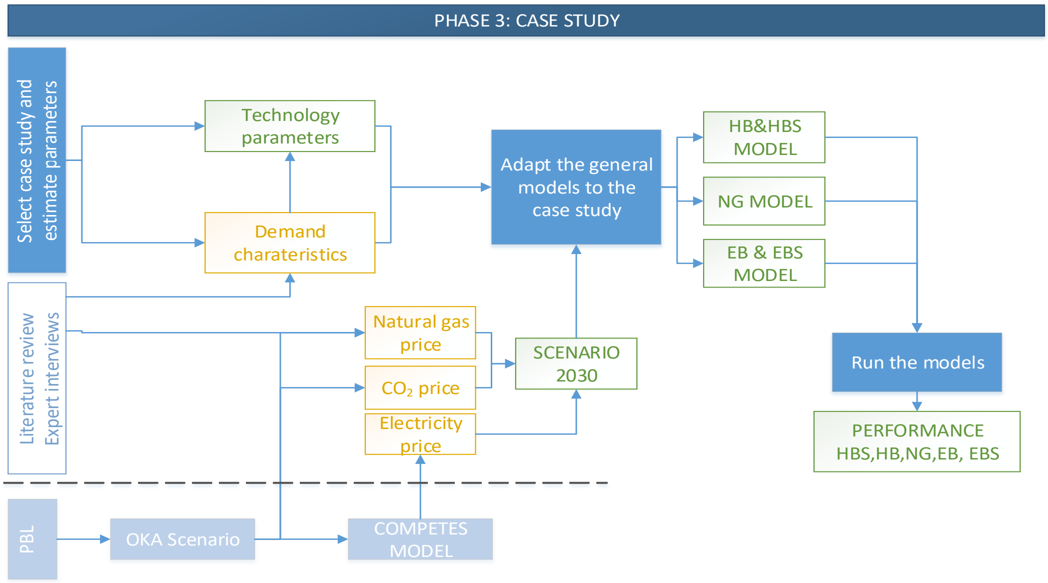

Figure 2.5: Methodology in Phase 3.

2.4 PHASE 4: ANALYSIS

In this section deeper insight into the results is provided analysing the decisions made regarding the parameters of the hybrid boiler systems and the capacity of the units. In addition, a sensitivity analysis is required to provide insight into the uncertainty of the 2030 scenario (electricity price, natural gas price and CO_2 price) which can change the performance of the hybrid boiler systems. Finally, the indirect emissions are estimated as well as the the price of the steam considering the Network tariffs which represent additional costs to the industry. These analysis are enumerated below:

1. The technical parameters of the hybrid boiler systems were estimated for the case study. In this section (Section 7.1, the relevance of these parameters for the performance of the hybrid boiler is analysed. The parameters selected for the analysis are: start-up costs, start-up time and capacity (boilers and storage). For this analysis the parameters were changed in order to analyse the impact on the performance of the hybrid boiler.
2. The model presented in this thesis is a deterministic model. In the model all the inputs parameters are known for the whole year. However, in reality the electricity prices are not available for one year but for shorter periods (days). Therefore the prediction horizon is shorter and this would affect the optimisation. In this section the model is run for a prediction horizon of 2 days and a control horizon of 1 day.
3. The direct emissions of CO_2 are an important indicator to measure the benefit of hybrid boiler systems in comparison with natural gas boilers. However, there are also indirect emissions from the electricity consumption. The indirect emissions are estimated grouping the electricity prices in three ranges and assuming different emission factors

for every range of electricity prices (see Section 7.3).

4. The impact of network tariffs on the performance of the system is analysed. The network tariffs considered are the grid connection tariff and the transmission tariff. Installing an electric boiler might increase the grid connection required. This implies an additional investment that might affect the price of the steam produced in comparison with a natural gas. In addition transmission tariffs can increase the costs of the hybrid system.

5. The uncertainty of the performance of the boiler related to the scenario for 2030 is analysed. Different bandwidths are considered for the prices of electricity, natural gas and CO_2 for 2030. The bandwidths are selected from [PBL, 2019b]. The prices were varied considering all possible combinations within the bandwidths (see Section 7.5). These combinations result in 27 possible scenarios for 2030.

6. The uncertainty is also analysed for two different measures to reduce the emissions in the industry. In the Tax scenario the CO_2 tax is set to 120 € while in the Cap scenario the emissions are capped. The scenarios are set to represent the same emission reduction so that the operation costs are compared (see Section 7.6). In this analysis a representative week is selected. This week represented a similar share of electricity consumption as the entire year.

The results from Phase 3 and the analysis in Phase 4 together with literature review are discussed to answer the sub-research questions. Furthermore, the limitation of this research to answer the questions is also discussed. Finally, in the conclusion the main research question is answered.

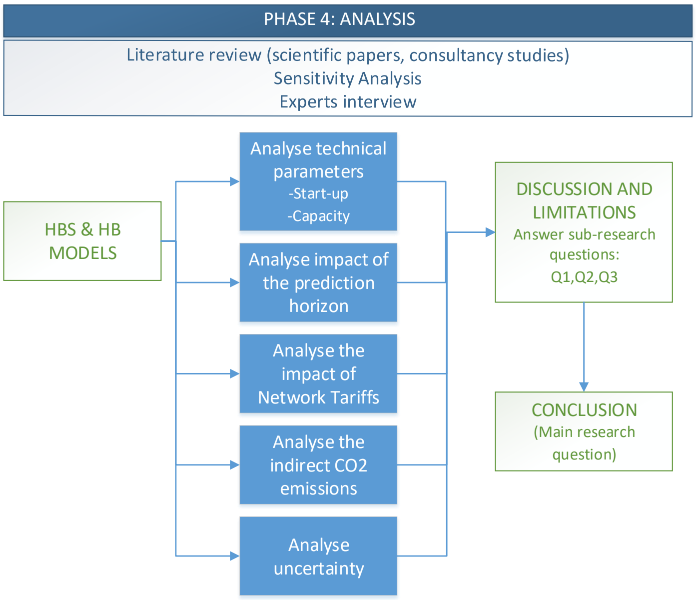

Figure 2.6: Methodology in Phase 4.

3 MODEL FRAMEWORK

3.1 HEAT IN THE INDUSTRY

In this section an overview of the heat production in the Dutch industry is presented. Moreover, the steam production in the industry is classified and described. Finally, the potential of hybrid boiler systems for steam production in the industry is introduced.

In Figure 3.1 the heat demand in the Netherlands is classified by temperature. It can be seen that the demand of low temperature heat ($< 100^oC$) is considerably higher than the demand of high temperature heat ($> 1,000^oC$). Only the industrial sector present heat demand higher than 100^oC.

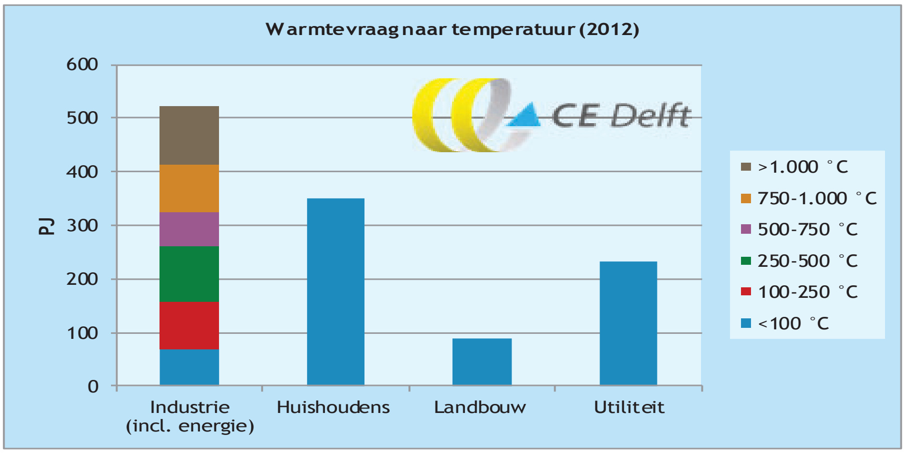

Figure 3.1: Heat demand per temperature in the Netherlands, in 2012 [Schepers and Aarnink, 2014]

In [Roelofsen et al., 2017] the source of emissions from the industrial sector in the Netherlands are classified. Among these sources there is the production of heat which is generated from different sources (see Figure 3.2). The production of heat in the Dutch industry is divided into three categories:

1. Low-temperature heat generation which corresponds with temperatures lower than 100^oC for drying and distillation processes. In some facilities, this heat is obtained from residual heat from other processes at medium or high temperature heat.
2. Medium-temperature heat generation corresponds with temperatures between 100-500^oC for applications such as evaporation, distillation and driving turbines. Medium-temperature heat is usually produced with natural gas used in boilers or cogeneration units.

3. High-temperature heat generation corresponds with temperatures above 500^oC. This heat is usually produced using fossil fuels in furnaces.

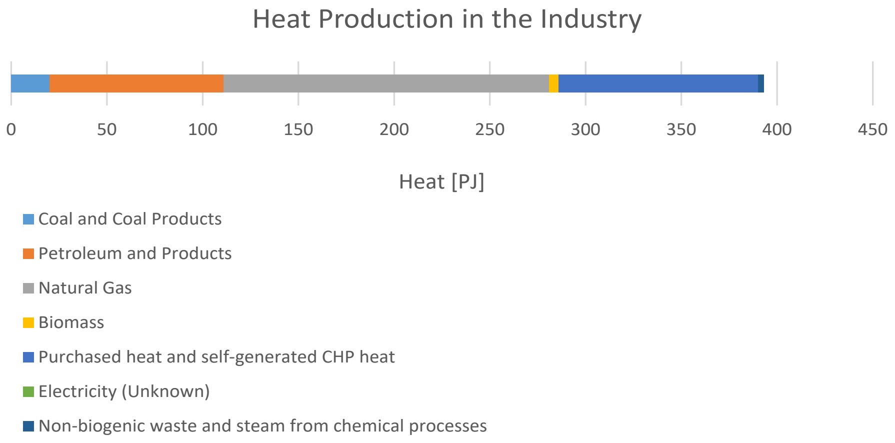

Figure 3.2: Final energy consumption for heat generation by energy carrier in the industry in the Netherlands, in 2015 [Menkveld et al., 2017].

In 2007 steam production represented 38% of the industrial energy use worldwide and consequently 24% of the CO_2 emissions are related to the industry [Arij van Berkel, 2018]. Steam is an essential energy carrier in many industrial processes. According to [Arij van Berkel, 2018] the steam production can be divided in two types based on temperature and pressure:

1. Low and medium temperature steam corresponds with steam at temperatures up to 200^oC and pressures up to 15 bar.

2. High temperature steam corresponds with temperatures higher than 200^oC.

Low and medium temperature steam represents 75% of the steam used in the industry. This steam is used in different sectors as pulp, food, fine chemicals and textile. While high temperature steam is important for the energy sector. For instance, it is used in steam turbines to produce electricity.

Medium-temperature heat is generally produced in boilers or co-generation [Roelofsen et al., 2017]. In Figure 3.3 it can be seen the total natural gas used by sector and the average used per company. The natural gas consumption per sector can provide insight into the potential of implementing hybrid boiler systems in the different sectors. The sectors with high potential are the chemical industry, greenhouses, food industry, paper industry, metal industry and building materials industry.

The heat production in the industry represents approximately 60% of the total CO_2 emissions from the industry (direct and indirect) [Roelofsen et al., 2017]. The main decarbonisation options proposed in [Roelofsen et al., 2017] for the industry are efficiency improvement, electrification of the heat generation, feedstock switching, carbon capture and storage or usage,

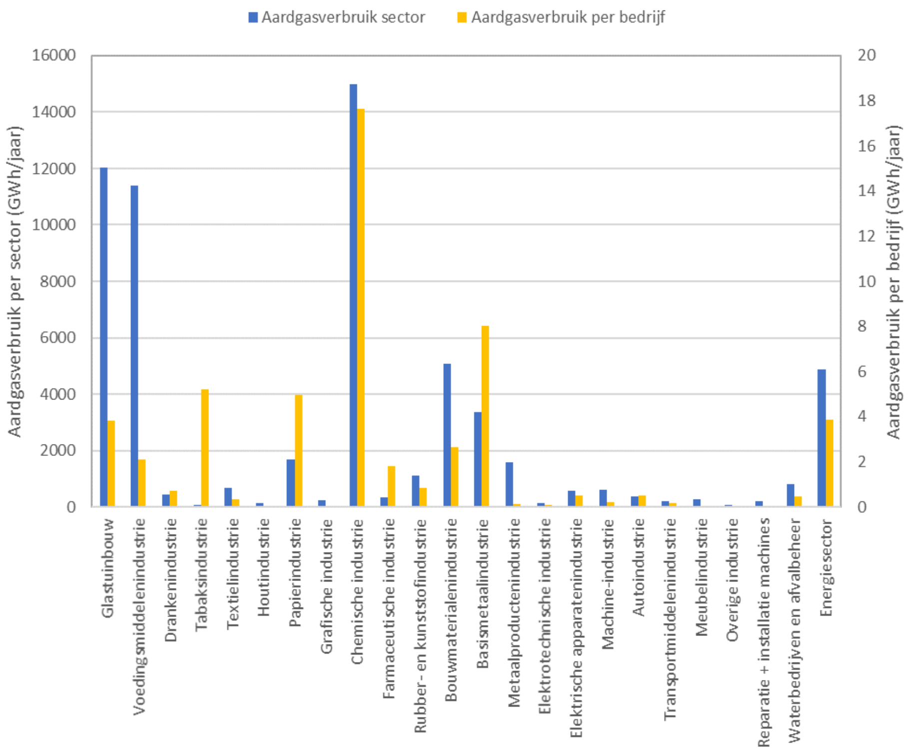

Figure 3.3: Final natural gas consumption in the different sectors of the Dutch industry and the average consumption per company for boilers with a capacity larger than 1 MW [Jansen et al., 2019]

among others. The electrification of medium and high temperature heat production is expected to play an important role in this transition [Roelofsen et al., 2017; den Ouden et al., 2017]. For the medium-temperature heat hybrid boilers are ready to be implemented. Hybrid boiler systems switch between electricity and natural gas. These systems provide to the industry the possibility of switching to the less expensive source. Moreover the hybrid boilers can be an innovative solution to connect the intermittent nature of electricity from VRE to the nature of the industrial process which is continuous [den Ouden et al., 2017]. In the future, hybrid boiler systems can switch between hydrogen and electricity instead of natural gas and electricity.

In this master thesis we focus on the medium temperature steam generation (200°C). Furthermore, the quality of the steam required in the process is assumed to be constant during the entire year and only the mass-flow rate changes.

3.2 HYBRID BOILER SETUPS

In this section the concept of hybrid boiler is defined and the different types of hybrid boilers are introduced.

Hybrid boilers are systems that can switch between natural gas and electricity to produce steam. There are different setup possibilities for a hybrid boiler. In [Jansen et al., 2019] four different setups for a hybrid boiler are proposed:

1. Electric air heater parallel to the firebox. Hot air can substitute the flue gas that heats the water. This hybrid systems do not require a modification in the boiler structure. The low specific heat of the air and the space required to place the air heater make this option less attractive.
2. Electric resistance elements can be placed in the boiler to heat the water inside the boiler. This is only possible for fire-tube boilers because there is space to place the resistance element in the water (see Figure 3.4).

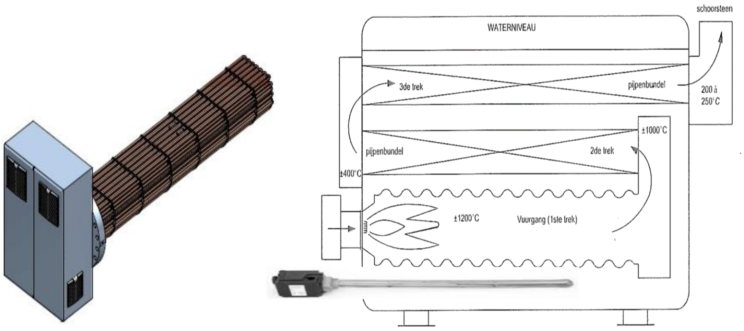

Figure 3.4: Electric resistance element in a fire-tube boiler [Jansen et al., 2019] .

3. An electric flow heater can be placed to heat water flow which enters the boiler. This water can be withdrawn from the boiler itself to be conducted through the flow heater and finally return to the boiler (see Figure 3.5). This process is more suitable for fire-tube boilers.

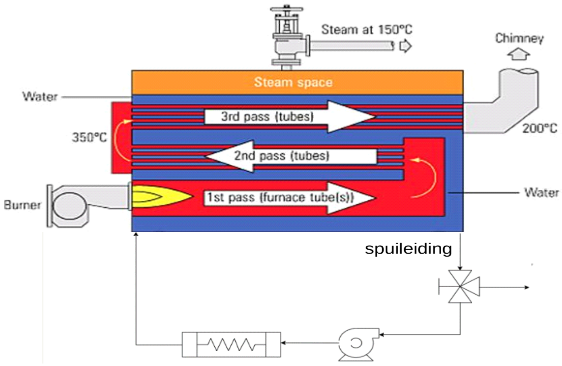

Figure 3.5: Electric flow heater with a fire-tube boiler [Jansen et al., 2019]

4. An alternative option presented in [Jansen et al., 2019] is placing an electric element in the degasifier on the boiler feedwater to maintain water at the right temperature.

Another model is possible which is proposed in [Akzo Nobel, 2018; Verschuur, 2019]. This system consists of placing an electric boiler in parallel with a gas boiler. The model proposed in this master thesis analysed the case in which an electric boiler and a gas boiler work in parallel to satisfy the steam demand. In addition to the hybrid boiler a thermal storage is added. In this master thesis the thermal storage considered is a steam accumulator. The steam accumulator stores steam when electricity prices are low and releases the steam when the price is high. In this master thesis a hybrid boiler alone (HB) (see Figure 3.6) and a hybrid boiler with a steam accumulator (HBS) are considered (see Figure 3.7) .

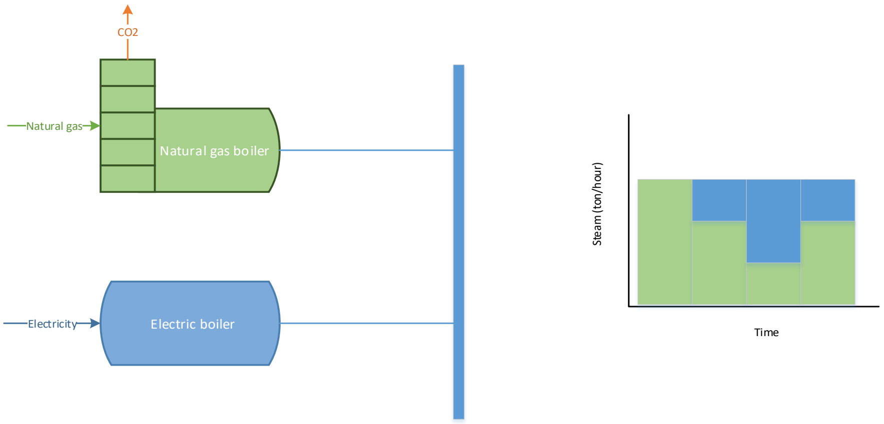

Figure 3.6: Hybrid boiler without storage (HB) setup.

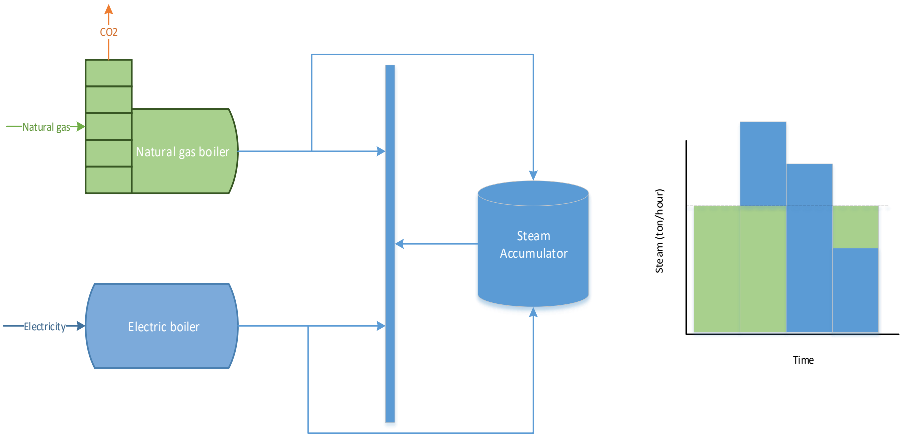

Figure 3.7: Hybrid boiler with storage (HBS) setup.

3.3 TECHNICAL PARAMETERS

In this section a general description of the technologies included in hybrid boiler systems (electric boiler, natural gas boiler, steam accumulator) is presented. These technologies are characterised by their technical specifications. In this section, technical parameters are selected to define the characteristics of each technology. The parameters selected in Table 3.1 will be use to formulate the model for the hybrid boiler systems.

Table 3.1: Parameters selected to characterise the technologies

Parameters	**Symbol**	**Unit**
Boilers Parameters		
Thermal Capacity	Q_{max}	MW
Minimum Boiler Output	Q_{min}	MW
Cold start-up time	TD	MW/h
Ramp-up	R_{up}	MW/h
Ramp-down	R_{down}	MW/h
Water Volume	V	m^3
Boiler Efficiency	η	%
Storage Parameters		
Storage capacity	E^s_{max}	MW
Heat flow	S_{flow}	MW
Heat loss coefficient	S_{loss}	-

3.3.1 Natural Gas Boiler

Combustion boilers are broadly used to produce steam for industrial applications and power generation. The boilers can be categorised in two types: water-tube and fire-tube boilers. In the former, the tubes inside the boiler contain water which is heated from combustion gases outside the tubes, while in the latter case, the combustion gases are contained in the tubes and the water flows outside.

The fire tube boilers are mostly used for low and medium steam pressures. As a reference, the fire tube boilers are considered for steam flow rates up to 28 ton/h and pressures up to 30 bars. The water-tube boilers are used for high pressure requirements and high steam demand. The capacity of a water-tube boiler can go from 4.5 t/h to 120 t/h of steam and can work with high pressures (above 350 bar) [Gentili et al., 2014].

The boilers are characterised by several technical specifications [Cannon Bono Energia, 2013]. In this master thesis the following specifications are selected to characterise the natural gas boiler:

- **Thermal capacity** is the full boiler power output. This parameter determines the maximum power output that the boiler can deliver.
- **Minimum boiler output** is the power output when the boiler is operating at low fire (minimum stable combustion) [AENOR, 2003]. The minimum operating point is charac-

terised by the boiler turndown which is a ratio between the full boiler output and the minimum boiler output. The ability of the boiler to turndown reduces on and off cycling. Every time the boiler is shut down (i.e. cycles off) it must go through a start-up process which requires time, maintenance as well as it increases the probability of failure. Moreover, switching on and off the boiler affects the lifecycle of the boiler components. When the boiler is shut down, in case of a sudden change in demand the boiler cannot accelerate the start-up process. Therefore, maintaining the boiler at a minimum can provide a quick response to load change [CleaverBrooks, 2019]. The burner minimum turndown ratio for fuel gas should be 10:1 (10% of the maximum load capacity) [Bahadori, 2016; ClearBrooks, 2019].

- **Cold start-up time** is the time that it takes to switch on the boiler. The time can vary depending on the type of boiler.
- **Ramp up/down** represents the maximum change in the heat output per time step. For instance, for a time step of one hour the ramp up is the maximum MW output that can be increased in one hour.
- **Water volume** is the amount of water inside a boiler. The volume depends on the water level when the boiler is operating. The water level changes during the operation of the boiler however for sake of simplicity the water volume in the boiler is considered constant. The water volume can be obtained from the technical specifications of the boiler.
- **Boiler efficiency** is defined as the fuel-to-steam efficiency. This efficiency takes into account the effectiveness of the heat exchanger and the losses due to radiation and convection [CleaverBrooks, 2010]. The amount of fuel input required depends on the overall thermal efficiency. Natural gas boilers can reach efficiencies of 75% [Van Wortswinkel and Nijs, 2010] however this efficiency is increased by recovering heat loss. In this case the efficiency can go up to 95% [CleaverBrooks, 2010].

3.3.2 Electric Boiler

The electric boiler consists of a large electric resistor. There are two types of electric boilers: electrical boilers and electrode boilers. The former uses an electric heating element and the latter uses the water as a resistor dissipating the energy directly in the water [Arij van Berkel, 2018]. In the electrode boiler the current flows from the phase electrodes to the water which is heated. The current depends on the active area of the electrodes and the conductivity of the water. The electrode boilers can produce superheated steam with temperatures up to $350^{o}C$ [TNO, 2019]. In this thesis the electrode boiler is selected for the hybrid boiler analysis.

Similar to the natural gas boiler the electrode boiler is characterised by the following parameters:

- **Thermal capacity** is the maximum power output that the boiler can deliver.
- **Minimum boiler output** in an electrode boiler is defined as the standby mode during which the boiler is maintained hot with a heating element to start fast. During the

standby mode there is no output from the boiler [CleaverBrooks, 2013]. The minimum load can be between less than 1% and 5% of the thermal capacity [RVO, 2015; PARAT, 2019; Energistyrelsen, 2016] .

- **Cold start-up time** is the time that it takes to switch on the boiler. Some electric boiler have very fast cold start-up [PARAT, 2019; Energistyrelsen, 2016]. The absence of fuel combustion avoids the thermal stress during cycling or high temperature difference [CleaverBrooks, 2013].
- **Ramp up/down** represents the maximum change in the heat output per time step. For instance, in the case of a time step of one hour the ramp up/down is the maximum MW output that can be increased/decreased in one hour.
- **Water volume** inside the boiler depends on the water level in the boiler. The water level is considered constant.
- **Boiler efficiency** considers the conversion of electricity into steam as well as the heat losses. The efficiency of the conversion from electricity to steam is between 99% and 100% [CleaverBrooks, 2013; PARAT, 2019]. The heat losses to the surroundings are minimal.

3.3.3 Steam Accumulator

A steam accumulator is a thermal energy storage that can compensate the imbalance between the supply and the demand of steam. Steam accumulator are commonly used in industrial processes as buffer storage. In addition it can act as an instant steam reserve when the boilers are in stand-by [Gibb et al., 2018].

The process consists of a storage process and a release process. In the storage process the steam supply delivers steam at higher temperature than the one inside the steam accumulator. When the valves open the steam enters automatically. Inside the steam accumulator there is saturated water and saturated steam at relatively low temperature and pressure. The high-temperature steam enters the storage and heats the saturated water and steam. During the steam release process, the outlet valve opens and the steam is released automatically due to the lower pressure in the pipes [Sun et al., 2017].

The dynamics of a steam accumulator have been simulated in [Shnaider et al., 2010]. However in this master thesis the steam accumulator is simplified as presented in [Nielsen et al., 2016] where the following parameters characterise the performance of the steam accumulator[1]:

- **The storage capacity** corresponds to the maximum energy that the steam accumulator is capable to store.
- **The heat flow** is the maximum amount of heat that can be transferred from and to the storage.
- **The heat loss** during the storage and release process in the steam accumulator.

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[1] The minimum load of the steam accumulator is 0 according to [EIFER, 2019]. In addition the start-up time is less than 30 seconds [EIFER, 2019]. Therefore these parameters are not considered for the steam accumulator.

3.4 HYBRID BOILER SYSTEM OPERATION

This master thesis aims to analyse the performance of hybrid boiler systems. To this end, model is developed to simulate the operation of a natural gas boiler, electric boiler and a steam accumulator. In order to formulate the model, the operation of the boilers is simplified distinguishing three different states: cold start-up, online operation and shutdown. The steam accumulator operation is simplified into charge and discharge. In the model the operation of the technologies is defined by the decision variables. The decision variables determine the operation of the technology at every hour.

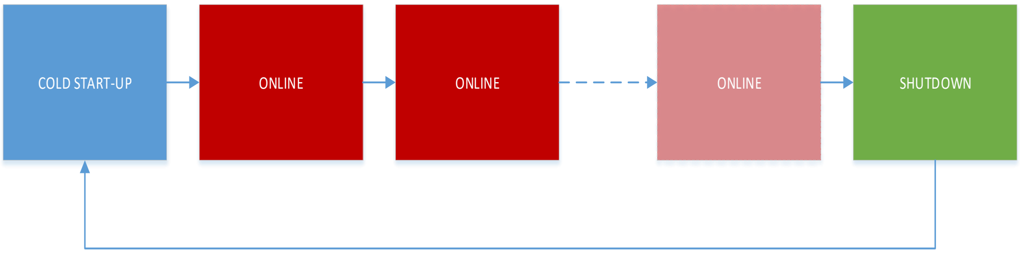

Figure 3.8: Operation of the boilers

3.4.1 Cold start-up

The cold start-up is defined as the transition during which the boiler goes from ambient temperature to the operating point (e.g. temperature, pressure) required by the demand. In this transition the boiler is switched on and the water volume inside the boiler as well as the steel (boiler structure) is heated up until the conditions required. During the cold start-up the valve to the demand is considered closed therefore the mass flow rate is zero.

Modern natural gas boilers are operated mostly automatically, however operators are required to oversight, respond to alarms, operate (e.g. cold starts), perform boiler maintenance and record keeping. The cold starts should be performed according to the instructions of the manufacturer to avoid boiler failures [Roberts et al., 2017] . This process takes time and it differs from boiler to boiler as it depends on the thermal stress specifications of the boiler. The thermal stress limits the heating and cooling rate (i.e. temperature changes) [Taler and Węglowski, 2014]. The time for a cold start-up is determined by the maximum temperature change per minute (ºC/min).

3.4.2 Online Operation

The online operation is defined as the state in which the boiler is delivering the steam to the demand. The main parameter during the online operation is the power output.

The model is discretised in hourly time steps. During the online operation the power output is considered constant for every time step. During this time step the boiler is considered to operate in steady state (e.g. the conditions and parameters do not change for a period of time).

The transition from one steady state to the next steady state is determined by the dynamics of the boiler. The dynamics of a natural gas boiler were simulated in [Taler and Węglowski, 2014; Bell, 2000; Beyne et al., 2019; Ejaz Ul Haq et al., 2016] through a mass balance, energy balance and momentum balance. This is a tedious task and it is specific for the type of boiler that it is simulated. In this master thesis changes in the parameters in the boilers (e.g. pressure, temperature, mass-flow rate, etc.) during the transition are neglected.

In order to characterise the online operation the boiler is considered as an open system (see Figure 3.9). Energy may enter and leave the system by means of heat transfer Q, work modes (e.g. shaft work) and material which is leaving and entering (input and output streams).

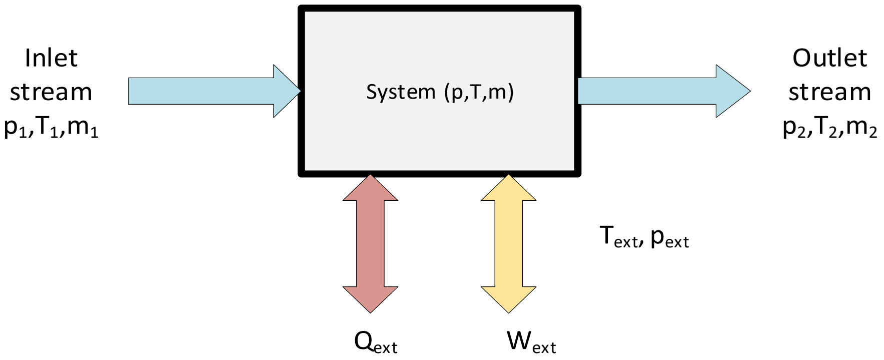

Figure 3.9: Open system.

For the analysis we consider steady-state flows of mass and energy. The mass balance in terms of flow rates of material for a steady-state is presented in Equation 3.1. The flow rate of material and energy are indicated with an over-dot. The conservation of mass is applied.

$$\dot{m}_1 = \dot{m}_2 \tag{3.1}$$

The First Law for open systems in steady-state is applied [O'Connell and Haile, 2005]. The general energy balance is simplified to Equation 3.2.

$$h_1 * \dot{m}_1 - h_2 * \dot{m}_2 + \dot{Q} + \dot{W}_{ext} = 0; \tag{3.2}$$

Finally, in case of a workfree process the heat transferred can be simplified as the difference of enthalpy between the input and output [O'Connell and Haile, 2005].

$$\dot{Q} = \dot{m} * \Delta h(p, T) \tag{3.3}$$

In this thesis, the heat demand is calculated as the heat transferred to the system to bring the mass-flow rate from 25° C and 1 bar to the operating conditions required. The heat demand is expressed in kW and the notation is q.

$$q = \dot{m} * \Delta h(p, T) \tag{3.4}$$

Where:

q is heat output as steam (kW)

$\dot{m}$ is mass-flow rate (kg/s)

$\Delta h(p, T)$ is difference of enthalpy (kJ/kg)

In the model the online operation is limited defining restrictions to the power output and the transitions:

- The power output (q) of the boiler is limited by the thermal capacity and the minimum boiler output (e.g. MW).
- The transition from one hour to the next hour (in case the time step is 1 hour) is limited by ramp up/down. This represents the maximum change in power output per hour (e.g. MW/h).

3.4.3 Shutdown

The natural gas boiler is considered shut down when the burner is switched off. The shutdown of the boiler is limited by thermal stress caused by the change in temperature [Taler et al., 2014]. In this master thesis the process is simplified considering that the burner can switch off from one hour to the next hour. In the case of the electric boiler, it is considered that the boiler shuts down when the boiler is switched off and the power is disrupted.

3.4.4 Charge and Discharge

The steam accumulator operation is simplified into charge and discharge. The steam accumulator operation was modelled in [Nielsen et al., 2016] for the Danish district heating. In the hybrid boiler system when the steam accumulator is charging steam can come from the natural gas boiler or/and the electric boiler. The discharge of the steam is released to the demand. The steam accumulator cannot charge and discharge at the same time. In addition, the steam charged/discharged at every time step (e.g. hour) is limited by the maximum heat flow (e.g. MW/h) that can go to and from the steam accumulator.

3.5 OPERATION COSTS

The performance of the hybrid system is determined by the costs incurred during the operation. The operation costs are defined by the production costs and the cold start-up costs. The production costs include: electricity price, natural gas price and CO_2 emission costs.

3.5.1 Production Costs

- Electricity price. In the industry the electricity is usually bought through long-term contracts. In this thesis we assume that the electricity is bought in the Day-ahead market and therefore the operation of the hybrid system will depend on the hourly prices of electricity in the Day-ahead market. The hybrid boiler can participate in other markets (e.g. intraday market, imbalance market, etc.) however in this master thesis we focus on the Day-ahead market. In the Day-ahead market buyers and suppliers bid one day in advance. Once the market closes, the results from matching the supply and demand are sent to the bidders. In the model it is assumed that the industry has perfect foresight of the prices and the operation of the boiler is scheduled according to these prices.

- Natural gas price. In the Netherlands the gas is traded through TTF (Title Transfer Facility) which is a hub where to buy and sell gas. Reference prices for spot market are published in Powernext Commodities Market Notices [PEGAS, 2019a,b].
- CO_2 emission costs. The industries participates in the EU ETS (European Emission Trading System) where the emissions allowances are traded. The emission allowances represent the right to emit a specific volume of greenhouse gases. Supply and demand determines the price of the emission allowances [NEa (Dutch Emissions Authority), 2019]. Therefore direct emissions from the natural gas boiler incur in costs. The emissions from the natural gas boiler are calculated taking into account the fuel consumed and the emission factor of the fuel [**?**]. The emission factor for natural gas in the Netherlands is 56.6 kg CO_2/GJ and the Net Calorific Value of the natural gas is 31.65 MJ/Nm^3 [Zijlema, 2019].

$$Emissions = Fuel * NCV * EF \tag{3.5}$$

Where:

Fuel is volume of fuel (Nm^3).

NCV is Net Calorific Value (GJ/Nm^3)

EF is emission factor (kg of CO_2 per GJ of fuel).

3.5.2 Cold start-up costs

The total energy consumed during the cold start-up can be estimated as the energy required to bring the water volume in the boiler to the operating conditions of temperature and pressure. This energy is estimated with the difference of enthalpies of the water at 25 ○C and 1 bar and the steam at the conditions required.

$$E_{water} = m * \Delta h(p, T) \tag{3.6}$$

In addition, the heat loss (E_{loss}) during the start-up process of the boiler is estimated. This heat loss is approximated considering that part of the heat applied to the boiler is stored in the steel structure (e.g. tubes, walls). This heat loss is estimated using the lumped-capacity model for transient heating [Bejan and Kraus, 2003]. The lumped-capacity approach states that when a solid is internally heated assuming that there is no external cooling, the solid experience a constant rise in temperature according to Equation 3.7 [Bejan and Kraus, 2003] . This approach assumes that all the mass of the solid is represented by one temperature.

$$\frac{dT}{dt} = \frac{q}{mc}(K/s) \tag{3.7}$$

The heat loss is estimated with the mass of steel, the specific capacity (c_p) of the steel and the temperature increase of the steel (see Equation 3.8). In order to estimate the heat loss, we assume that the steel structure reaches the same temperature as the steam produced. The heat loss to the exterior is neglected as well as efficiency of the combustion in the case of the natural gas boiler.

$$E_{loss} = c_p * m * \Delta T \tag{3.8}$$

The cold start-up costs at time t ($C_{SU,t}$) is calculated as the cost to produce the total energy consumed during the start-up (E_{SU}) process. The energy price (p_t) considered is the price for the hour in which the boiler is switched on.

$$E_{SU} = E_{water} + E_{loss} \tag{3.9}$$

$$C_{SU,t} = p_t * E_{SU} \tag{3.10}$$

3.6 ECONOMIC PARAMETERS

The economic parameters are used to calculate the levelised cost of the steam generated (LCOP). The economic parameters considered for each component are the nominal investment, the fixed O&M and the lifetime (see Table 3.2). In addition the discount rate is included.

The hybrid boiler systems include different units with different economic parameters. The economic parameters for the hybrid boiler are estimated as the sum of the investment costs of each component. The same principle is applied to the fixed O&M. The lifetime of the hybrid boiler is approximated at the lowest lifetime of the components, in this case it is the electric boiler which is 20 years. The lifetime of storage is assumed to be the same as the natural gas boiler, 25 years (data about lifetime was not found). This assumption is based on that steam accumulators work together with boilers so that to increase the lifetime of the later in case of variable steam demand.

Table 3.2: Economic parameters

Parameter	Value	Unit	Reference
Natural gas boiler			
Nominal investment	0.05	M€/MW	[Energistyrelsen, 2016]
Fixed O&M	1,900	€/MW/year	[Energistyrelsen, 2016]
Lifetime	25	years	[Energistyrelsen, 2016]
Electrode boiler			
Nominal investment	0.06	M€/MW	[Energistyrelsen, 2016]
Fixed O&M	1,020	€/MW/year	[Energistyrelsen, 2016]
Lifetime	20	years	[Energistyrelsen, 2016]
Steam Accumulator			
Nominal investment	70	€/kWh	[Gibb et al., 2018; EIFER, 2019]
Discount rate (r)	7	%	Assumed

4 MATHEMATICAL FORMULATION

In this thesis the techno-economic performance of hybrid boiler systems is assessed. To this end, the operation of the hybrid systems is simulated for which a model is required. In this chapter, a deterministic model is formulated using mixed-integer linear programming to optimise the operation of the hybrid boiler system. This approach was used in [Nielsen et al., 2016] to optimise the operation of a hybrid system which included a CHP unit, a heat pump, an electric boiler and a steam accumulator. This system was optimised to deliver heat to the heat district minimizing the total operation costs [Nielsen et al., 2016]. Similarly, the hybrid boiler system has to deliver heat to satisfy the demand of heat in a production process. Therefore, the formulation in the paper mentioned is used as a reference to formulate the hybrid boiler system.

The technical restrictions of the boilers determine their ability to respond to the price signals. Cold start-up restrictions are not included in [Nielsen et al., 2016] therefore, the formulation presented in [Morales-España et al., 2013] for thermal units in power systems is also used as a reference. Thermal units (i.e. coal power plant) use the combustion of a fuel (i.e. in boilers) to produce heat that it is further transform into electricity. Both papers will be used to present the mathematical formulation of the problem.

In order to formulate the problem the parameters and the decision variables are defined in Table 4.1. The parameters are presented in capital letters and the decision variables are presented in lower case letters. The nomenclature of the problem is presented considering that the time step $\Delta t = 1$ hour as the market analysed in this thesis is the Day-ahead market in which the prices change hourly. This formulation can be easily adapted to other markets changing the time step and consequently the units of the parameters and the decision variables (i.e. from MW/h to MW/min). The model can be divided in two steps. The first step consists of an optimisation problem for which the simulation of the hybrid systems is performed to minimise the operation costs. The operation of the hybrid system is then assessed with the performance indicators.

In this thesis, two hybrid boiler systems are considered 1) including a steam accumulator, 2) excluding the steam accumulator. The mathematical formulation changes for each hybrid boiler system. In this section the formulation of the optimisation problem and the performance indicators are presented for the hybrid boiler system including a steam accumulator. In Appendix A this formulation is adapted for the hybrid boiler system excluding the steam accumulator. In addition, the performance of the hybrid boiler systems is compared to a natural gas boiler, the electric boiler and the electric boiler with storage. The models for these systems can be found in Appendix A.

Table 4.1: Nomenclature for indices, parameters and variables

NOMENCLATURE	
Indices and Sets	
b$\in \{ng, eb\}$	Boiler units (ng: natural gas, eb: electric boiler)
d,b	Boiler unit to demand
d,s	Storage to demand
s	Storage
s,ng	Natural gas boiler to storage
s,eb	Electric boiler to storage
t$\in$ T	Hourly periods from 1 to T hours
Parameters	
C^{CO_2}	CO_2 price for the heat production from natural gas(€/MWh)
C_t^{ng}	Natural gas price in hour t (€/MWh)
C_t^{ele}	Electricity price in hour t (€/MWh)
$C_{su,t}^b$	Cold start-up cost for boiler unit b at hour t (€)
D_t	Steam demand in hour t (MW)
E_{max}^s	Maximum energy capacity of the storage (MWh)
Q_{max}^b	Maximum heat output of the boiler unit b (MW)
Q_{min}^b	Minimum heat output of the boiler unit b (MW)
R_{up}^b	Ramp-up rate of the boiler unit b (MW/h)
R_{down}^b	Ramp-down rate of the boiler unit b (MW/h)
TD^b	Minimum downtime of the boiler unit b (h)
S_{flow}	Maximum heat that can flow from and to the storage (MW)
S_{loss}	Coefficient of energy loss during storage process
η^b	Total efficiency of the boiler unit b
Variables	
A. Positive and Continuous variables	
$q_t^{d,b}$	Heat from the boiler unit b to demand in hour t (MW)
$q_t^{d,s}$	Heat from storage to demand in hour t (MW)
$q_t^{s,b}$	Heat from the boiler unit b to storage in hour t (MW)
s_t	Energy stored in the steam accumulator in hour t (MWh)
B. Binary variables	
u_t^b	Boiler unit b status in hour t which is 1 if the boiler is on and 0 otherwise
v_t^b	Boiler unit b start-up status in hour t which is 1 if the boiler starts-up and 0 otherwise
w_t^b	Boiler unit b shutdown status in hour t which is 1 if the boiler shuts down and 0 otherwise

4.1 OPTIMISATION

- The objective function

  The hybrid boiler system seeks to minimise the operation costs which are defined by the production costs and the cold start-up costs explained in Section 3.5.

  $$\min \sum_{t \in T} c_t^{tot} \tag{4.1}$$

  $$\begin{aligned} c_t^{tot} = (C_t^{ng} + C^{CO2})(q_t^{d,ng} + q_t^{s,ng})\Delta t/\eta^{ng} + C_{su}^{ng} v_t^{ng} \\ + C_t^{ele}(q_t^{d,eb} + q_t^{s,eb})\Delta t/\eta^{eb} + C_{su}^{eb} v_t^{eb} \end{aligned} \tag{4.2}$$

  In the first term of the Equation 4.2, the costs related to the heat produced from natural gas are formulated. The costs related to the natural gas consumption are the price of natural gas at every time step in addition to the CO_2 price ($C_t^{ng} + C^{CO2}$). The decision variable is the heat (e.g. MW) produced from natural gas at every time step. The heat from natural gas can be delivered to the storage and to the demand, therefore two decision variables are required ($q_t^{d,ng} + q_t^{s,ng}$). The costs are in terms of euros per energy (e.g. €/MWh). Therefore the total fuel consumed at every time step is calculated with the efficiency of the boiler, the time step and the heat delivered (see Equation 4.3). Similar approach is applied to the production costs related to the heat from electricity. The decision variables are the heat to the storage and the heat to the demand ($q_t^{d,eb} + q_t^{s,eb}$) produced from electricity at every time step.

  $$Energy_t = (q_t^{d,b} + q_t^{s,b})\Delta t/\eta^b \qquad \forall t,\ \forall b \tag{4.3}$$

  Finally, the costs due to the cold start-up are formulated in Equation 4.2. The cold start-up cost related to the natural gas boiler (C_{su}^{ng}) is multipled by the start-up status of the boiler at every time step which is represented by a binary variable (v_t^{eb}). Similar approach is applied for the electric boiler.

- Heat balance

  Equation 4.4 forces the heat balance at every hour. In this thesis we assume that the steam demand must be fulfilled at every time. Consequently, the sum of the heat delivered from the boilers and the storage is equal to the demand at every hour [Nielsen et al., 2016].

  $$\sum_b q_t^{d,b} + q_t^{d,s} = D_t \qquad \forall t,\ \forall b \tag{4.4}$$

- Ramping limits

  The ramping constraints apply for the boilers. This restrictions imply that the boilers can only increase or decrease their heat production by a limited amount in a time step. In this thesis we work with time steps of one hour. For hourly steps the ramping constraints are neglected, however they are included in the formulation so that the model can be adapted to other time steps [Morales-España et al., 2013; Nielsen et al., 2016].

$$(q_t^{d,b} + q_t^{s,b}) - (q_{t-1}^{d,b} + q_{t-1}^{s,b}) \leq R_{up}^b \qquad \forall t,\ \forall b \tag{4.5}$$

$$(q_{t-1}^{d,b} + q_{t-1}^{s,b}) - (q_t^{d,b} + q_t^{s,b}) \leq R_{down}^b \qquad \forall t,\ \forall b \tag{4.6}$$

- Logical constraint

  The logical constraints ensure that the variables v_i and w_i, which represents the start-up and shut-down state respectively, take the corresponding values according to the boiler state (u_i) [Morales-España et al., 2013].

$$u_t^b - u_{t-1}^b = v_t^b - w_t^b \qquad \forall t,\ \forall b \tag{4.7}$$

- Minimum downtime

  Cold startups in boilers require time to reach the right conditions before it can produce steam. The Minimum downtime constraint ensures that the boiler will be allowed to switch on (cold start-up) only if it has been switched off for the minimum time required by the cold start-up [Morales-España et al., 2013].

$$\sum_{i=t-TD^b+1}^{t} w_i^b \leq 1 - u_t^b \qquad \forall t \in [TD^b, T],\ \forall b \tag{4.8}$$

- Minimum heat output

  The boilers require a minimum heat production when they are operating. In particular the minimum heat production of natural gas boilers is determined by a stable combustion. The minimum operation is important to avoid switching off frequently which would lead to a cold start-up. The cold start-up incurs into costs, time and maintenance (see Section 3.4).

$$q_t^{d,b} + q_t^{s,b} \geq u_t^b Q_{min}^b \qquad \forall t,\ \forall b \tag{4.9}$$

- Capacity constraints

  The maximum heat production is limited by the maximum capacity of the boilers. Similarly the storage capacity is limited by the maximum energy that can store [Nielsen et al., 2016].

$$q_t^{d,b} + q_t^{s,b} \leq u_t^b Q_{max}^b \qquad \forall t,\ \forall b \tag{4.10}$$

$$s_t \leq E_{max}^s \qquad \forall t \tag{4.11}$$

- Storage operation

  The storage is characterised by the heat level at every point in time. In this thesis the heat level (MWh) is determined every hour. The heat level is formulated as the previous heat level (MWh) plus the net heat flow (MWh) to the storage. The net heat flow (MWh) is the amount of heat from the boilers to the storage minus the heat extracted from the storage to the demand. The parameter S_{loss} is used to introduce a heat loss related to the storage process [Nielsen et al., 2016].

$$s_t = s_{t-1} + q_t^{s,ng} \Delta t + q_t^{s,eb} \Delta t - S_{loss} q_t^{d,s} \Delta t \qquad \forall t \tag{4.12}$$

In addition, the amount of heat that can flow to and from the storage is limited [Nielsen et al., 2016].

$$q_t^{d,s} \leq S_{flow} \qquad \forall t \tag{4.13}$$

$$\sum_b q_t^{s,b} \leq S_{flow} \qquad \forall t\ \forall b \tag{4.14}$$

4.2 PERFORMANCE INDICATORS

Performance indicators are defined to assess the operation of the hybrid systems. Moreover the performance indicators facilitates the comparison between the hybrid boiler systems and other technologies (e.g. natural gas, electric boiler). The performance indicators were defined the methodology in Chapter 2. In this section, the performance indicators are formulated:

- Total operation costs include the production costs derived from the natural gas and/or electricity consumption plus the costs incurred during cold start-ups.

$$C_{total} = \sum_{t \in T} c_t^{tot} \tag{4.15}$$

- The LCOP is an economic performance indicator which estimates the price of the steam generated (levelised costs of the steam).

$$LCOP = \frac{\sum_{i=1}^{n} \frac{I_i + O_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{P_i}{(1+r)^i}} \tag{4.16}$$

Where:

$LCOP$ is levelised cost of product (€/ton steam)

I_i is investment costs in year i (€/a)

O_i is operational costs in year i (€/a)

r is real discount rate, (%)

P_i is production of steam in year i (steam)

- CO_2 direct emissions include the CO_2 emissions released from the natural gas boiler (ton).

$$CO_2 = \frac{\sum_{t \in T}((q_t^{d,ng} + q_t^{s,ng}) * \Delta t + E_{SU}^{ng} * v_t^{ng})(MWh)}{\eta^{ng}} * \frac{3.6(GJ/MWh) * 56.6(kg/GJ)}{1000(kg/t)} \tag{4.17}$$

- Total system efficiency represents the total energy output (steam) from the hybrid boiler divided by the total energy input to the hybrid boiler. The total energy input includes the electricity and natural gas bought (input) to produce the steam in the hybrid boiler system. Equation 4.18 includes the energy using the heat supply to the demand and the energy required (E_{SU}) during the the start-ups.

$$E_{Input} = \sum_{t \in T}[(q_t^{d,ng} + q_t^{s,ng})\Delta t/\eta^{ng} + (q_t^{d,eb} + q_t^{s,eb})\Delta t/\eta^{eb} + E_{SU}^{ng} * v_t^{ng} + E_{SU}^{eb} * v_t^{eb}] \tag{4.18}$$

Finally the efficiency is calculated.

$$\eta_{hybrid} = \frac{\sum_{t \in T} D_t}{E_{Input}} \tag{4.19}$$

5 CASE STUDY: 2030 SCENARIO

Hybrid boiler systems are an already available technology which can take advantage from the fluctuation of electricity prices. As mentioned in the literature review the fluctuation of the prices is expected to increase by 2030 [Van Hout et al., 2014] [Sijm et al., 2017]. In addition hourly electricity prices for 2030 were facilitated by PBL. Therefore, a scenario for 2030 is built to analyse the performance of the hybrid boiler and eventually compare this performance with alternative configurations: natural gas boilers, electric boilers and electric boiler with storage.

In this section the scenario, for which the techno-economic performance will be assessed, is described. First, the Apollo Vredestein industry is selected to characterise the steam demand required by a production process. This industry was selected because data about the steam demand for the production process as well as the capacity of the boiler were available. In addition the heat demand in this industry is representative of the medium heat temperature demand (200^{o}C) [Chikri et al., 2019]. This industry manufactures tyres and the production process is described in [Chikri et al., 2019]. Second, the parameters of the hybrid boiler system described in Section 3.3 are determined. Third, the model is adapted to the case study presented (e.g. some restrictions might be irrelevant). Finally, the operation costs are characterised for this case-study.

5.1 DEMAND AND TECHNICAL PARAMETERS

The case-study selected to simulate the steam demand is the steam consumption in a tyre manufacturer. The manufacturing process requires steam for the vulcanisation of the tyre which is a thermal treatment [Chikri et al., 2019]. The following assumptions are considered for the demand:

- It is assumed that the steam required for the process is saturated steam. The pressure of the the steam produced is 14.5 bars [Chikri et al., 2019]. The temperature corresponding to a pressure of 14.5 in case of saturated steam is approximately 200°C. In [Chikri et al., 2019] the temperature of the process is 190°C however this temperature is lower than the saturated temperature. In order to be coherent with the case study in which saturated steam is assumed, the temperature used is 200 °C. The specific enthalpy of the operating point $h(14.5bar,\ 200°C) = 2,792(kJ/kg)$ [TLV, 2019] and the reference point $h(1bar,\ 25°C) = 104.8$ [The Engineering Toolbox, 2019b] are used to calculate the heat demand (see Equation 5.1).

- The mass-flow rate of the steam is assumed to be 10 t/hour [1]. The demand is calculated according to Equation 5.1. The estimated demand is approximately 7.5 MW considering the difference of enthalpies and $\dot{m}$=10 ton/h.

$$D = \dot{m} * (h(14.5bar,\ 200°C) - h(1bar,\ 25°C)) \tag{5.1}$$

- The factory works 24/7 during the entire year.
- The steam demand cannot be interrupted.
- The steam delivered should be at the required conditions. The conditions of the steam could impact the production process however in this model we considered that the steam is always delivered at the required conditions.

The boiler parameters are selected according to the demand described in [Chikri et al., 2019], literature review and estimations. Other parameters as the capacity of the electric boiler are assumed.

- According to [Chikri et al., 2019] the capacity of the boiler is 9 MWth.
- The electric boiler capacity is assumed to be the same as the natural gas boiler. In the studies [Akzo Nobel, 2018] [Verschuur, 2019] the electric boiler considered had the same capacity as the natural gas boiler.
- The minimum boiler output parameters were retrieved from literature review and boilers technical data sheets (see reference in Table 5.1).
  - The minimum output of the natural gas boiler is calculated as the 10% of the maximum capacity according to the description in Section 3.3.
  - The minimum output of electric boiler is considered 5% of the maximum capacity according to the description in Section 3.3.
- The boilers are assumed to be able to go from minimum load to maximum load in less than one hour therefore the ramp up/down parameters are neglected. The ramp up/down are applied when the boilers are online.
  - In the case of the gas boiler it is assumed that it can go from the minimum heat output to the required condition in 10 min [Romero-Anton et al., 2018]. Moreover it is considered that the boiler can go from maximum load to zero instantaneously therefore the ramp-down is not considered.
  - According to [Nielsen et al., 2016] the electric boiler can go from zero to maximum load in minutes or seconds. This also applies when it goes from full load to zero. Therefore ramping constraints for the electric boiler are neglected.
- The start-up time for the gas boiler is assumed. However for the electric boiler the start-up time is retrieved from literature review.

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[1] This mass-flow rate is approximated from the total natural gas consumed in the vulcanisation process in one year [Chikri et al., 2019], the efficiency of the boiler, the difference in enthalpy (Δh) and assuming that the boiler worked 8760 h. The estimated mass-flow rate estimated is 10.7 t/h. For this thesis the mass-flow rate is approximated to 10 t/h

  - The natural gas boiler takes 2 hours to start-up.
  - The electric boiler is assumed to start-up in less than 1 hour. According to [PARAT, 2019] the boiler can go from cold to full load in 5 minutes.

- Water volume parameter is required to calculate the start-up costs defined in Section 3.5.2. In the case of the electric boiler the water volume is not considered as the start-up costs are assumed to be zero [Energistyrelsen, 2016]. The water volume for the gas boiler is retrieved from boiler technical specifications with similar capacities as the boilers required in the production process.
- The storage capacity is assumed to be 10 MWh.
- The storage can be fully charge/discharge in one hour therefore in this case the maximum heat flow (S_{flow}) restriction does not apply.
- The heat loss coefficient is retrieved from [Nielsen et al., 2016].

Table 5.1: Parameters selected to characterise the technologies

Parameters	Symbol	values	Unit	Reference
Natural gas boiler				
Thermal Capacity	Q_{max}	9	MW	[Chikri et al., 2019]
Minimum Boiler Output	Q_{min}	0.9	MW	[Romero-Anton et al., 2018] [Bahadori, 2016] [ClearBrooks, 2019]
Cold start-up time	TD	2	h	Assumed
Ramp-up	R_{up}	-	MW/h	-
Ramp-down	R_{down}	-	MW/h	-
Water Volume	V	11	m^3	[Cannon Bono Energia, 2013]
Boiler Efficiency	η	90	%	[Cannon Bono Energia, 2013]
Electric boiler				
Thermal Capacity	Q_{max}	9	MW	Assumed
Minimum Boiler Output	Q_{min}	0.45	MW	[CleaverBrooks, 2013] [RVO, 2015] [PARAT, 2019]
Cold start-up time	TD	-	h	
Ramp-up	R_{up}	-	MW/h	-
Ramp-down	R_{down}	-	MW/h	-
Water Volume	V	-	-	-
Boiler Efficiency	η	99	%	[PARAT, 2019] [CleaverBrooks, 2013]
Storage Parameters				
Storage capacity	E^s_{max}	10	MWh	Assumed
Heat flow	S_{flow}	-	MW	-
Heat loss coefficient	S_{loss}	1.05	-	[Nielsen et al., 2016]

5.2 OPERATION COSTS

5.2.1 Production Costs

In December 2018 the draft Climate Agreement (Ontwerp Klimaatakkord) was released. This document was a result of negotiations to take measures and instruments in order to reduce 49% of greenhouse gas emissions by 2030. In [PBL, 2019b] the cost-effectiveness of the policies proposed in the draft agreement were analysed. In this document a scenario for 2030 according to the draft agreement is assumed and it is called the OKA (ontwerp Klimaatakkord) scenario. In this thesis the OKA scenario is assumed for the model. According to this scenario the natural gas price and the CO_2 price for 2030 are defined.

The electricity prices are expected to increase in 2030 as well as the volatility of the prices. The volatility is particularly relevant for the hybrid boiler systems due to the fact that this technology takes advantage of the fluctuations of the prices (the system consumes electricity during hours in which the prices are low). Therefore, the fluctuations of electricity prices are important to analyse the operation of the hybrid boiler system. Hourly electricity prices for 2030 are retrieved from the COMPETES model. This model simulates the European electricity market.

The COMPETES model was run for the OKA scenario. The hourly electricity prices resulting from the model were provided by PBL to be used as an input to the hybrid boiler model. In Figure 5.1 the prices from COMPETES for 2030 year are presented. The first day of simulation is 1^{st} of January. In addition the electricity prices for 2018 are also presented.

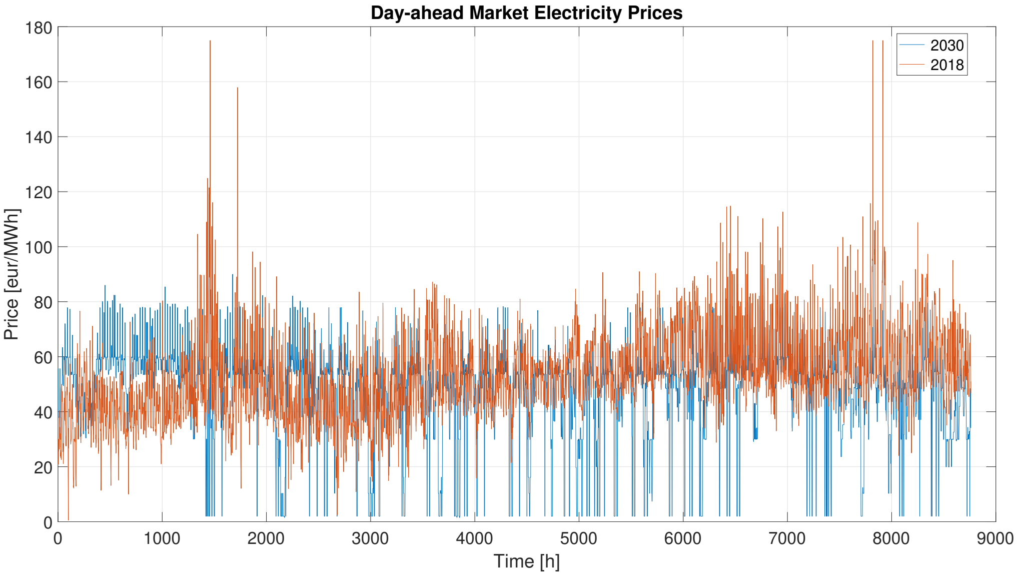

Figure 5.1: Day-ahead electricity prices for Netherlands in 2018 [ENTSO-E, 2018] and 2030 (COMPETES).

The wholesale natural gas price is retrieved from the OKA scenario description in [PBL, 2019b]. In the document an average price of €25/MWh is estimated for 2030. To simulate the monthly fluctuations of the natural gas price for 2030, the fluctuation of natural gas prices in Germany in 2018 are used [PEGAS, 2019a] increasing the average of 2018 to €25/MWh (see Figure 5.2). Finally, in the OKA scenario the CO_2 price for 2030 estimated was €46.3/t. The emission factor of natural gas used to estimate the CO_2 price per MWh of natural gas consumed (C^{CO_2}) (€/MWh) is 0.2 t/MWh.

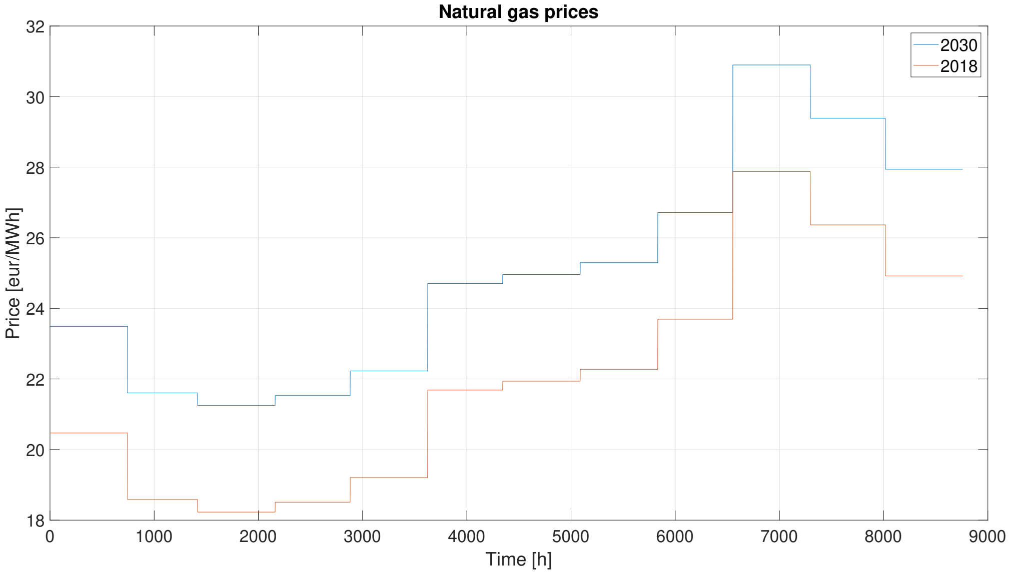

Figure 5.2: Natural gas prices in Germany for 2018 [PEGAS, 2019a] and 2030 (OKA scenario).

5.2.2 Cold start-up costs

The cold start-up costs are described in Section 3.5.2. The parameters presented in Table 5.2 are used to estimate the energy required (E_{SU}) during the start-ups. The energy estimated is used in the optimisation problem to calculate the start-up costs which depends on the price of the natural gas when the boiler is switched on.

Table 5.2: Cold start-up energy considered for the case study

Parameter	Value	Unit	Reference
M^{ng}_{water}	11	m^3	[Cannon Bono Energia, 2013]
M^{ng}_{steel}	24,300	kg	[Cannon Bono Energia, 2013]
$\Delta h(14.5bar, 200°C)$	2,687	kJ/kg	[The Engineering Toolbox, 2019b] [TLV, 2019]
C_p^{steel}	0.49	kJ/(kg °C)	[The Engineering Toolbox, 2019a]
ΔT	(200-25)	°C	-
E_{SU}	8.8	MWh	Equation 3.6

5.3 ECONOMIC PARAMETERS

The investment costs of every component in a hybrid boiler system are presented in Table 3.2 in Section 3.6. The total investment costs and fixed O&M for the system of the case study are presented in Table 5.3. For the hybrid boiler systems the investment costs of every component are added up. The lifetime considered for the four cases is 20 years.

Table 5.3: Calculated economic parameters for the case study

Parameter	Value	Unit
HB		
Nominal investment	990	k€
Fixed O&M	26,280	€
HBS		
Nominal investment	1,690	k€
Fixed O&M	26,280	€
Natural gas boiler		
Nominal investment	450	k€
Fixed O&M	17,100	€
electric boiler		
Nominal investment	540	k€
Fixed O&M	9,180	€

5.4 MODEL CONSTRAINTS

According to the technology parameters and assumptions listed, the formulation for the HBS system is adapted to the case study. The adapted formulation for the HB system, the natural gas boiler, the electric boiler and, the electric boiler with storage are presented in Appendix B.

The total production (P) of steam to calculate the LCOP is obtained from the total energy demand of the year, in this case $Total\ demand = 7.5MW\ x\ 8760h$. The total energy demand is converted into tonnes of steam. The energy in 1 tonne of steam at the temperature and pressure of the case scenario is 0.74 MWh (see Table 5.4).

5.4.1 Hybrid boiler system HBS

Table 5.4: Formulation of the hybrid system with storage for the Scenario 2030.

Optimisation	
The objective function	$\min \sum_{t \in T} c_t^{tot}$ $c_t^{tot} = (C_t^{ng} + 0.2 * 46.3)(q_t^{d,ng} + q_t^{s,ng}) * 1/0.90$ $+ 8.8 * \ C_t^{ng} v_t^{ng} + C_t^{ele}(q_t^{d,eb} + q_t^{s,eb}) \ * 1/0.99$
Heat balance	$q_t^{d,ng} + q_t^{d,eb} + q_t^{d,s} = 7.5 \qquad \forall t, \ \forall b$
Logical constraint	$u_t^b - u_{t-1}^b = v_t^b - w_t^b \qquad \forall t, \ \forall b$
Minimum downtime	$\sum_{i=t-2+1}^{t} w_i^{ng} \leq 1 - u_t^{ng} \qquad \forall t \in [2, 8760]$
Minimum heat output	$q_t^{d,ng} + q_t^{s,ng} \geq 0.9 \ * u_t^{ng} \qquad \forall t$ $q_t^{d,eb} + q_t^{s,eb} \geq 0.45 \ * u_t^{eb} \qquad \forall t$
Capacity constraints	$q_t^{d,ng} \leq 9 \ * u_t^b \qquad \forall t$ $q_t^{d,eb} + q_t^{s,eb} \leq 9 \ * u_t^{eb} \qquad \forall t$ $s_t \leq 10 \qquad \forall t$
Storage operation	$s_t = s_{t-1} + q_t^{s,ng} * 1 + q_t^{s,eb} * 1 - 1.05 \ q_t^{d,s} * 1 \qquad \forall t$
Performance Indicators	
Total operation costs	$C_{total} = \sum_{t \in T} c_t^{tot}$
LCOP [2]	$LCOP = \frac{\frac{I + C_{total}}{(1+0.07)^1} + \sum_{i=2}^{20} \frac{C_{total}}{(1+0.07)^i}}{\sum_{i=1}^{20} \frac{7.5 * 8760/0.74}{(1+0.07)^i}}$
CO_2	$CO_2 = \frac{\sum_{t \in T}((q_t^{d,ng} + q_t^{s,ng}) * 1 + 8.8 * v_t^{ng})(MWh) * 3.6(GJ/MWh) * 56.6(kg/GJ)}{0.90 * 1000(kg/ton)}$
Total energy input	$E_{Input} = \sum_{t \in T}[(q_t^{d,ng} + q_t^{s,ng}) * 1/0.9 + (q_t^{d,eb} + q_t^{s,eb}) * 1/0.99$ $+ 8.8 * v_t^{ng}]$
Total system efficiency	$\eta_{HBS} = \frac{7.5 * 8760}{E_{Input}}$

5.5 ROLLING HORIZON

The rolling horizon is implemented following the steps in the diagram in Figure 5.3.

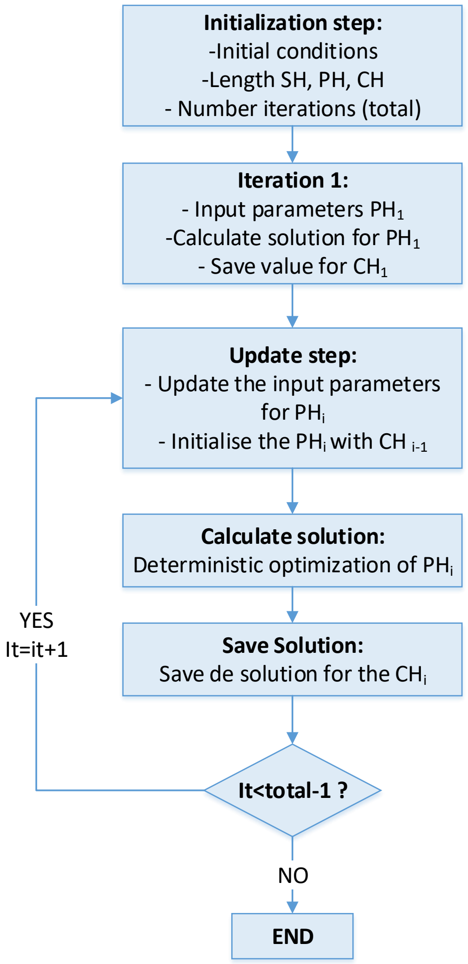

Figure 5.3: Flowchart of the rolling horizon method.

The initialisation of the model and the length of the intervals are presented in Table 5.6. The parameters for the rolling horizon were selected calculating the costs for different scenarios. First 168 hours (1 week) for the Control Horizon are selected. Then the model is simulated varying the Prediction Horizon. In the first case the Prediction Horizon was 1 week and the overlap was 0. Then the PH was increased by 1 week every time. Increasing the PH will impact the solution until a certain length. At this point the solution does not change and indicates that longer PH does not influence the solution of the optimisation (e.g. increasing the period of forecast will not affect the optimisation results in for the control horizon).

In table 5.5 it can be seen the total costs of each hybrid boiler system simulated for the whole year considering different PH with a fix CH of 1 week. The first row corresponds with a PH of 1 week and the total operation costs are presented. In the subsequent rows which correspond with longer PH the costs presented are the variation respect to total costs for a PH=1 week. It is observed that for the HB increasing the PH does not reduce significantly the the total costs moreover for PH longer than 2 weeks the solution does not change. In the case of the HBS it can be seen that the PH has a slightly higher impact. However the impact is still low in comparison with the total costs. The solution of the HBS is almost constant with PH longer than 3 weeks.

Table 5.5: Solution of the optimisation for different PH.

Prediction Horizon	Total costs HB	Total costs HBS
1 week	2,301,430	2,270,779
2 weeks	-2,376	-2,749
3 weeks	-2,376	-2,758
4 weeks	-2,376	-2,753

In this master thesis we consider perfect foresight therefore 3 weeks of PH are selected as it is closer to the optimal solution. The parameters for the rolling horizon are presented in Table 5.6.

Table 5.6: Initialisation of the variables and rolling horizon parameters

Initial Conditions	Value
u_{ng}, u_{eb}	1,0
w_{ng}, w_{eb}	0,0
v_{ng}, v_{eb}	0,0
q_{ng}, q_{eb}	7.5,0
Parameter Rolling Horizon	**Value**
Scheduling Horizon	8760 h
Prediction Horizon	504 h
Control Horizon	168 h
Overlap	336 h
Iteration	53

5.6 MODEL VERIFICATION

The verification is a procedure to determine if the model has been implemented correctly. This process checks if the model developed matches with the description of the hybrid boiler systems (conceptual model). The verification is analysed for the hybrid boiler with storage system. We assumed that if this model is verified also the hybrid boiler without storage is verified, as the later represents a simplified version of the former.

The model is verified first checking that the hourly operation of the hybrid system respects the technical restrictions of the system described. Secondly, the model is verified looking at the operation of the model during extreme scenarios. The second verification is performed assuming extreme scenarios in which the boiler would work exclusively with natural gas or exclusively with electricity. A period with high electricity fluctuations is selected for the model verification: Week 9. In Figure 5.4 the heat flow between the boilers, the demand and the storage is presented. This diagram is used as a reference to present the hourly operation of the models in the graphs.

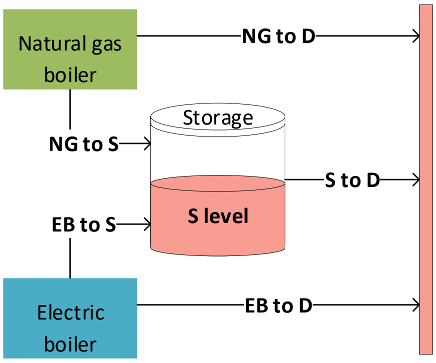

Figure 5.4: Heat flow legend.

5.6.1 Technical restrictions

In this section we verify that the model satisfies all the restrictions defined in the model formulation (see Section 5.4.1). The hourly operation of the boilers and the storage is presented in Figure 5.5. In Figure 5.5 **(a)** the costs of producing the steam from electricity and natural gas are displayed.

The heat delivered at every hour to the demand from the HBS system is presented in Figure 5.5 **(b)**. The heat to the demand can come from the natural gas boiler, the electric boiler and the storage. In Figure 5.5**(c)** the heat from and to the storage is presented as well as the energy level (MWh) of the storage at every hour.

In Figure 6.2 **(b)** and **(c)** the left 'y' axis represents the heat in MW and the 'x' axis time in hours. The legend of the heat flows in **(b)** and **(c)** corresponds with the diagram in Figure 5.4. In addition, in Figure 6.2 **(c)** the right 'y' axis represents the energy level of the storage in MWh.

Finally, a sign convention for the heat flow is introduced. In Figure 6.2 **(b)** the heat flow delivered to the demand is considered positive. In Figure 6.2 **(c)** the heat flow to the storage (i.e. charging) is positive and the heat flow from the storage (i.e. discharging) is negative.

Figure 5.5: Hourly operation of the HBS system.

It can be seen that in the first part of the week the boiler produced steam from natural gas as the cost was lower than the steam from electricity (Figure 5.5 **(a)**). From t=1417 the cost of producing steam from electricity decreases and becomes cheaper than natural gas. Accordingly the production of steam in Figure 5.5 **(b)** switches to electricity maintaining the natural gas boiler at the minimum heat production. The technical restrictions defined in the formulation are verified:

- **Heat balance**. It can be seen in Figure 5.5 **(b)** that the heat demand is satisfied at every hour. The total heat from the HBS to the demand is 7.5 MW at every hour.
- **Logical constraint**. The logical constraints are satisfied at every hour. This can be seen in Table 5.7 in which the value of both sides of the constraint (Equation 5.2) from t=1416 to t=1434 are presented for the natural gas boiler and the electric boiler. In Figure 5.5 **(b)** it can be seen that at t=1417 the electric boiler switches on and accordingly in Table 5.7 the variation presented is $u^{eb}_{1417} - u^{eb}_{1416} = 1$.

$$u^b_t - u^b_{t-1} = v^b_t - w^b_t \qquad \forall t,\ \forall b \tag{5.2}$$

Table 5.7: Verification of the logical constraints.

	From t=1416 to t=1434																		
$u^{ng}_t - u^{ng}_{t-1}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$v^{ng}_t - w^{ng}_t$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$u^{eb}_t - u^{eb}_{t-1}$	0	1	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	-1
$v^{eb}_t - w^{eb}_t$	0	1	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	-1

- **Minimum downtime**. This restriction can not be verified in this week as the natural gas boiler does not switch off. Thorough the year, when the natural gas boiler switches off it is for periods longer than 2 hours. In order to verify that this constraint is working, the prices are modified artificially. First the CO_2 price is set to zero. In this case the cost of production of steam depends on the commodities price (electricity and natural gas) and the efficiency of the boilers. Second, the price of electricity and natural gas is modified for two consecutive hours to force the boiler to switch from natural gas to electricity and subsequently from electricity to natural gas. Due to the minimum downtime constraint if the boiler switches off it can not start again in the subsequent hour. In Table 5.8 it can be seen the prices modified for two consecutive hours. Setting the natural gas price to zero in the second hour implies that the cold start-up cost at this hour is also zero. This assures that the operation of the boiler is not affected by the cold start-up cost but only by the minimum down time restriction.

Table 5.8: Prices set for the verification of the Minimum downtime constraint.

Price	t=1351	t=1352
Natural gas	€200	€0
Electricity	€0	€200

In Figure 5.6 the hourly operation of the HB system and the HBS system are presented to verify the correct implementation of the minimum down time restriction. In Figure 5.6 **(a)** it can be seen that at t=1351 the natural gas costs are high while the electricity costs are zero. Subsequently, at t=1352 the opposite effect is observed.

Consequently, in Figure 5.6 **(b)** it can be seen that the HB system switches from natural gas to electricity, however, although the natural gas costs are very high the natural gas boiler is not switched off. The reason is that the natural gas must work at a minimum so that it is not forced to stay off for two hours as this would incur in high costs in the next hour in which the electricity price is very high.

Conversely, in the case of the HBS system (see Figure 5.6 **(c), (d)**) , the natural gas boiler is switched off at t=1350 and is switched on at t=1352. The boiler is able to switch on in t=1352 because it was switched off two hours before. During t=1350 the storage delivers the steam to the demand instead of the natural gas boiler.

- **Minimum heat output**. In Figure 5.5 **(b)** and **(c)** it can be seen that the natural gas boiler produces at least 0.9 MW when it is on. When the costs of producing steam from natural gas is higher than electricity the natural gas boiler is maintained at the minimum heat output instead of being switched off. This is due to the start-up costs related to the boiler. The operation of the boiler accords with the conceptual description in Section 3.4. Similarly, the electric boiler always produces heat higher than its minimum heat output: 0.45 MW. In the case of the electric boiler, the cold start-up costs are zero therefore when it is cheaper to produce steam with natural gas the electric boiler switches off.
- **Capacity constraints**. In Figure 5.5 **(b)** and **(c)** it can be seen that the heat produced in the boilers did not exceed 9 MW. The electric boiler reached the maximum capacity at t=1421 during which it supplies 7.5 MW to the demand (Figure 5.5 **(b)**) and 1.5 to the storage (Figure 5.5 **(c)**). In the case of the storage, in the Figure 5.5 **(c)** it can be seen that

the energy level of the storage reaches the maximum capacity of 10 MWh several times. This capacity was not exceeded.

- **Storage operation**. In Figure 5.5 **(c)** it can be seen that the storage don't charge and discharge at the same time which confirms that the implementation is correct.

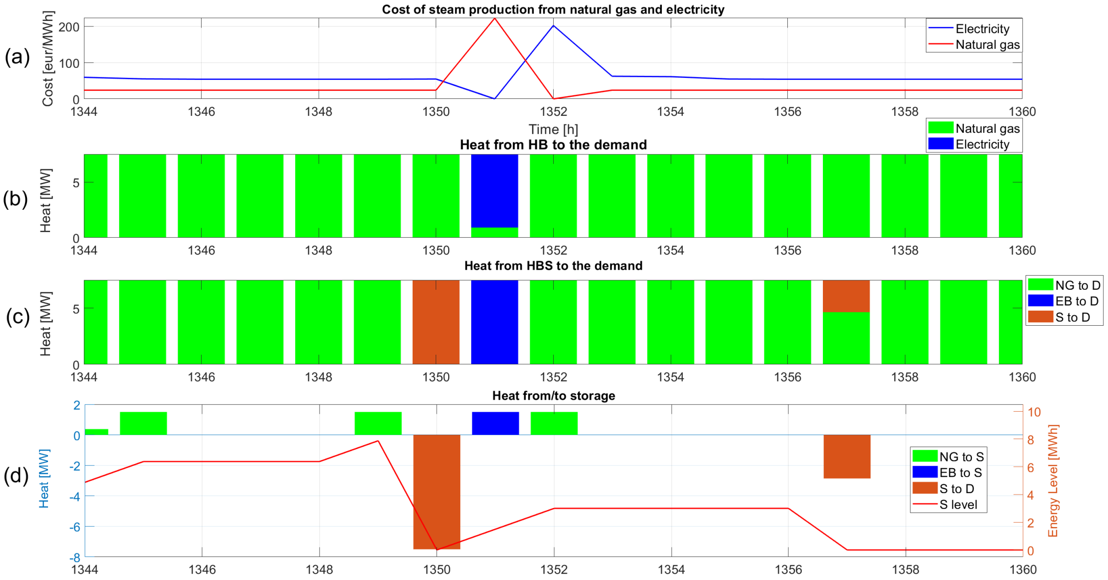

Figure 5.6: Hourly operation of the **(b)** HB system and the **(c)**,**(d)** HBS system for a scenario with **(a)** extreme fluctuation of the prices .

5.6.2 Extreme scenarios

In this section two scenarios in which the boiler would work exclusively with natural gas or electricity are simulated.

- The hybrid system works exclusively with natural gas when the costs of producing the steam from natural gas is lower than producing it from electricity. This scenario can be set reducing the natural gas price and the CO_2 price to zero. In Figure 5.7 **(a)** it can be seen that the costs of electricity are always lower than natural gas. Accordingly in Figure 5.7 **(b)** shows that the hybrid system worked exclusively with natural gas. The storage in this case is not used (see Figure 5.7) **(c)** as there are not fluctuation in the cost of natural gas prices which are set to zero.

- The hybrid system works exclusively with electricity when the costs of producing the steam from electricity are lower than producing the steam from natural gas. This scenario can be set multiplying the CO_2 price by a factor 3.5. In Figure 5.8 **(a)** it can be seen that the cost of producing steam with natural gas was higher than electricity during most of the hours. During the hours in which the costs of producing the steam with electricity are higher, the demand is supplied with steam from the storage. This steam is produced in previous hours in which the costs are lower. The hybrid system avoids the use of natural gas during the hours in which the costs of producing with this fuel are lower than electricity due to the cold start-up costs. The model operation matches with the conceptual operation of the boiler.

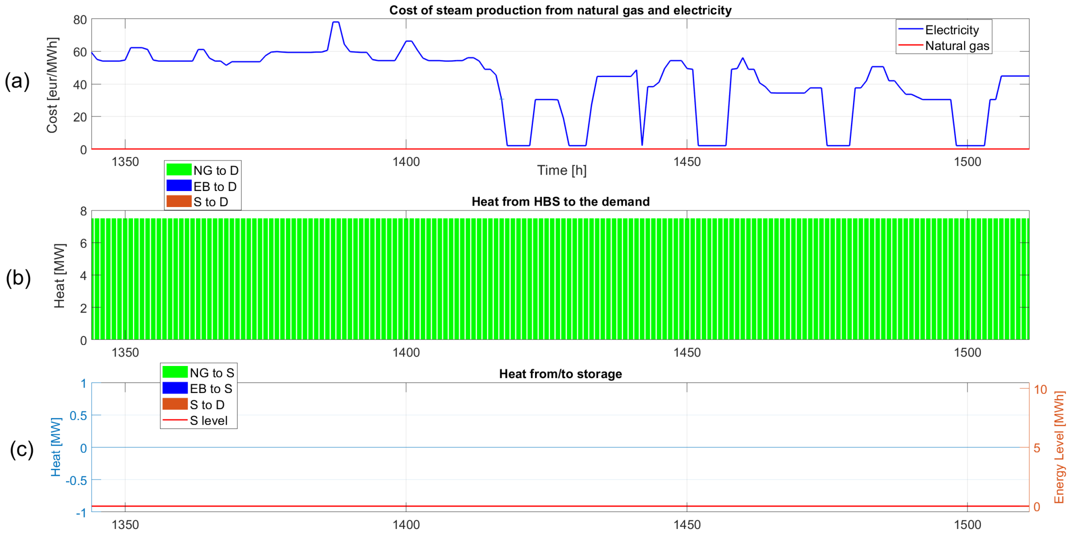

Figure 5.7: Hourly operation of the HBS system with low natural gas and CO_2 prices.

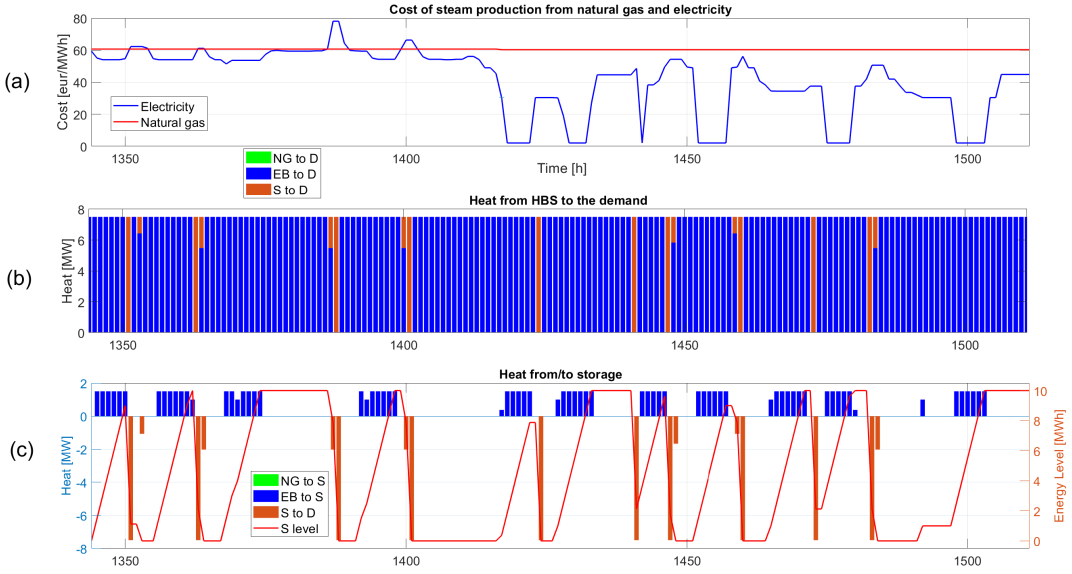

Figure 5.8: Hourly operation of the HBS system with high CO_2 price.

6 RESULTS

In this section the results from the models are presented and compared. First the hourly operation of the HB system, the HBS system and the EBS system are presented. The operation is shown for a period with fluctuations in the electricity price in order to observe changes in the performance. Subsequently, the performance indicators from the different configurations are compared.

6.1 OPERATION OF THE STEAM PRODUCTION UNIT

The hourly operation of the different configurations is described in this section. The hourly operation is presented for the HB system, the HBS system and the EBS system. The operation of these systems is optimised depending on the prices of electricity, natural gas and CO_2. The hourly operation is shown in graphs in which it can be seen the variation of the hourly performance. In the case of the natural gas boiler (NG) and the electric boiler (EB), the hourly operation is not shown. This is because the performance does not depend on the commodities prices so the operation does not vary thorough the whole year.

In addition to the hourly operation of each configuration, the number of hours that each boiler works during the year is presented for each configuration. The hours are divided in three categories:

- $q_t = OFF$: the number of hours during which the boiler is switched off.
- $q_t = Q_{min}$: the number of hours during which the boiler worked at its minimum heat output to avoid going into a cold start-up.
- $q_t > Q_{min}$: the number of hours during which the boiler worked over the minimum heat output (i.e. the boiler is the main generator of steam).

6.1.1 HB system

In the Figure 6.1 the steam generation in the HB from each boiler is presented. In Figure 6.2 **(a)** the hourly electricity and natural gas prices are presented. In Figure 6.2 **(b)** the heat from the boilers to the demand is illustrated. In this graph, the 'y' axis represents the heat in MW and the 'x' axis time in hours. The heat delivered to the demand can come from the natural gas boiler and the electric boiler. It can be seen that the natural gas boiler produces the steam for most of the hours for the period presented in the graph. Then, at low electricity prices the electric boiler switches on. In some cases, during the hours in which the electric boiler is on, the gas boiler works at its minimum to avoid the cold start-up.

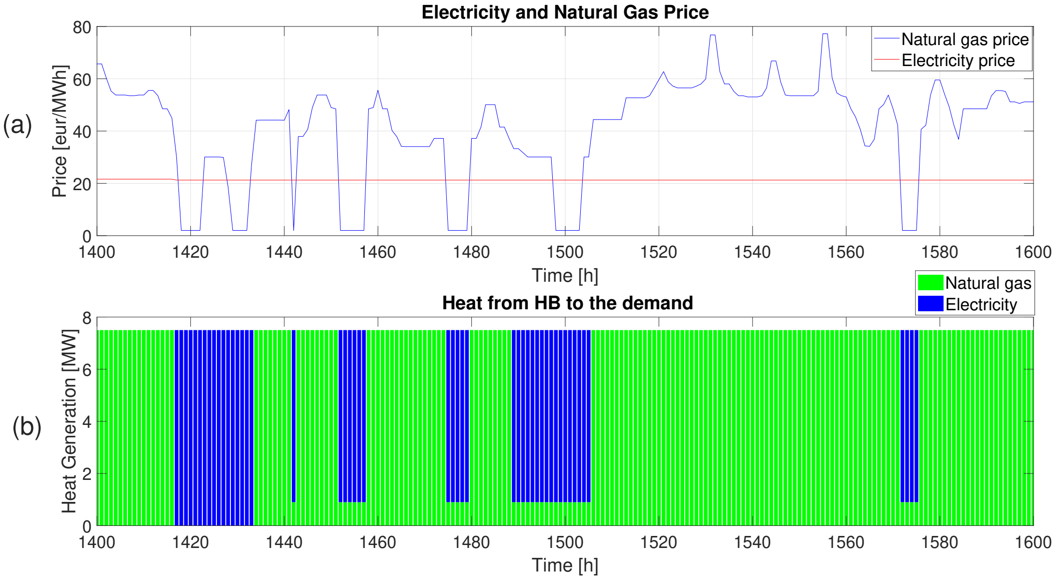

Figure 6.1: Hourly operation fo the HB system.

In Table 6.1 the number of hours that each boiler worked during the year is shown. It can be seen that the electric boiler worked during 20% of the hours of the year. However, during 60% of these hours the natural gas boiler is working at its minimum.

Table 6.1: Number of hours that the HB boilers works in each state.

Time (h)	**NG**	**EB**
$q_t = OFF$	860	7,008
$q_t = Q_{min}$	892	0
$q_t > Q_{min}$	7,008	1752

6.1.2 HBS system

In Figure 6.2 the hourly heat generation of the HBS system is presented. In this figure there are three graphs:

- In Figure 6.2 **(a)** the hourly electricity and natural gas prices are presented.
- In Figure 6.2 **(b)** the heat from the boilers and storage to the demand is illustrated.
- In Figure 6.2 **(c)** the heat from and to the storage is presented as well as the energy level (MWh) of the storage at every hour.

In Figure 6.2 **(b)** and **(c)** the left 'y' axis represents the heat in MW and the 'x' axis time in hours. Moreover, the legend of the heat flows in **(b)** and **(c)** corresponds with the diagram in Figure 5.4. Finally, in Figure 6.2 **(c)** the right 'y' axis represents the energy level of the storage in MWh.

Finally, a sign convention for the heat flow is introduced. In Figure 6.2 **(b)** the heat flow delivered to the demand is considered positive. In Figure 6.2 **(c)** the heat flow to the storage (i.e. charging) is positive and the heat flow from the storage (i.e. discharging) is negative.

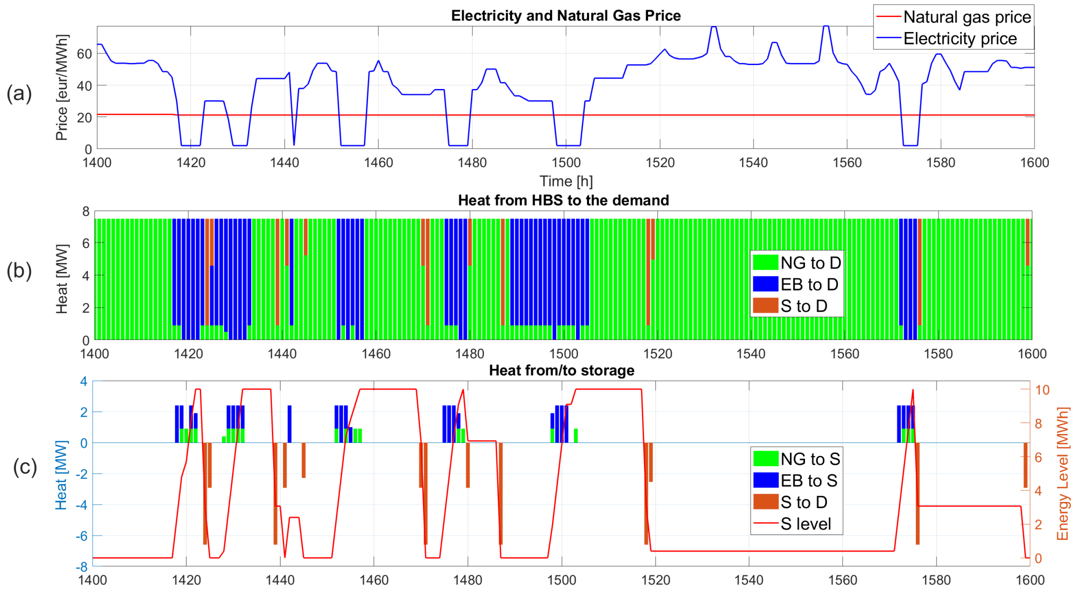

Figure 6.2: Hourly operation of the HBS.

In Figure 6.2 **(a)** it can be seen that at t=1420 the electricity price is lower than the natural gas price. Accordingly, in t=1420 in Figure 6.2 **(b)** the electric boiler is producing heat. At this hour, the natural gas boiler reduces its consumption to the minimum (0.9 MW), delivering the heat to the storage (see Figure 6.2 **(c)**).

The performance of the storage can be seen in Figure 6.2 **(c)**. In t=1400, it can be seen that the storage is completely empty. In t=1420, heat from the natural gas boiler and the electric boiler flows to the storage, thus charging the storage. Accordingly, the energy level in the storage increases until it is completely full. The storage is charged during hours of low electricity prices and it is discharged before the next period of low electricity prices (e.g. during t=1441).

In Table 6.2 the number of hours that each boiler worked during the year is shown. It can be seen that the electric boiler worked during 19.8% of the hours of the year. However, during 62% of these hours the natural gas boiler is working at its minimum.

Table 6.2: Number of hours that the HBS boilers works in each state.

Time (h)	**NG**	**EB**
$q_t = OFF$	816	7,023
$q_t = Q_{min}$	1,075	2
$q_t > Q_{min}$	6,869	1,735

6.1.3 EBS system

In Figure 6.3 the hourly operation of the EBS system is presented. In Figure 6.3 **(a)** the hourly prices of electricity are shown. Below, in Figure 6.3**(b)** the heat flow to the demand from the electric boiler and the storage is presented. Finally in Figure 6.3 **(c)** the heat to and from the storage as well as the energy level of the storage are shown. In the figure it can be observed that the storage charges during the hours of low electricity prices and discharges when the electricity price is high.

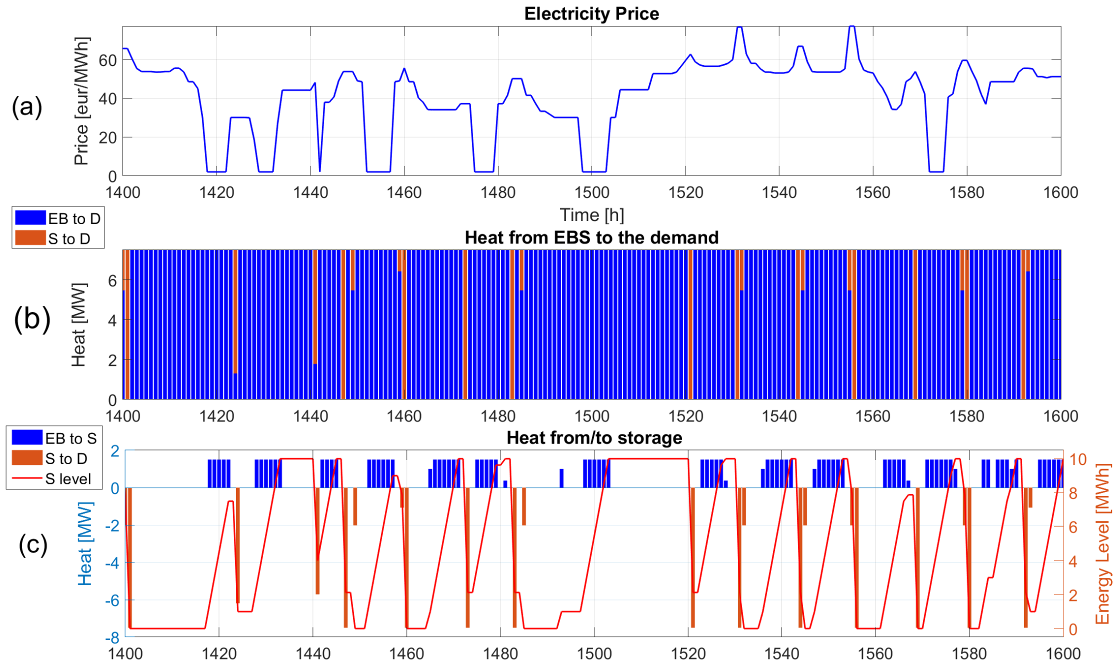

Figure 6.3: Hourly operation of the EBS system.

6.2 PERFORMANCE INDICATORS

In this section the performance indicators are presented. The performance indicators can be divided into economic indicators and technical indicators. The economic indicators include the operation costs and the LCOP. Whilst the technical indicators include the efficiency (energy consumption) of the system and the total direct emissions.

6.2.1 Economic indicators

The economic performance indicators are the production costs and the LCOP. In Figure 6.4 these indicators are illustrated for the HB system, the HBS system, the NG system the EBS system and the EB system. In addition, the investment and the O&M costs are illustrated.

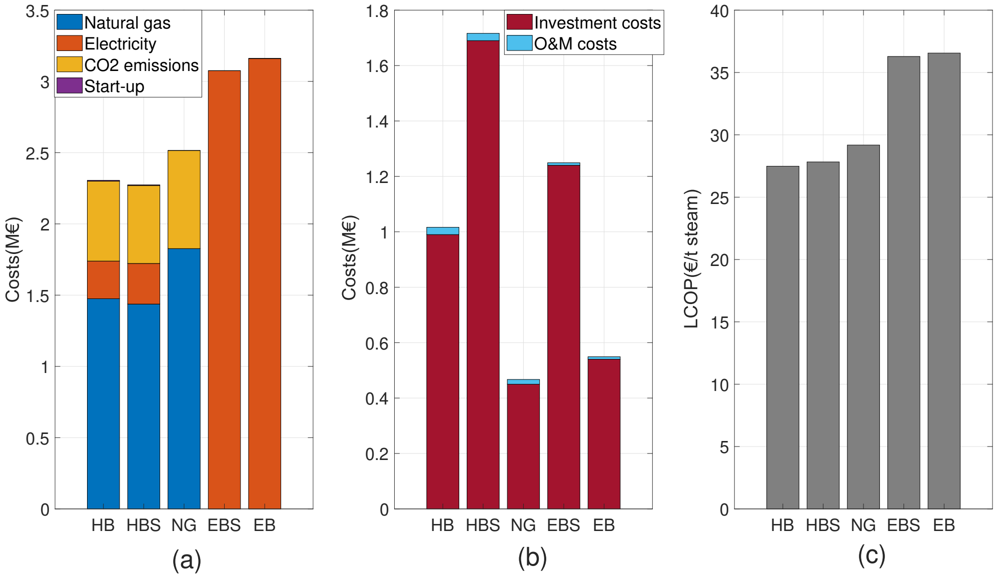

Figure 6.4: **(a)** Operation costs, **(b)** investment and O&M costs, and **(c)** levelised costs of the steam produced for the different configurations.

In Figure 6.4 **(a)**, the total operation costs of each boiler is illustrated. In addition, the operation cost are divided into natural gas costs, electricity costs, CO_2 costs and start-up costs. The hybrid systems present lower operation costs than the other configurations. In particular, the HBS system represents the lowest operation costs. In the other hand, the electric boiler presents the highest operation costs. The start-up costs in the hybrid systems are relatively low, this is because the natural gas boiler in the case of the HB and the HBS systems switches off during 860 hours and 816 hours respectively. This represents approximately less than 10% of the total hours in the year. Furthermore, in Figure 6.4 **(a)** the total operation costs of the EBS are also presented. The operation costs are reduced by approximately 3% in comparison with EB configuration. However the operation costs are still considerably higher than the NG configuration.

In Figure 6.4 **(b)** the investment costs and the O&M costs are illustrated. The costs for the hybrid systems are estimated as the sum of the costs for the electric boiler and the natural gas boiler, therefore these costs are considerably higher than the alternative configurations. In the case of the HBS the investment costs increase by 275% in comparison with the natural gas boiler, this is due to the high investment costs of the storage. Similarly, the investment costs for EBS are considerably higher than the electric boiler due to the storage.

In Figure 6.4 **(c)**, the price of 1 ton of steam produced is illustrated for each configuration. It can be seen that the hybrid options produce steam at the lowest price, in particular the price of the steam produced in the HB system is approximately 6% lower than the NG configuration. In the case of the HBS, despite of the high investment costs the LCOP slightly increases. This is because the operation costs for the HBS are lower than the HB. Furthermore, in Figure 6.4 **(c)** the LCOP for the EBS is shown. The price of the steam produced is slightly lower than the EB configuration, however it is 24% higher than the NG configuration. Therefore it is an expensive alternative in comparison with the hybrid systems.

6.2.2 Technical indicators

Finally the technical indicators are illustrated in Figure 6.5. The technical indicators are the energy input, the efficiency of the boiler and the direct CO_2 emissions. In Figure 6.5 **(a)** the natural gas and electricity consumed in each boiler are presented as well as the efficiency of each boiler. The hybrid systems are a combination of an electric boiler and a natural gas boiler, therefore the efficiency is between 90% and 99%. The efficiency of the hybrid systems increase with the consumption of electricity. The share of the electricity consumed in the HB and the HBS is approximately 17% and 19% respectively. This electricity substituted the natural gas consumption during the hours in which the electricity prices were low. As a consequence the direct CO_2 emissions of the steam generation decreases by 18.5% in the HB and 20.5% in the HBS respect to the natural gas boiler (see Figure 6.5 **(b)**).

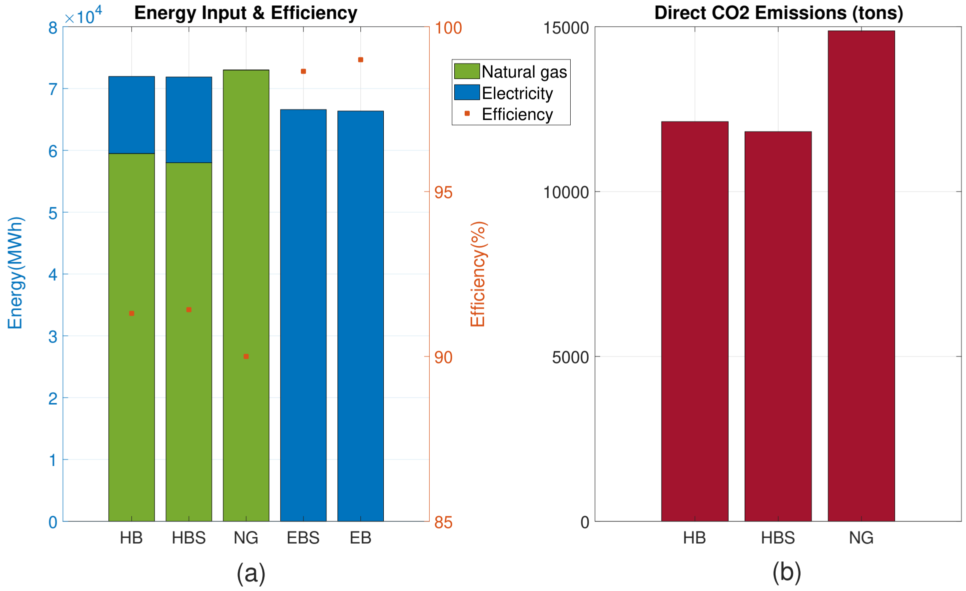

Figure 6.5: Direct and indirect CO_2 emissions.

6.2.3 Conclusion

The the results show that the HBS reduces the operation costs of the system by approximately 9.6% (8.3% in the case of the HB) respect to the natural gas boiler. The costs saved corresponds to €241,477/year. In addition, the energy saved respect to the natural gas is 1.5% (1.4% in the case of the HB) which corresponds with 1,132 MWh/year. Finally, the direct CO_2 emissions are reduced by 2,751 t/year for the HB system and 3,055 t/year in the case of HBS system.

7 ANALYSIS

In this chapter the case study presented is analysed to provide a deeper insight into the assumptions and decisions in the model. First, the technical parameters assumed are analysed: start-up costs, start-up time, boilers and storage capacity in Section 7.1. Second, the impact of the electricity prices forecast is analysed reducing the prediction horizon in Section 7.2. In addition, the indirect CO_2 emissions and the grid connection costs, which were neglected in the case study, are included in Section 7.3 and Section 7.4 to complete the results presented in Chapter 5. Furthermore, the uncertainty related to the scenario for 2030 (electricity price, natural gas price and CO_2 price) is discussed through a sensitivity analyses in Section 7.1. Finally, measures for a deep decarbonisation are analysed in Section 7.6.

7.1 TECHNICAL PARAMETERS

7.1.1 Start-up cost and time

The start-up cost for the gas boiler was estimated as the energy required to bring the water volume in the boiler to the operation conditions. In addition, the heat loss during the cold start-up was estimated as the energy stored in the steel structure which results in an increase in the temperature of the steel. The amount of steel was approximated to the weight of the empty boiler. In this section, the impact of the start-up cost and time in the performance of the boiler are analysed. In order to analyse the parameters and the interactions different cases are assumed to compare with the base case (see Chapter 5).

In Figure 7.1 **(a)** the variation in the total operation costs for different start-up time and costs are shown. In Figure 7.1 **(a)** left the start-up time is fixed in 2 hours (same as in the case study). For this start-up time the start-up costs are modified: (1) increased by 50% , (2) decreased by 50% and (3) decreased by 100% respect to the base case study. Similarly, in Figure 7.1 **(a)** right the start-up time is assumed to be less than 1 hour (negligible). Again, the start-up costs are varied for the same cases as in Figure 7.1 **(a)** left.

In Figure 7.1 **(b)** the variation of cost related to natural gas consumption are presented for the same scenarios as in Figure 7.1 **(a)**. Moreover, in Figure 7.1 **(c)** the variation of the cost related to electricity consumption are shown for the same scenarios as in Figure 7.1 **(a)** and **(b)**.

In the Figure 7.1 it can be seen that the variation in the costs for different start-up times (left and right) is identically the same, therefore it can be concluded that the start-up time is not a critical parameter for a time step of 1 hour and longer periods. In these cases the restriction could be neglected for the hybrid system optimisation.

The total costs of the system increased with increasing start-up costs (see Figure 7.1 **(a)**). In addition, it can be seen that reducing the start-up costs decreased the costs related to the natural gas consumption (see Figure 7.1 **(b)**) while the costs related to the electricity consumption increased (see Figure 7.1 **(c)**). This effect is higher when the start-up costs are reduced by 100%. This is due to the fact that during periods of high fluctuations in the prices the start-up costs prevent the boiler from switching on/off frequently. Thus, forcing the gas boiler to work at its minimum heat output when the electricity price is lower than the natural gas price.

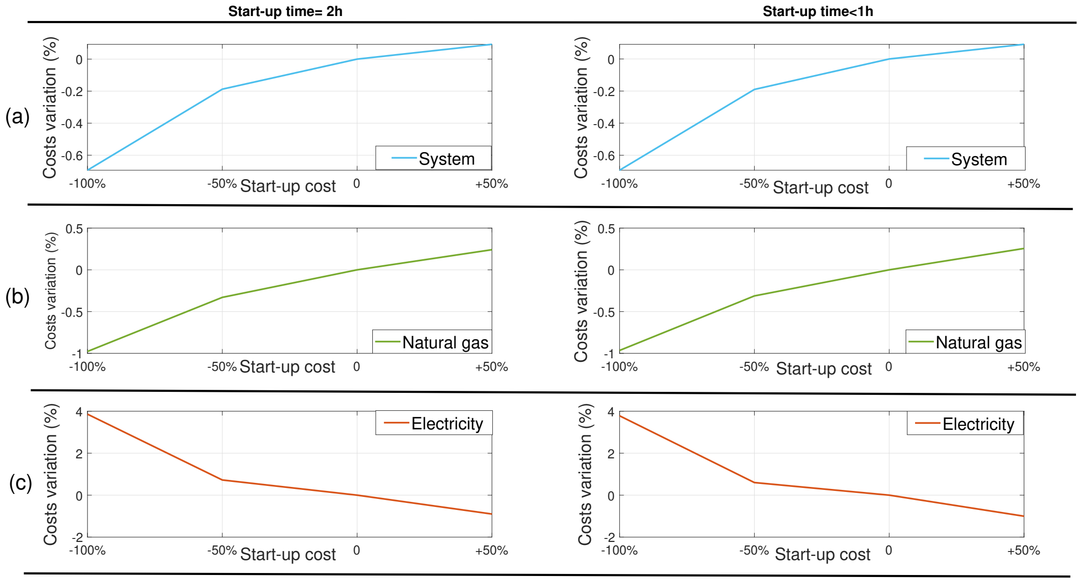

Figure 7.1: Percentage of increase or decrease respect to the operation costs in the base case scenario.

In Figure 7.2 the heat generation of the HBS is presented in the case of zero start-up costs. It can be seen that the natural gas boiler switched off instead of working at its minimum as observed in the results of the base case scenario in Figure 6.2. Thus, in the case of zero start-up costs, the use of the natural gas is reduced while the use of the electric boiler is increased. Similar conclusions result from the hybrid boiler without a storage.

Despite of the fact that the start-up cost had an impact on the performance of the hybrid boiler in comparison with the start-up time, the total operation costs decreased by less than 1% while the direct CO_2 emissions were 1.26% lower when the start-up restrictions were neglected. The impact of these restrictions in the performance of the hybrid boiler system for a time step of one hour are negligible.

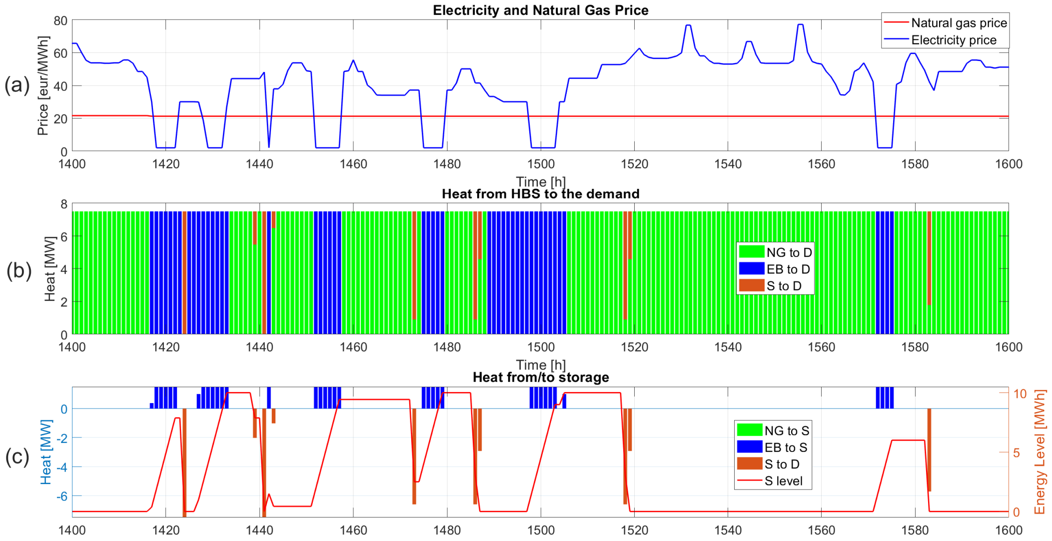

Figure 7.2: Hourly operation of HBS system in case of zero start-up costs.

7.1.2 Boilers and storage capacity

The hybrid boiler analysed in this master thesis is assumed to be formed by two separate boilers which work together, therefore the capacity of the boilers can be different.

In the base case study the capacity of both boilers were assumed to be the same. The results for different capacities are presented in Figure 7.3. The operation costs, the investment costs and the LCOP of different configurations are compared. Reducing the capacity of any of the boilers increased the operating costs and decreased the investment costs. Despite of the drop in the investment costs the LCOP of the three cases were higher than the base case study. It can be concluded that in the case of two boilers with the same capacity produced the steam with the lowest price.

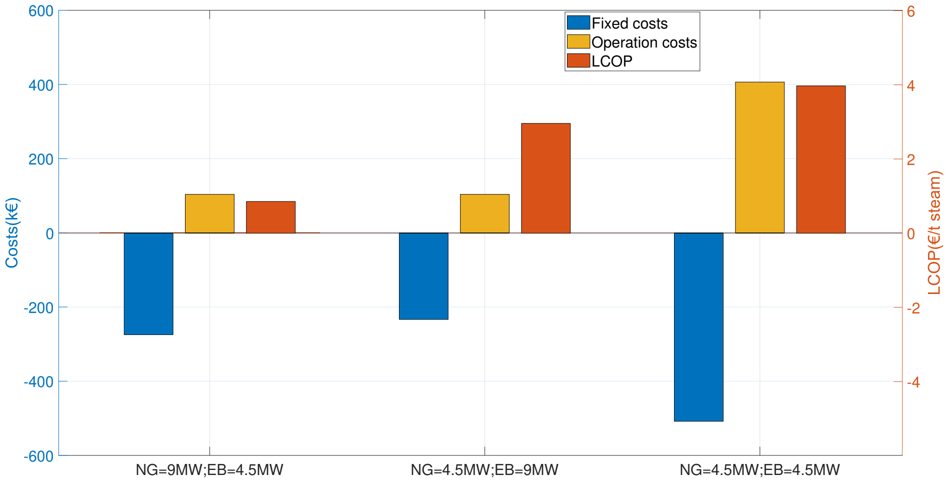

Figure 7.3: Difference in investment costs, operation costs and LCOP for scenarios with different boilers capacities and the base case study.

In the base case study the capacity of the boiler was assumed to be 10 MWh. The operation costs, the investment costs and the LCOP are compared for storage capacities of 5 MWh and 15 MWh in Figure 7.4. It can be seen that reducing or increasing the capacity of the storage impacts the investment costs of the hybrid system while the variation in the operation costs is relatively low. Therefore, reducing the capacity of the storage reduced the price of the steam produced in comparison with the base case study, while increasing the capacity increases the steam price.

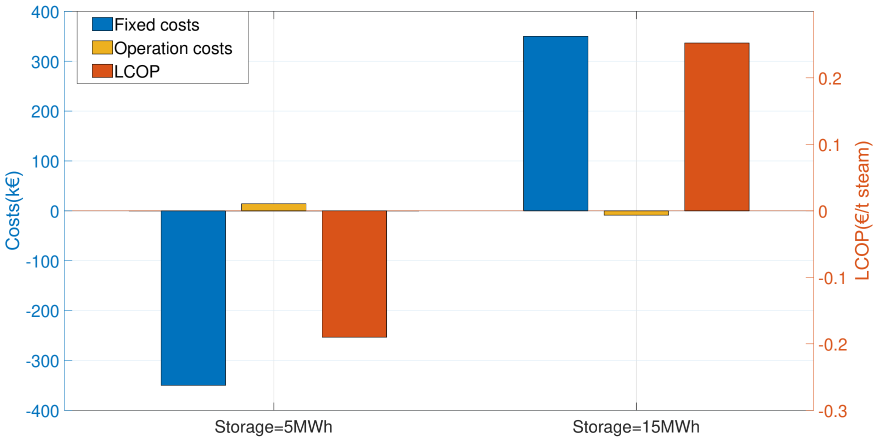

Figure 7.4: Difference in investment costs, operation costs and LCOP for scenarios with different storage capacities and the base case study.

7.2 PREDICTION HORIZON

In the case study presented in Chapter 5 the rolling horizon was applied to solve the model for a whole year. The rolling horizon divides the year into chunks which are optimised separately. These chunks are called prediction horizon (PH) and for the case study they represented 504 hours which are 21 days. However in reality this period might be shorter for instance 2 days. In this case, the performance of the hybrid boiler system would be optimised looking only 2 days ahead which could impact the operating costs as the optimum could be different when optimising the model for 21 days.

In this section the model is run applying the rolling horizon for a whole year with a prediction horizon of 2 days and a control horizon of 1 day. Figure 7.5 shows the difference between the operation costs of a PH=2 and the base case study for every week. In Figure 7.5 it can be seen that the variation of the PH is not relevant in the case of the HB system as the operation costs at every week is the same as in the base case study. In the case of the HBS system a shorter prediction horizon slightly changes, however the difference in the total operation costs of the system was negligible. The optimisation of 1 day of operation could be performed with 2 days of prediction as the inputs for further hours do not affect the operation of the system.

The maximum difference in operation costs can be seen in week 37 and 39 in which the costs increases €382. While the maximum decrease in operation costs happened in week 9, approximately €452. On the other hand, the weeks between week 40 and 51 the difference is zero or negligible.

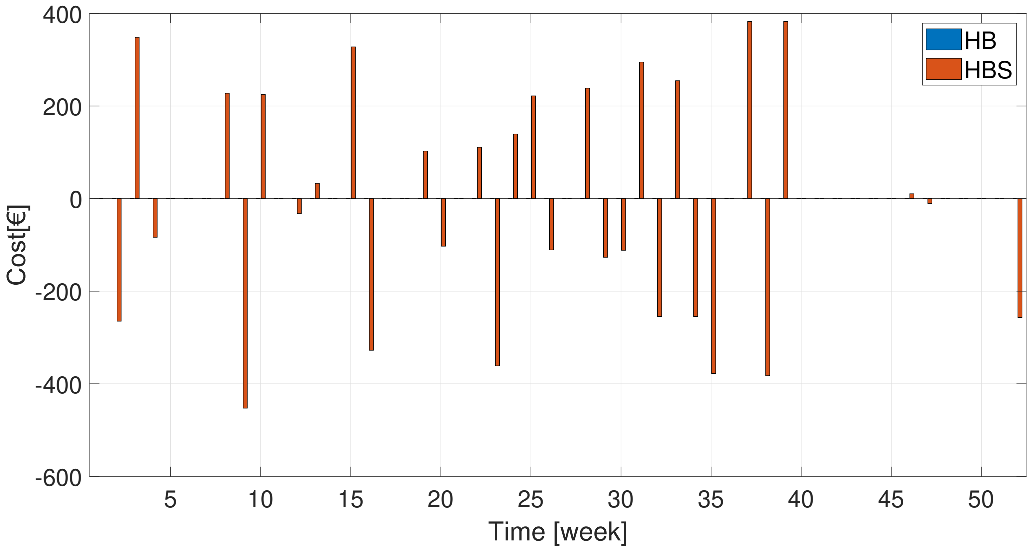

Figure 7.5: Difference in costs between the hybrid systems optimise with a rolling horizon of a $PH = 2$ days and a the $PH = 21$ days .

In Figure 7.6 the electricity prices for week 41, week 37 and week 9 are presented. In the Figure 7.6 **(a)** we see that during this week the electricity price did not fluctuate and it is higher than the natural gas at every hours. In the contrary during week 37 and 9 in which the costs vary, it can be seen that there is a higher volatility of the electricity prices.

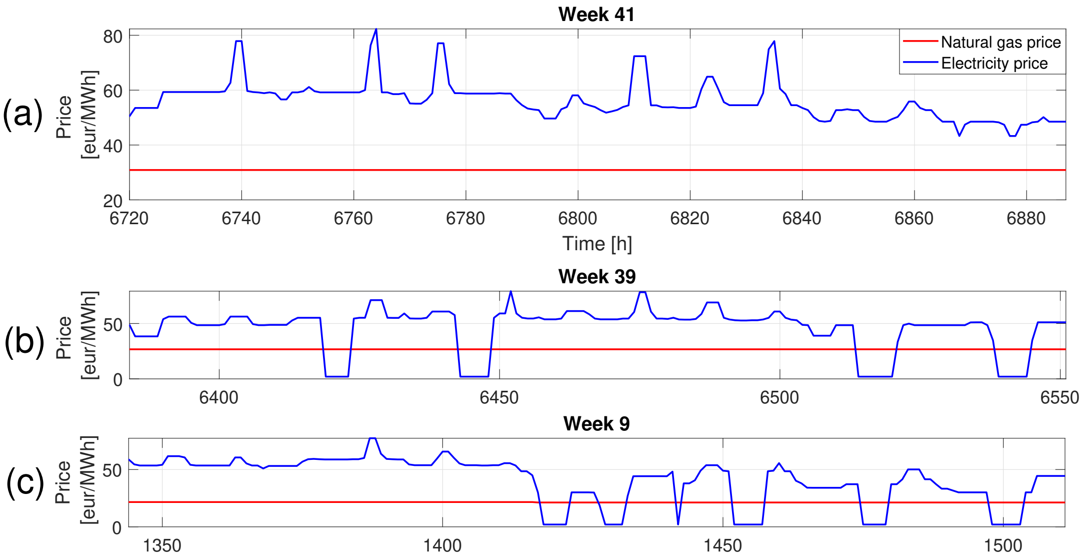

Figure 7.6: Electricity price and natural gas price during week 41, week 39 and week 9.

Despite the weekly cost difference in the operation costs in the case of the HBS, the total operation costs of the system remained almost the same. In the Figure 7.7 the total steam generation from natural gas and electricity during week 9 for a PH of 21 days (Figure 7.7 **(a)**) and a PH of 2 days (Figure 7.7 **(b)**) are presented. It can be seen that the production of steam changed however this change is relatively negligible.

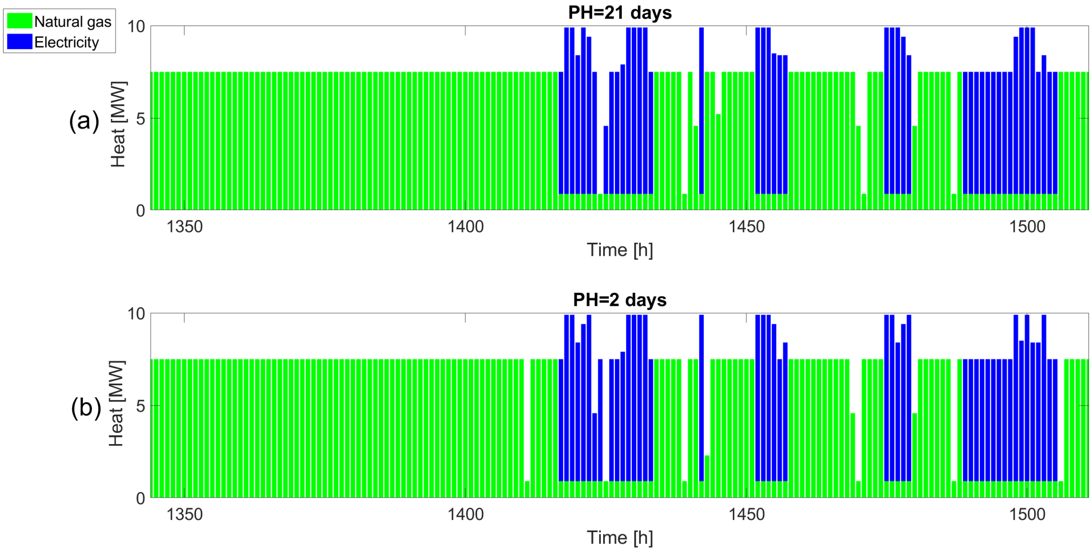

Figure 7.7: Steam production in the HBS system at every hours during the week 9 for **(a)** $PH = 21$ days and **(b)** $PH = 2$ days.

7.3 INDIRECT CO_2 EMISSIONS

The results from the simulation for 2030 showed the direct CO_2 emissions from the natural gas combustion in the gas boiler. The indirect emissions from the electricity consumption were not considered assuming that the electricity was consumed from renewable energy generation (wind, solar). However the emission factor of the electricity depends on the energy mix of the energy system and the technologies that are generating the electricity each hour. In Table 7.1 the emission factors for each technology are presented. It can be seen that the emission factor of the electricity generated from a gas power plant and a coal plant are much higher than the direct emission for natural gas combustion in the boiler.

Table 7.1: Emissions

CO2-eq emission	**Value**	**Unit**
Gas power plant	0.61	kg CO_2eq/kWh
Coal power plant	0.86	kg CO_2eq/kWh
Solar energy	0.09	kg CO_2eq/kWh
Wind energy onshore	0.01	kg CO_2eq/kWh
Wind energy offshore	0.01	kg CO_2eq/kWh
Gas boiler (direct emission)	0.20	kg CO_2eq/kWh

The energy mix in the Netherlands is expected to change for 2030. In particular, it is expected that the coal plants will be phased out. In addition the renewable energy share will increase. The energy mix for 2030 according to the Climate Agreement is presented in Table 7.2.

Table 7.2: Energy mix in 2030

Generation source	**Value**	**Unit**
PV technology	18	TWh
Wind onshore	26.2	TWh
Wind offshore	61.9	TWh
Gas power plant	18.8	TWh

There is not a direct relationship between the prices of electricity and the technology which is generating the electricity, however we consider that during low prices of electricity renewable energy is the dominant source of electricity. While at prices closer to the average price of electricity gas power plants are also producing [Afman, 2020]. Thus, increasing the emission factor of the electricity generated.

In this master thesis we assume three ranges of electricity prices. Subsequently, different emission factors are assigned to each range in order to analyse the indirect emissions of the hybrid systems (see Table 7.3). For prices between €20 and €60 an average emission factor[1]

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[1] The emission factor is estimated from [Jansen et al., 2019] where the total indirect CO_2 emissions from an electric boiler (1MW) operating during 2030 were estimated according to the emission factors presented in Table 7.1 and the energy mix presented in Table 7.2

for 2030 was used. For prices lower than €20 it is assumed that renewable energy is producing. In the contrary for prices higher than €60 it is assumed that a higher share of electricity is produced from gas power plants. In the Table 7.3 the number of hours in each price range for the electricity prices in 2030 are presented.

Table 7.3: Emissions

Price range (€)	**EF (kg CO_2-eq/kWh)**	**Hours (h)**
0-20	0.01	726
20-60	0.13	7,306
>60	0.25	728

In the Table 7.4 the indirect emissions for each configuration are presented. It can be seen that the HBS system incurred in slightly higher indirect CO_2 emissions than the HB system due to a higher consumption of electricity. The electric boilers within the hybrid configurations operated during hours in which the electricity prices were lower than the average price (€47.6). The EBS reduced the indirect emissions in comparison with the EB, this is because the use of the storage reduced the consumption during hours of high electricity prices (> 60). The indirect emissions during these hours were reduced by approximately 56% respect to the electric boiler.

Table 7.4: Emissions

Price range (€)	Indirect emissions (ton CO2-eq)			
	HB	HBS	EB	EBS
0-20	52.3	60.6	55	63.4
20-60	940.6	1,015	7,195	7,526
>60	0	0	1,379	608
Total	993	1,075	8,629	8,198

In Figure 7.8 the total CO_2 emission from every technology are presented. The electric boiler reduced the emissions by 42% in comparison with the natural gas. However this reduction is subjected to the emissions factors assumed for the analysis. In the case of the hybrid systems the indirect emissions represented approximately 8% of the total emissions.

7.4 NETWORK TARIFFS

In this master thesis it is assumed that the industry has already a connection to the natural gas and electricity network. However, in case of the electricity the industry might need to increase the connection to the grid. This additional investment can affect the price of the steam produced (LCOP). In the agreements on the instrument for power to heat (Climate Agreement), the Dutch government will review if more flexibility can be provided for dynamic tariff structures in the network tariffs for transport and distribution to facilitate more flexibility [Dutch Government, 2019a]. In this section, the impact of the network tariffs on the LCOP of the

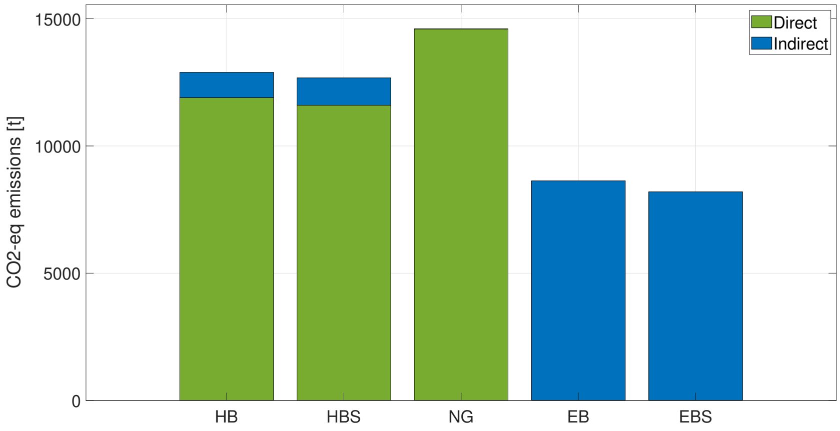

Figure 7.8: Direct and indirect emissions for different configurations of heat generation.

hybrid systems is analysed.

Consumers connected to the national grid in the Netherlands pay a fee to TenneT (transmission system operator) for this connection. The fee covers the costs related to the installation, maintenance and replacement of the connection. The Tennet tariffs are divided into the connection and the transmission tariffs [TenneT, 2019].

- The connection tariffs include two components. An initial component which covers the initial costs of creating a grid connection. In addition, there is a periodic tariff to maintain the connection which is a fix amount per year [TenneT, 2019]. The periodic connection tariff is not considered in this master thesis. In case an electric boiler is installed in the industry a new grid connection might be required. The grid connection costs can represent an additional investment cost of k€130 /MW [Sebastiaan Hers et al., 2015].

- The transmission tariffs include two types of transmission tariffs: the non-transmission-related consumer tariff (TOVT) and the transmission-related consumer tariff (TAVT). The TOVT is realted to the costs that are not directly related to the transmission of electricity, such as metering data and administration. The TAVT is directed related to the electricity transmission and it depends on the total number of hours that the user is operating [TenneT, 2019]. In the Netherlands the year of transport can be between 20 k€/MW and 25 k€/MW a year and it varies from region to region [Sebastiaan Hers et al., 2015]. This tariff depends on the capacity consumed and not in the volume which can results in high costs for an infrequent high capacity consumption [Sebastiaan Hers et al., 2015]. The transmission costs considered for the analysis are 23 k€/MW yearly.

We analyse the impact of the additional investment due to the grid connection costs in the price of steam (LCOP) for hybrid configurations. In Figure 7.9 the difference between the LCOP of the different hybrid configurations and the natural gas boiler is presented. The hybrid configurations considered in the graph are the following:

- HB/HBS: the hybrid systems considered in the base case.
- HB-N/HBS-N: the hybrid systems in addition to the grid connection and transport costs (Network).
- HB-N-EB/HBS-N-EB: the hybrid systems considering the network costs. In addition the electric boiler capacity is reduced to 4.5 MW to reduce the investment costs.

In Figure 7.9 it can be seen that the network costs increase the price of the steam produced. The network costs increase the LCOP of the hybrid configurations above the LCOP of the steam produced in a natural gas boiler. The network costs increase the price of the steam by almost 13% for both the HB and HBS system. The rise in the LCOP can be dwindled by reducing the capacity of the electric boiler.

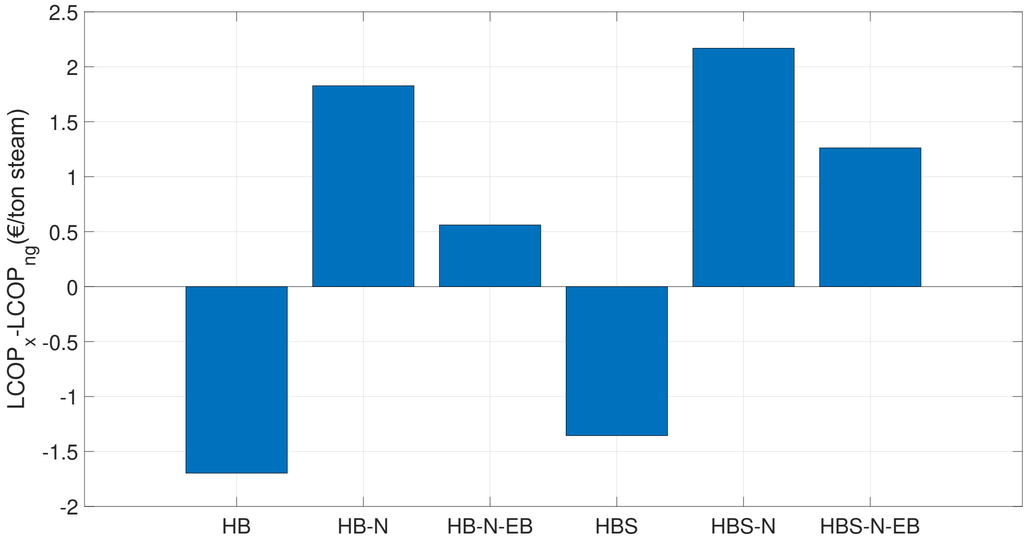

Figure 7.9: Difference between the LCOP of the hybrid configurations and the LCOP of the natural gas boiler.

7.5 UNCERTAINTY OF 2030 SCENARIO

The hybrid systems were modelled for the scenario 2030 estimated according to the Climate Agreement [PBL, 2019b]. In this section we analyse the impact on the results of the uncertainties of the prices of electricity, natural gas and CO_2 assumed for the 2030 scenario. To this end, the prices used in the scenario of 2030 are varied based on the bandwidths presented in [PBL, 2019b] which are retrieved from [Schoots et al., 2017].

In this thesis, the extremes of the bandwidths are presented as the percentage of variation respect to the prices considered in the base case study. According to the bandwidth in [PBL, 2019b], the natural gas and CO_2 price could vary approximately by +/-36% and +/- 73% respectively. In the case of the electricity price, the price is assumed to vary approximately by +/- 10% [2]. In the Figure 7.10 the average prices are presented with the bandwidth considered for the uncertainty analysis.

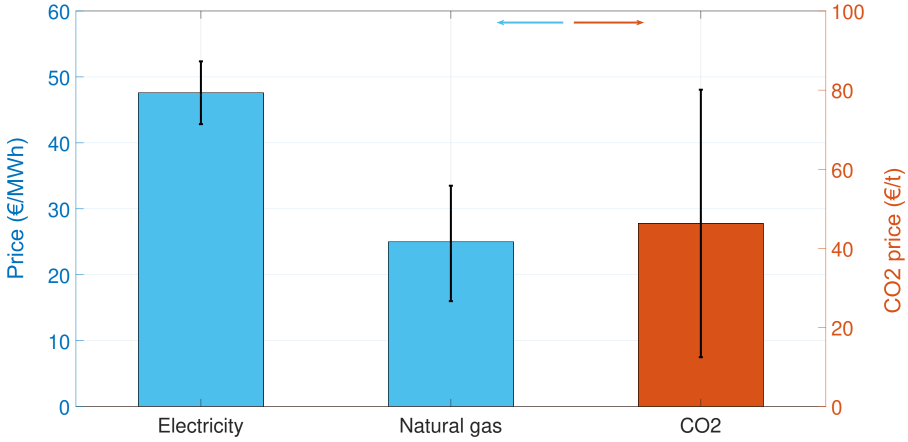

Figure 7.10: Bandwidth respect to the average prices in the base case scenario.

The interaction between the prices is relevant for the analysis. Therefore 27 scenarios are analysed in which all the possible combinations for the three inputs (electricity price, natural gas, CO_2 price) are considered. The scenarios are presented according to the legend in Table 7.5.

Table 7.5: Legend for the possible price inputs in the uncertainty analysis.

Electricity		**Natural gas**		**CO2**	
E	Base case	**N**	Base case	**C**	Base case
E+	+10%	**N+**	+36%	**C+**	+73%
E-	-10%	**N-**	-36%	**C-**	-73%

In the uncertainty analysis the difference in the operation costs and the emissions respect to to the base case scenario (ENC) for every combination is analysed. The emissions are an

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[2] The bandwidth of the electricity price is estimated with the difference between the price forecast for 2030 in the 'basispad' scenario and the 'Actuele prijsverwachting' scenario presented in [PBL, 2019b]. The price vary by approximately 8%, in this thesis this variation is approximated to +/- 10%.

indicator of the variation in the share of electricity consumption in the hybrid configurations. In this analysis only the HBS is considered as variations for the HB case are approximately the same.

7.5.1 Electricity price

In Figure 7.11 **(a)** it can be seen that the operation costs (i.e. variation respect to the ECN) in every scenario is almost the same in case of increasing (E+) or decreasing (E-) the electricity price. Therefore, it can be concluded that the variation of electricity within the bandwidth of +/-10% has a negligible impact on the total operation costs. This is because the share of natural gas in the energy consumption is much higher than electricity, therefore the operation costs are more influenced by the natural gas price and CO_2 price.

The electricity price variation has more impact on the N+C+ scenario in which increasing (E+) or decreasing (E-) the electricity price results in different operation costs. In addition, in Figure 7.11 **(b)** it can be seen that for the scenario N+C+ reducing the electricity price (E-) results in a significant decrease of the emissions. It can be concluded that lower electricity prices do not lead to an increase in the electricity share in the hybrid boiler operation if the natural gas and CO_2 prices are low. The higher share of electricity in the hybrid system occurs with E-N+C+ scenario.

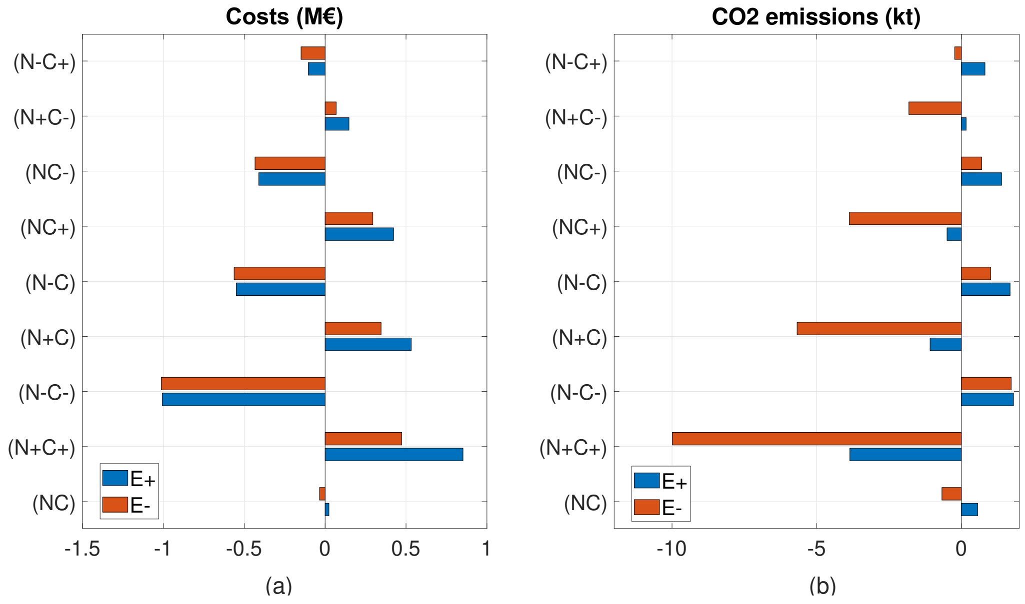

Figure 7.11: Difference in **(a)** the operation costs and **(b)** the emissions respect to the base case scenario (ECN).

7.5.2 Natural gas price

The variation of the natural gas prices has a larger impact on the operation costs of the hybrid boiler in comparison with the electricity price. This is due to the high share of natural gas consumption. It can be seen that for the scenarios with the same CO_2 price the operation costs were almost the same independently of the variation of the electricity price (e.g. E+C-, EC- and E-C-). However for these same scenarios it can be seen that the electricity did impact the variation of the emissions, for instance for the scenario E-CN+ and E+CN+ the operation costs were almost the same however the difference in emission reduction is much higher. Finally, it can be seen that the share of electricity in the hybrid boiler increased significantly with the increase of the natural gas price, in particular in the scenario N+E-C+ and N+EC+.

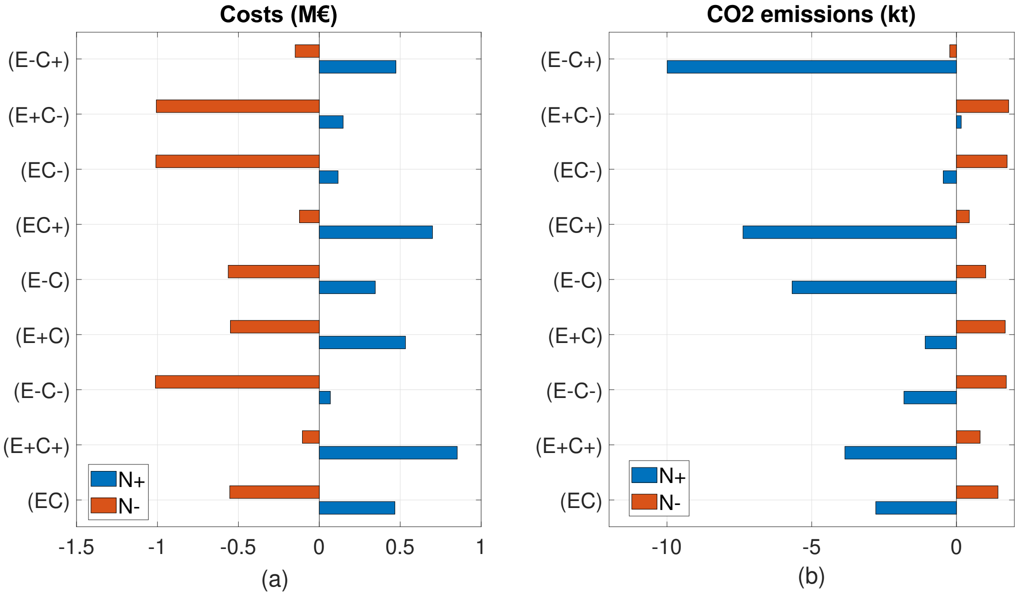

Figure 7.12: Difference in **(a)** the operation costs and **(b)** the emissions respect to the base case scenario (ECN).

7.5.3 CO_2 price

In Figure 7.13 **(a)** it can be seen that the operation costs decrease significantly in case of C- only if the natural gas prices decreases (N-). Similarly, in the case of C+ the operation costs increase significantly only if the natural gas price is high N+. In addition, in Figure 7.13 **(b)** it can be seen that overall the price of CO_2 does not have a significant impact on the performance of the hybrid boiler in terms of electricity share for scenarios in which the natural gas price is N or N- . In the contrary, in case of N+ the difference between C+ and C- is significant. Therefore, the impact of the CO_2 price in operation costs and the emissions depends on the natural gas price.

Similar as in the Figure 7.12, it is observed that although the variation of the electricity price for the same scenarios of natural gas and CO_2 prices did not impact the operation costs conversely it did impact the emissions. This can be observed comparing the scenarios E-NC+ and E+NC+.

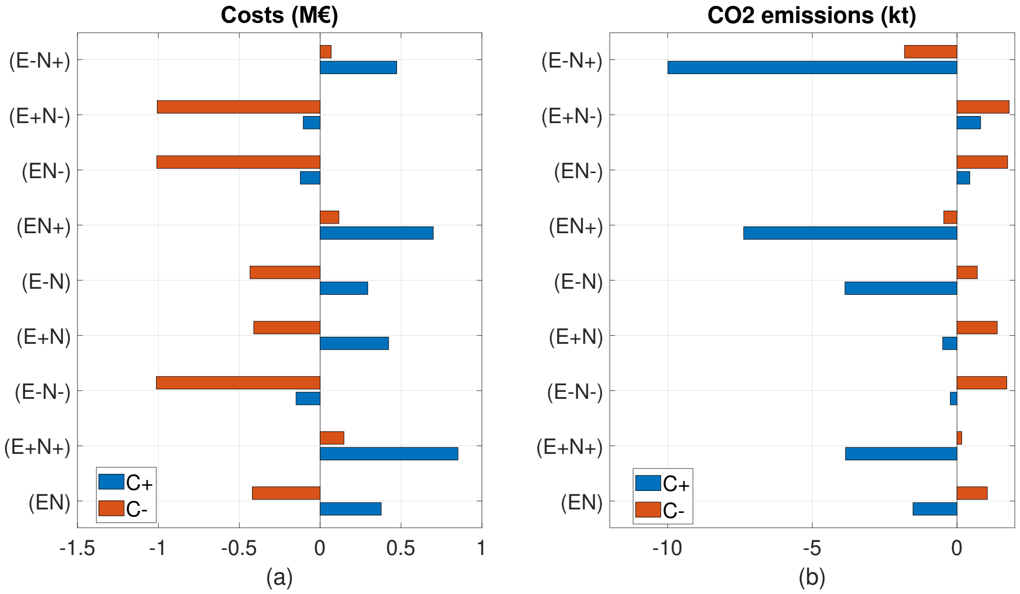

Figure 7.13: Sensitivity of **(a)** the operation costs and **(b)** the emissions to the CO_2 price.

7.5.4 Abatement factor

The scenarios in which the emissions dropped are further analysed. From the 26 sensitivity scenarios (base case is excluded), 13 scenarios presented a drop in the emissions respect to the base case study. For these scenarios the cost of reducing the emissions is compared. In Figure 7.14 the electricity prices and the natural gas prices are presented for the scenarios in which the emissions decreased. The scenarios are ordered from the one with the largest difference between electricity and natural gas to the scenario with the lowest difference.

In Table 7.6 the scenarios in which the emissions are reduced in comparison with the base case scenario are presented. For each scenario the percentage of emission reduction respect to the base case study is presented. In addition the cost of reducing the emissions is presented with an abatement factor (AF) calculated according to the Equation 7.1 [3]. In the Table 7.6 only the scenarios in which the emissions decreased are analysed while the scenarios in which the emissions increased are excluded (white area in the table).

$$AF = \frac{OP_s - OP_{ECN}}{|CO2_s - CO2_{ECN}|} \tag{7.1}$$

Where:

AF is abatement factor (€/t)

OP_s is operation costs of the scenario analysed (€)

OP_{ECN} is operation costs of the base case scenario (€)

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[3] The difference of emissions is in absolute value because only scenarios in which the emissions were reduced respect the base case study are analysed.

$CO2_s$ is emission of CO_2 in the scenario analysed (t)

$CO2_{ECN}$ is emission of CO_2 in the base case scenario (t)

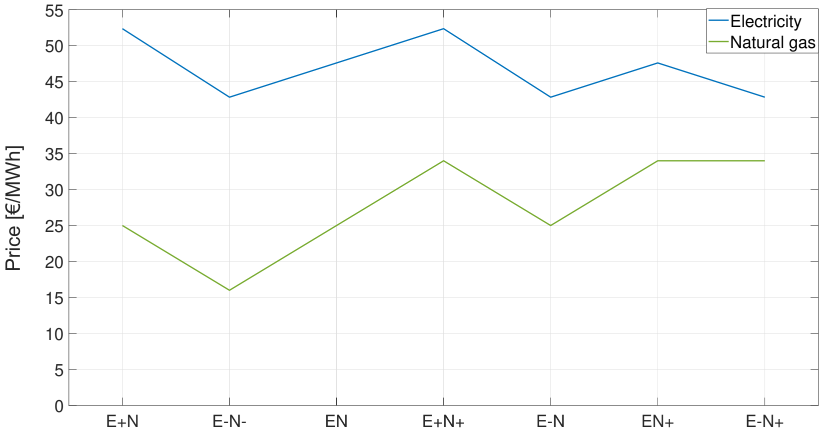

Figure 7.14: Prices of electricity and natural gas for the different scenarios.

Table 7.6: Percentage of the emissions reduced and the costs of reducing the emissions.

Scenarios	**C+**		**C**		**C-**	
	$\Delta CO2(\%)$	**AF (€/t)**	$\Delta CO2(\%)$	**AF (€/t)**	$\Delta CO2(\%)$	**AF (€/t)**
E+N	5	854				
E-N-	5	-646				
EN	11	248				
E+N+	33	221	12	492.7		
E-N	30	76	5	-52		
EN+	66	95	35	168	4	254
E-N+	88	47	43	61	14	38

In Table 7.6, it can be seen that the percentage of the emissions reduction increases for scenarios in which the difference between the price of natural gas and electricity was lower. In addition, the costs of reducing the emissions also decreases with lower differences. It can be seen that for similar percentage of reduction: 30%, 33%, 35% and 43% the costs of reduction differ considerably. In particular the costs varied between €221 and €70.

When the difference of electricity and natural gas is low the hybrid boiler works mostly with electricity (baseload electrification) because is more efficient . This case corresponds with the E-N+C+ scenario and the emissions were reduced at the lowest price (€47.4). Conversely, it can be seen that with the same prices of natural gas and CO_2 (N+C+) as the privious scenario, if the electricity price increases 10%, the emissions are only reduced by 33% at a much higher cost (€221).

In addition, in the table it can be seen that for the scenarios E-NC and E-N-C+ the costs are negative, this means that in this scenarios the emissions decreased while saving operation costs. However in this scenarios the reduction of emissions is negligible, in this case the operation of the hybrid system is the same as in the base case study.

7.5.5 Extreme scenarios

The variation in the prices separately have a relatively low impact on the performance of the hybrid boiler in terms of electricity share. However, the interaction of the different commodities can impact the performance of the boiler considerably. In the Figure 7.15 the share of natural gas and electricity in the total energy consumed in the scenario E-N+C+ and E+N-C- are presented. These cases are the most extreme scenarios in which the HBS works mostly with natural gas or electricity. In these cases the difference between the price of natural gas and electricity is the largest, therefore the interaction between the prices is reduced. In this case the hybrid boiler does not correspond with a flexible electrification as it is working as a baseload electrification or a natural gas boiler.

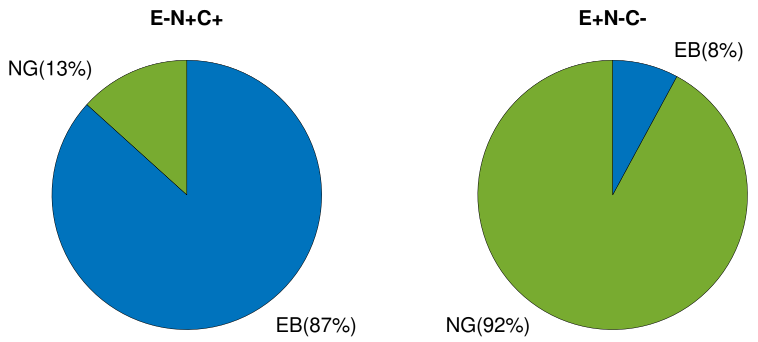

Figure 7.15: The share of natural gas and electricity in the total energy consumed in the E-N+C+ and E+N-C- scenarios.

7.6 TAX AND CAP SCENARIOS

Accelerating the energy transition in the industry can be set in different ways (taxes, subsidies, directly limiting the emissions,etc). In this section two possible measures to reduce the direct CO_2 emissions are analysed.

1. Tax scenario: the CO_2 emissions can be reduced increasing the price of CO_2 through taxes. In this scenario we assume that the CO_2 price is €120 which represents more than twice the price assumed in the base case scenario (€46.3).

2. Cap scenario: the CO_2 emissions can be directly limited. The industry is assigned a maximum amount of CO_2 emissions. In this case the price of CO_2 is the same as the price assumed in the base case study.

7.6.1 Tax and Cap scenarios implementation

The models cannot be run in one simulation for a complete year which is required in the case of the cap scenario analysis. Therefore a period of 30 days is selected for the simulation. The period selected has to represent the operation of the boiler during the year. The criteria of selecting this period is the share of energy consumed in the hybrid system. The share of energy consumed is an indicative of the volatility of electricity prices, choosing a period with similar energy share as the whole year would guarantee that the hours with high volatility have approximately the same weight as during the year. The period from t=3800 to t=4519 is selected. The share of energy consumed for the simulation of one year and during the 30 days for both hybrid systems are presented in Table 7.7.

Table 7.7: Share of natural gas consumed in the hybrid systems for 1 year and the 30 days selected.

Share (%)	HB	HBS
1 year	82.7	80.7
30 days	83.4	80.7

The analysis is implemented following the subsequent steps:

1. First, the base case scenario is run for the period selected for the HB and the HBS systems.

2. Then the HB and HBS models are run for the Tax scenario. The emissions of CO_2 resulting from the Tax scenario simulations are used as the maximum amount of emissions for the Cap scenario.

3. The emissions are capped calculating the maximum amount of heat (MWh) from the natural gas boiler (E^{ng}_{cap}) which corresponds with the total emissions from the Tax scenario.

4. In order to implement the Cap scenario in the models, additional equations have to be included. These equations limit the total amount of natural gas consumed during the period of simulation. It assures that the total heat produced from natural gas during the Cap scenario is less or equal than the heat produced from natural gas in the Tax scenario.

   - HBS formulation

   $$\sum_{t \in T}((q_t^{d,ng} + q_t^{s,ng}) * \Delta t + E^{ng}_{SU} * v_t^{ng}) \leq E^{ng}_{cap} \tag{7.2}$$

   - HB formulation

   $$\sum_{t \in T}(q_t^{d,ng} * \Delta t + E^{ng}_{SU} * v_t^{ng}) \leq E^{ng}_{cap} \tag{7.3}$$

5. In order to avoid the optimisation to stop abruptly at the last hour of the week, the hybrid systems operation in the last hour is forced to be the same as in the first hour. This condition is implemented adding Equation 7.4, 7.5 and 7.7 to the HBS formulation in Section 4.1. The simulation period of 30 days corresponds to $T = 720\ h$.
   - The amount of heat from the boiler to the demand in t=720 is the same as in t=1.

$$q_{720}^{d,b} = q_1^{d,b} \qquad \forall b \tag{7.4}$$

   - The amount of heat from the boiler to the storage in t=720 is the same as in t=1.

$$q_{720}^{s,b} = q_1^{s,b} \qquad \forall b \tag{7.5}$$

   - The energy level in the storage in t=720 is the same as t=1.

$$s_{720} = s_1 \qquad \forall b \tag{7.6}$$

6. Similarly, this is implemented in the HB formulation. In this case only the heat from the boilers to the demand is forced to be the same in the first and the last hour. Equation 7.7 is added to the formulation in Appendix A.

$$q_{720}^{d,b} = q_1^{d,b} \qquad \forall b \tag{7.7}$$

7. In this analysis the rolling horizon method is not used as it is not required to run the simulation for one year.

8. Finally the operation costs in the Tax scenario and the Cap scenario are compared with the base case study.

7.6.2 Tax and Cap scenarios results

The increase of the price of CO_2 to €120 resulted in a drop of approximately 50.3% and 52.5% of the emissions for the HB and the HBS respectively. The energy share of electricity and natural gas is shown in Figure 7.16. The Tax scenario has a similar impact on the performance of both hybrid systems. The HBS systems has a higher electricity consumption due to the storage which stores steam during low prices of electricity to substitute the use of natural gas.

The CO_2 emissions from the Tax scenario are imposed for the Cap scenario. In Figure 7.17 the operation costs for the base case scenario, the Tax scenario and the Cap scenario are presented for the HB and the HBS systems. It can be seen that the Tax scenario increases significantly the operation costs respect to the base case scenario, approximately by 35.4% in the case of the HB system and 34.9% for the HBS systems.

The HB and HBS systems are simulated for the respective emissions cap. The emissions limit is established from the results in the Tax scenario. It can be seen that the Cap scenario increases the operation costs respect to the base case study, approximately by 15% and 16% for the HB system and HBS system respectively. In this case the operation costs in the Cap scenario is slightly higher for the HBS system because the emissions cap is lower (see Figure 7.16).

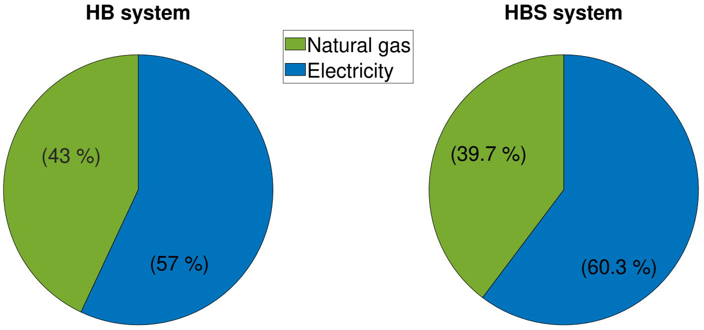

Figure 7.16: Share of energy consumption in the hybrid systems.

It can be concluded that for the same emissions reduction the Cap scenario incurs in lower operation costs in comparison with the Tax scenario. This a straightforward result as the hybrid boiler is forced to increase the consumption of electricity. The hybrid boiler increases the consumption in the same hours for the Tax scenario and the Cap scenario, therefore the costs of the electricity are the similar. The difference is the price of CO_2 in the Tax scenario. The costs increased in the Cap scenario could be seen as a subsidy to increase the hours of electricity used in the hybrid configurations. A subsidy instead of high CO_2 tax could increase the share of electricity consumption at lower costs for the industry. This could reduce the uncertainty observed due to the interaction of future prices of electricity and natural gas.

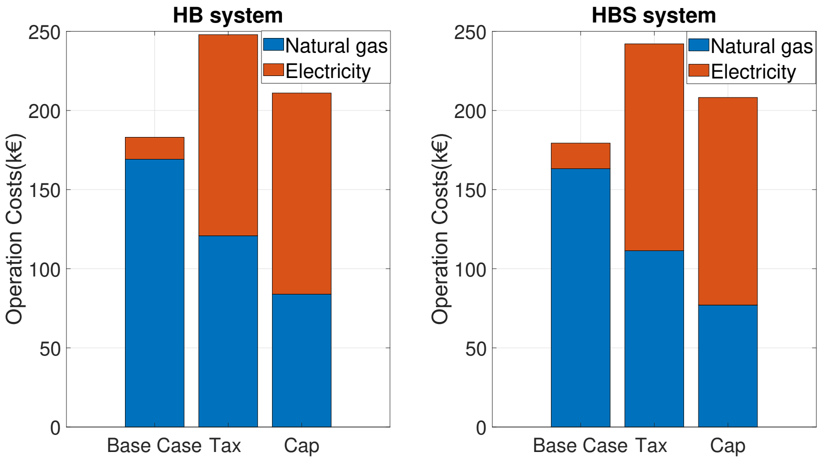

Figure 7.17: Operation costs of the hybrid systems for the base case, cap scenario and tax scenario.

8 DISCUSSION

In this research a techno-economic assessment of hybrid boiler systems is performed to analyse the potential of this technology to cost-effectively decarbonise the steam generation in a production process. In order to answer to the main research question proposed in this thesis, sub-research questions were formulated in Section 1.4. A methodology was proposed to answer the sub-research questions. From this methodology, models to analyse the techno-economic performance of the hybrid systems were developed. Following the methodology, further analysis was presented to provide a broader insight into the results from the models. In this chapter, the results from the models in Chapter 6 and the analysis in Chapter 7 are discussed for each sub-research question. In addition, the limitation of the research to answer the sub-research questions is discussed.

8.1 SIMULATION OF HYBRID SYSTEMS

In this section the sub-research question *Q1* is discussed. In order to analyse the techno-economic performance of hybrid systems, the operation of the systems must be simulated. To this end, technical parameters were selected to simulate the operation of the systems. The sub-research question *Q1* refers to the relevance of the technical parameters selected for the simulation of the hybrid systems operation.

> *"Q1: Which technical parameters are relevant to simulate the operation of hybrid boiler systems?"*

8.1.1 Methodology results

Hybrid configurations are characterised by their ability to take advantage of electricity prices fluctuations. This ability, in practice, is determined by the technical restrictions of the technology. In Chapter 3 the technical parameters to define the operation of the hybrid configurations were selected from literature review and experts interviews. These technical parameters were used to formulate the technical restrictions of the technology operation. The relevance of the technical parameters selected were analysed for the base case scenario presented in Chapter 5. In the scenario proposed, the hybrid systems operated in the Day-ahead market in which the price signals are hourly. The conclusion from the analysis is presented:

1. **Ramp up/down**. From literature review it was concluded that the ramp-up/down parameters are not critical for the hourly operation of the hybrid systems.
2. **Heat flow**. For the case study proposed it was assumed that the storage can be emptied or refilled completely in one hour therefore no restrictions for the heat flow into and

from the storage were considered. This can be assumed for a relatively small storage. In addition, data about the nominal power discharge, which determine the heat flow constraint, for the storage of the base case scenario was not found. In this thesis the relevance of the heat flow parameter of the charge was not analysed.

3. **Start-up time and costs**. From the simulation results, it was observed that the natural gas boiler worked at its minimum during hours in which the costs of producing steam with electricity was cheaper than natural gas. This is due to the start-up constraints of the natural gas boiler. However, from the analysis of the start-up parameters in section 7.1.1 it was concluded that the impact of these parameters on the total operation costs and the emissions of the boiler were negligible.

4. **Minimum heat output**. The minimum heat output is only relevant when the boiler does not switch off to avoid the start-up costs. Therefore, in case that the start-up costs and time are ignored, the influence of the minimum heat output parameter in the operation of the boilers is negligible.

5. **Capacity**. In Section 7.1.2 the capacity assumed for the boilers and the storage were analysed.

   a) Boilers: from the analysis it was concluded that the capacity of the boilers influences the hourly operation of the hybrid system. In [Akzo Nobel, 2018] it was assumed that the electric capacity of the hybrid system is the same as the natural gas. In this thesis the hybrid systems were analysed for different capacities. In the analysis it was concluded that having the same capacity for both sources produced the steam with the lowest price. This is because reducing the electricity capacity reduces the amount of steam that can be produced during hours of low electricity prices, thus increasing the operation costs.

   b) Storage: from the analysis it can be concluded that the capacity of the storage had less impact on the operation costs than the boiler capacity. Increasing or decreasing the capacity by 5 MWh barely increased/decreased the price of the steam produced. The configuration of the hybrid boiler with storage did not improve the techno-economic performance of the system significantly. This is because the storage was charged during hours of low electricity prices, the number of hours that the storage was charged in the case study were 339 hours which represents 4% of the year. The storage improved the performance of the hybrid system respect to the HB during weeks of high fluctuations of the prices. Therefore, the storage would be a better option for markets with higher prices volatility. The storage could be relevant in case of demand fluctuations, in this thesis the demand was considered constant.

6. **Efficiency**. The relevance of the efficiency of the boiler is not analysed. In literature review the efficiency is the main parameter used for the analysis of hybrid electrification. This parameter was assumed to be relevant.

The parameters analysed revealed that simulating the boiler neglecting the start-up constraints barely changed the operation of the boiler for the case study presented. It was concluded that the hourly operation of hybrid systems could be simulated only considering two parameters: capacity and efficiency. This conclusion stands for hourly or longer price signals. In this thesis, the relevance of the start-up parameters were not analysed for shorter price signal periods. In the case of the Day-ahead market (hourly prices), the relevance of the start-up parameters also depends on the fluctuation of the prices. In case that the fluctuation of the prices increases both in frequency and magnitude, the start-up parameters could become relevant in terms of operation costs and emissions. It can be concluded that the research papers and studies cited in the literature review [Jansen et al., 2019; Akzo Nobel, 2018; Härtel and Sandau, 2017], in which hybrid systems were simulated considering only the capacity and the efficiency of the technology, incurred in a negligible error. Hybrid boiler systems can react to the hourly fluctuations of the electricity price. In addition, the storage did not make a significant difference for the 2030 scenario analysis, therefore this configuration could be neglected.

8.1.2 Limitations

In this research only hourly operation of the hybrid systems is analysed. The analysis of the operation of hybrid systems for shorter periods (i.e. 30 min, 15 min, 30 s) would have provided insight into at which period the technical parameters neglected start to impact the responsiveness of the system to the prices signals. In this thesis, the evaluation of the relevance of the parameters is limited.

The models formulated did not consider the quality of the steam generated. The quality of the steam (pressure, temperature) can be relevant in case that the steam is directly used in the production process. In the case study presented in Chapter 5 the steam is used in the vulcanisation process of the tyre. During this process the temperature and the pressure of the steam affects the quality of the product. This issue could incur in additional costs for the industry. In this cases, a collaboration with the industry could provide more insight into the restrictions of the system operation caused by the production process and the possible additional costs.

In this thesis, two configurations of hybrid systems were analysed. These configurations had slightly different techno-economic performance. Therefore, the incorporation of the storage to the hybrid boiler would not provide significant advantages. In addition, the space required for the equipment can be specially relevant in the case of the storage. In this thesis, the space available in the industry is not considered. There are electric boilers with a compact design, for the capacity required in the base case scenario the electric boiler can require an additional space of 5.5 m^2 [PARAT, 2019]. However in the case of including the storage the space required could be much larger.

8.2 PERFORMANCE OF HYBRID SYSTEMS

The operation of the hybrid configurations was simulated minimising the operation costs. The optimised operation was assessed by means of technical and economic indicators. In addition, the results were compared to alternative solutions for the steam generation unit. The alternative technologies are: natural gas boiler (NG), electric boiler (EB) and the electric boiler with storage (EBS). These technologies were simulated for the same scenario. This analysis was performed to answer to the sub-research question *Q2* which refers to the techno-economic valuation of the hybrid systems.

"Q2: What is the performance of hybrid boiler systems in terms of operation costs, efficiency, direct CO_2 emissions and levelised cost of the steam produced in comparison with other alternatives?"

8.2.1 Methodology results

The hybrid configurations reduced the natural gas consumption in the steam generation unit in comparison with the natural gas boiler. The natural gas was substituted with electricity during approximately 1752 hours, 20% of the year. In other studies in which the hybrid boiler operation was simulated for 2030 the electricity was used 14% of the year (1,200 hours) [Akzo Nobel, 2018]. In [Jansen et al., 2019], the electricity was used 6% of the year (524 hours). In this thesis the electricity prices were retrieved from COMPETES in which the Climate Agreement was used to set the scenario for 2030. In this scenario a higher CO_2 price is expected (46.3 €) as well as a higher share of renewable energy which increases the fluctuation of the prices both resulting in a higher use of electricity in the hybrid system.

The use of thermal storage resulted increased the use electricity to 21.6 % of the time. Only 1.6% increase respect to the HB system. It can be concluded that the use of the storage did not provide a significant increase in the total hours of electricity use. In a scenario with more fluctuations the difference between both configurations would be more significant.

In terms of energy consumption, the EB and the EBS consumed the lowest amount of energy. This is due to a higher efficiency of the electric conversion. In the case of the hybrid configurations the efficiency increased reducing the total energy consumption by less than 2% respect to the natural gas boiler. The increase of the efficiency is related to a higher share of electricity consumption. The share of electricity consumed is 17% for the HB configuration and 19% adding the storage. This share is lower than the share of hours during which the natural gas was substituted. This is because the natural gas boiler worked at its minimum during hours in which the electricity price was lower than natural gas to avoid the start-up costs.

The increase of the electricity consumption in the hybrid configurations reduced the direct CO_2 emissions. The reduction of the emissions is proportional to the share of electricity consumed. The hybrid systems reduced the CO_2 by almost 20%. In this scenario, a deep decarbonisation would be possible with the substitution of the natural gas with hydrogen or green gas. The substitution of the natural gas with other sources is not analysed in this thesis. Alternatively, the costs of producing steam with natural gas should be increased artificially to increase the share of electricity.

In addition, in this thesis the indirect emissions were estimated. In the analysis the indirect emissions were only 8% of the total emissions according to the emission factors assumed for the analysis. A full electrification of the system would reduce the total emissions (direct and indirect) by 42%. Including a storage to the electric boiler did not represent a significant reduction of the indirect emissions. These results are subjected to the assumption for the emission factor assumed. In [PBL, 2019c] an update of the green house emissions and the energy system in the Netherlands up to 2030 is provided. In this document the average emission factor for 2030 is estimated using two methods, therefore two possible emissions factors are presented, 0.09 kWh/kg CO_2 and 0.28 kWh/kg CO_2 [PBL, 2019c]. In this thesis the average emission factor used is 0.13 kWh/kg CO_2 which would correspond with most of the hours of the year. This number is between the averages estimated by PBL. However for hours with a higher share of fossil fuels the emission factor assumed is 0.25 kWh/kg CO_2 which could be low as the average for to 2030 could be 0.28 kWh/kg CO_2.

Subsequently the results of the economic parameters are discussed. The economic parameters provide insight into the costs of the decarbonisation of the steam generation. The economic indicators showed that the hybrid configurations saved operation costs by increasing the electricity share. Although the investment costs of the hybrid configurations are considerably higher than the natural gas boiler the price of the steam produced was lower due to the operation costs saved. However, these results did not consider the network tariffs due to an increase of the electricity capacity. The impact of the network tariffs in the price of the steam produced was analysed in Section 7.4. The network tariffs increased the price of steam hybrid configurations. The steam was 2 €/t higher than the price of the steam produced in a natural gas boiler. Due to the network tariffs the hybrid configurations became a more expensive alternative than the natural gas boiler. This conclusion was already drawn in the mentioned studies [Akzo Nobel, 2018; Jansen et al., 2019] with more conservative scenarios for the CO_2 price. It can be concluded that for the 2030 scenario presented in this thesis in which higher CO_2 prices are assumed due to the Climate Agreement in addition to more volatile electricity prices did not improve the business case of the hybrid configurations when network tariffs were considered. The costs saved were not enough to produce the steam at a lower price than the natural gas boiler.

8.2.2 Limitations

1. **Forecast and Day-ahead market**

   The hourly operation of the hybrid configuration was optimised considering the technical restrictions of the system and the prices of the commodities. The models minimised the operation costs of the systems scheduling the consumption at every hour. In this thesis it was assumed perfect foresight of the electricity prices for the entire year. However, in reality the forecast available is for shorter periods. In Section 7.2 the simulation of the heat production unit is performed assuming only 2 days of perfect forecast and it is optimised for 1 day. From the analysis it was concluded that the hourly operation of the HB system did not change while the change of the HBS system operation was negligible.

The operation of the system for 1 day could be optimised with two days of prediction. However this analysis does not provide information about the period of prediction for which the optimisation changes. In the analysis it was observed that higher deviation of the costs from the optimum was during in weeks with more fluctuations in the electricity prices. This analysis only gave insight into the impact of shorter optimisation periods (prediction horizon). In this thesis, hybrid systems were not analysed considering an error of the forecast which might affect the performance of the system.

In this thesis it is assumed that the industry participates in the Day-ahead market. The models used for the analysis considered perfect foresight of the prices. In reality, the industry would pay for forecast of the electricity prices. These prices are used to optimise the schedule of the boiler for a certain period. The deadline to submit the bids for the 24 hours of the day of dispatch is the previous day at 12 am. Once the market is closed, the bids are sent to the market operator to clear the market price. Once the market price is cleared a contract is established. The bids are based on the forecast of the electricity prices and this forecast is based on the information available before the deadline [Lago et al., 2018]. In addition, the price of the bid has to be set through a bidding strategy [Di Somma et al., 2019]. This complex process can be avoided through aggregators. The aggregators are energy players that can manage a portfolio of flexibility (demand side response) on behalf of the vendors for different markets [Ottesen et al., 2018]. However, contracting this service might incur in additional costs for the industry. In addition, the contracts required for the participation in the markets are subjected to technical conditions and costs which are not considered in this research. For instance, the Day-ahead market is operated by EPEX which charges 25,000€ for an entrance fee and 10,000€ annual fee per member [EEX Group, 2019].

2. Demand response programs

The industry can use the hybrid electrification to provide flexibility to the power system. In the Climate Agreement hybrid electrification including different forms of buffering is expected to provide flexibility to the system [Dutch Government, 2019a]. In this research it was assumed that the industry would participate in the Day-ahead market consuming electricity during hours in which the price of electricity was low. However the flexible consumption could also be used in different demand response programs.

Demand response (DR) is the action of the consumers to change their consumption of electricity power responding to price signals (changes in the price) or incentive payment to reduce the electricity consumption during high prices in the wholesale market. In addition demand response can be used to ensure the reliability of the power system [Lopes and Algarvio, 2018]. Usually, the consumers respond reducing the consumption at times of high market prices or rescheduling the consumption to another time period. The demand response can be classified in two categories: incentive-based DR programs and price-based DR programs. The price-based DR corresponds to changes in the consumption as a response to variation of the price of electricity while price-based demand response refers to the real-time pricing or time-based pricing.

a) The incentive-based programs are contractual arrangements which trigger demand reduction from the consumers when the system operator requires to ensure the reliability of the system or when the prices are high. These programs are separate from the retail electricity rates. There are different programs in which the consumer can participate: direct load control programs, interruptible rates, demand bidding programs, emergency demand response programs, capacity market programs and ancillary services market programs (for details see [Lopes and Algarvio, 2018]). In this section we only discuss ancillary services.

   In the case of ancillary services the consumer bid load curtailment as operating reserves in the organised wholesale market. In the Netherlands Tennet uses ancillary services for different purposes: balancing reserves, reactive power, redispatch, etc. Through the balancing reserves Tennet restore the power imbalance in the system. There are various services: the frequency containment reserves (FCR), the automatic Frequency Restoration Reserve (aFRR), the manual Restoration Reserve scheduled activates (mFRRsa) and the manual Frequency Restoration Reserve direct activated (mRRda) [Tennet, 2019]. In order to participate in these services technical requirements and specifications have to be fulfilled (for instance the FCR requires a response within 30 seconds, while for FRR the system has to reach the activation in 15 min). In [Jansen et al., 2019], hybrid boilers were analysed for the aFRR and the mFRR services. The market participants offer bids and the service is activated by Tennet. The business case of a hybrid boiler participating in these services is subjected to high uncertainties regarding the revenues. In addition the revenues could decrease if the offers of demand response increase.

   In this thesis the industry responds to the hourly change of the wholesale price. The model presented in the thesis can be easily adapted to other markets (e.i. imbalance market) changing the time step of the formulation and adjusting the parameters to the corresponding time step. In Chapter 7, it was concluded that the start-up costs and the start-up time can be neglected for the hourly operation. However for shorter periods these restrictions could impact the results. In addition, technical restrictions neglected in the Day-ahead market such as the ramp up/down of the boilers and the heat flow for the storage might become relevant.

   Participating in these services can be additional to participate in the Day-ahead market. These services can benefit the integration of renewable electricity. However, the impact in terms of direct emissions reduction in the industry is uncertain. These services can be an additional revenue to the industry, therefore the business case of hybrid electrification might be improved. In addition, the share of electricity might increase.

b) The price-based response programs corresponds with changes in the consumption of customers reacting to changes in the electricity price over time. By changing the consumption to periods of lower electricity price they reduce the electricity bill. The response to the prices is decided by the customer and it is voluntary. The most common tariffs are: time-of-use, real-time pricing and critical peak pricing. In the real time pricing (RTP) information about the price is provided to the costumers. The prices are market-based electricity prices which provides a link between the wholesale market and the retail market. This is the most common tariff for large and medium industrial consumers [Lopes and Algarvio, 2018].

In conclusion, hybrid electrification can be an opportunity to provide benefits to the power system while reducing the direct emissions. In the Netherlands, the government will review whether more flexibility can be provided with power-to-heat in the industry to link the electricity consumption with Renewable energy generation [Dutch Government, 2019a]. The demand response programs can be an incentive for industries to invest in power-to-heat technologies.

3. Taxes and Levies

In addition to the market price of natural gas and electricity there are government levies. The government levies include the VAT (Value Added Tax), the Energy Tax and the ODE levy (''Opslag Duurzame Energie").

a) The Energy Tax is a tax applied for gas and electricity consumption.

b) ODE levy is also called sustainable energy surcharge and contribute to the transition from fossil fuels to sustainable energy [RVO, 2019].

In this master thesis the levies were not considered for the hourly operation of the hybrid boiler. These levies are charged per volume of gas and electricity consumed, therefore it could be relevant for the performance of the boiler. According to [Ünlü, 2019] the taxes for small industrial consumers decreases the hours in which electricity is consumed by 16%. While for large industry consumers the electricity tax is not significant as it is marginally lower than gas. Therefore including the taxes in the model in case of large consumer it would increase the operating hours of electricity. In [Ünlü, 2019] the taxes for large consumers increase the electricity consumption by 11.7%. A tax shift which decreases the electricity energy tax and increases the natural gas can improve the business case of hybrid boilers [Ünlü, 2019; Akzo Nobel, 2018]. In the sensitivity analysis (see Section 7.5) it was observed that the difference between electricity and natural gas is relevant, therefore the energy tax could play an important role setting the right conditions to enhance the potential of hybrid systems as a decarbonisation pathway.

The SDE+ subsidy scheme is funded through the ODE tax. The ODE is charged half to households and the other half to businesses, however the government will increase the share for businesses to two thirds after 2020 [Dutch Government, 2019a]. Furthermore, the ETS, the energy tax and the ODE will be supplemented by a carbon levy [Dutch Government, 2019a]. The carbon levy is expected to start at 30 € per tonne by 2021 and increase linearly until 125-150 € per tonne including the ETS price which would be at

70-100 € per tonne.

Simulating the hybrid configuration for a carbon levy of 120 € for the scenario of 2030 changing only the carbon price, increased the share of electricity to approximately 60% (this was also observed in the analysis of the Cap scenario in Section 7.6). Similarly, increasing the carbon tax to 150 € it increased the electricity share to almost 90% (this was simulated increasing the CO_2 price of the scenario presented in Chapter 5 to 150 €). In this case, investing in a hybrid boiler would not be interesting. This scenario would result in a baseload electrification of the heat which would increase considerable the electricity demand. In addition, it does not assure that this electricity will come from renewable energy. Therefore, the CO_2 tax should be set studying the interaction with the electricity and natural gas prices.

4. **Alternative options**

   In this thesis, hybrid configurations were compared to alternative options (NG, EB, EBS). However there are more decarbonisation options that are excluded from the analysis. Alternative decarbonisation options are the use of biomass boiler, hydrogen boiler or biogas boiler. These options are specially relevant for processes at high temperature as the hybrid boiler is limited by the electric boiler which can produce steam up to 350^{o}C [TNO, 2019]. Hydrogen is an important alternative for temperature above 600^{o}C [Dutch Government, 2019a].

   In this thesis the use of biomass is not included. Biomass boilers are an available technology that could decarbonise the production of heat. This technology depends on the availability and price of biomass in the future (2030). Similar conclusion can be applied for the use of biogas. The substitution of the natural gas with biogas or hydrogen in the future could be an alternative hybrid solution. The use of these fuels depends on the availability of the network and the price of the fuel. In addition, in the case of using biogas upgraded to the quality of natural gas (green gas) no changes are required in the boiler. Whilst in the case of hydrogen the burners used for natural gas would be substituted by hydrogen burners. Hydrogen burners are commercially available [Hart et al., 2015].

5. **Network tariffs**

   The impact of the network tariffs was analysed as an additional investment cost that increases the price of the steam produced in the hybrid configuration. The network tariffs considered are the grid connection tariff and the transmission tariff. The grid connection tariff is an additional investment cost that might be required. The transport tariff is also included as an additional investment cost using an average yearly cost estimated for this tariff. However this tariff depends on the number of hours of electricity use and the capacity consumed. Therefore this tariff can affect the operation of the hybrid boiler. To analyse the impact of the transmission tariff on the operation of the hybrid boiler it should have been included as an additional operation cost in the model.

8.3 UNCERTAINTY IN 2030

In this section the sub-research question Q3 is discussed. The performance of the hybrid configurations in 2030 is subjected to the uncertainties regarding the scenario in 2030. The uncertainty is related to the natural gas, electricity and CO_2 price.

"Q3: To what extent is the operation of hybrid boiler systems sensitive to the uncertainty of the electricity, natural gas and CO_2 prices for 2030?"

8.3.1 Methodology results

In this thesis the operation of the hybrid configuration was analysed for 2030. The prices assumed for 2030 are uncertain therefore the operation of the hybrid boilers is analysed for different alternative scenarios for 2030. To this end, two analysis are presented in Chapter 7:

1. A sensitivity analysis is performed in which the prices of electricity, natural gas and CO_2 were varied within different bandwidths. In the sensitivity analysis, the prices are varied simultaneously as the operation of the boiler depends on the interaction of the prices. From this analysis it was concluded that the electricity price had little impact on the performance of the hybrid system in comparison with the natural gas and the CO_2 price. The increase of natural gas price had the largest impact on the performance of the boiler in terms of operation costs and emissions reduction. The extreme scenarios for 2030 occurred when the hybrid system worked almost entirely with electricity or natural gas. In this case the hybrid solution would not be a cost-effective solution as it would not work as a hybrid system.

   In addition, the scenarios in which the direct emissions were reduced it was observed that the emissions were reduced at different costs. For scenarios in which the amount of emissions reduced was similar (30 and 33 %) the costs highly varied (between 76-220€/ton). In this analysis it was observed that the impact of the carbon price strongly depends on the difference between the natural gas price and the electricity price. For the same carbon price the emissions could be reduced by only 5% in case of a relative high difference between natural gas and electricity. Conversely, with low differences the emissions were reduced by 88% respect to the base case study.

2. Deep decarbonisation measures were analysed for the hybrid configurations. The measures compared were a scenario with a high CO_2 tax (Tax scenario) and a scenario in which the emissions were capped (Cap scenario) maintaining the CO_2 price of the base case scenario. From this analysis it was concluded that for the same CO_2 emission reduction the Cap scenario incurred in lower operation costs.

8.3.2 Limitations

1. **Uncertainty scenarios**

The results from the 2030 scenario can seem positive as it was observed that operation costs were saved in the hybrid configurations while the direct emission decreased. The share of steam produced from electricity in the case study simulated for the HBS and the HB configuration were 19% and 17% respectively. These results are subjected to the uncertainty of the commodities prices assumed for 2030. For scenarios in which the electricity price was increased and the natural gas decreased the hybrid configuration worked mostly with natural gas. In these cases, the switch to hybrid configuration would not be justify. The same conclusion can be derived from the scenarios in which the hybrid configurations worked mostly based on electricity. In this case an electric boiler would be a more cost-effective decarbonisation strategy. The variation of the prices strongly influenced the performance of the hybrid configuration. In some cases the hybrid system represented very limited advantages respect to the natural gas boiler.

In this thesis 26 variations of the base case study scenarios were used to analyse the uncertainty of the operation of the hybrid system in 2030, however the inputs (electricity price, natural gas price and CO_2 price) were varied assuming that there is no correlation between the them. Therefore some of the scenarios proposed might not be realistic. In the base case scenario the hourly electricity prices were retrieved from the COMPETES model in which the CO_2 price and the natural gas price were inputs. Therefore the electricity price might be correlated to these prices. Moreover the price of natural gas was predicted considering the increase of the CO_2 price. Therefore, a more realistic uncertainty scenario could have been performed running the COMPETES model for different CO_2 price and natural gas prices to obtain the electricity price related to these prices.

For the analysis of the Cap and Tax scenario it is assumed that the industry knows before hand the prices of electricity for the whole year so that it can optimise the operation of the boiler according to the cap established for the emissions. This is not a realistic scenario as the forecast of the prices would be available for shorter periods. However the results from the cap scenario could be seen as an alternative option to reduce the emission based on a subsidy for the industry to increase the electricity consumption. Industrial electric boilers could be included in the SDE+ scheme which will be expanded in 2020. Options to reduce the CO_2 emissions would be considered eligible for subsidy [PBL, 2019a].

2. **Fluctuations of electricity prices**

The performance of the hybrid boiler relies also on the fluctuation of the electricity prices. In the literature review a higher volatility of the electricity prices are expected for 2030. The hybrid boiler takes advantage of these fluctuations switching to natural gas when the electricity prices are high and consuming electricity when the prices are low. In the base case scenario, the Day-ahead prices reached minimum prices of 1.5 € /MWh (see Figure **??**). Although very low electricity prices represented only 8% of the hours in a year the hybrid boiler saved operating costs due to the fact that the prices were almost zero. In case that electricity prices in 2030 do not fluctuate due to a high demand response available in the system which would balance the fluctuations of the renewable energy generation, the operation costs saved in the hybrid boiler would be reduced. This reduction can be observed when simulating the model for Day-ahead prices from 2018. In markets closer to real time (e.g. intraday market, imbalance markets) the volatility of the prices is higher which might benefit the performance of the hybrid boiler.

3. **Production costs**

   The industry has to deal with a high uncertainty in comparison with the current situation in which long term contracts are established for natural gas and electricity. Forward and future markets of electricity are contracts in which the price of electricity for a future consumption is agreed "today". Industry uses these markets to reduce the risks and vulnerability to scenarios in which price can increase. Long term contract reduce the uncertainty regarding the prices and facilitates the control of the costs of the production process. In this thesis there is little attention to the product of the industry. Analysing the share of the levelised costs of the steam in the total production cost of tyre could have given better insight into the impact of the uncertainty of the prices in the total production cost of the product.

8.4 FUTURE RESEARCH

This research provided insights into the performance of hybrid boilers in 2030 considering the new conditions established by the Climate Agreement. However, the scope of the research is limited. The limitations discussed in this chapter leads to more questions regarding the use of hybrid boilers in the industry.

This research looks into the potential of the hybrid boiler to reduce the direct emissions in the industry in the Day-ahead market. However, this research excluded other business cases which might exploit better the benefits from the hybrid technology, both for the industry and the power system. To provide a complete picture of the potential of hybrid boilers, the research should include the business cases which would be more interesting for this technology. In addition, this technology is characterised by its flexibility which depends on the technical restrictions related to its operation. The quantification of the flexibility could bring more insight into the possible business cases in which this technology could participate.

In addition, in this research it was seen that the interaction of the prices would strongly influence the operation of the hybrid boiler. Therefore reasearch into the interaction of the prices using realistic scenarios in which the prices are correlated could provide insight into the bounderies in which the hybrid boiler makes use of its flexible nature to reduce emissions while providing benefits to the power system. In the Climate Agreement hybrid electrification is presented as a possible tool to ensure the electrification of the industry, however more research is required to set the right conditions to encourage the use of this technology.

The case study presented in this research used a hybrid boiler in which a gas boiler and an electric boiler worked in parallel. The application of this setup is limited by the electric boiler which only produces steam at a maximum temperature of 350^{o}C [TNO, 2019]. Other setups might increase the application of hybrid boilers in the industry. In addition, the application of heat pumps as an alternative hybrid electrification for heat demand in the industry should be included.

Finally, in this research the hybrid boiler was analysed as a price taker which cannot influence the prices of electricity. However, the deployment of this technology might influence the prices of electricity mitigating the fluctuation of the price and therefore reducing the opportunities of saving costs during the fluctuations.

9 CONCLUSION

The Netherlands aims to accelerate the energy transition. Accordingly, ambitious targets have been set for the industrial sector. This will require additional investments in the Dutch industry which is expected to reduce the CO_2 emissions at limited costs in comparison with other sectors [Dutch Government, 2019a]. However, the ambition to reduce the emissions can create a risk of loss of activity and jobs if the industrial businesses prospects are not ensured.

Power-to-heat technology provides an opportunity to the industry to reduce the emissions for heating processes (assuming that there is a significant share of renewable electricity). This technology can be implemented in hybrid configurations to ensure the electrification of heat. Hybrid configurations are characterised by their ability to switch between natural gas and electricity to cost-effectively reduce the emissions consuming electricity at low prices. An example of hybrid electrification are hybrid boilers. Hybrid boilers combine the use of mature technologies (natural gas boilers and electric boilers) to create opportunities to reduce direct emissions. In this research, a techno-economic evaluation of hybrid boiler systems is performed to analyse the potential of this technology to cost-effectively reduce the CO_2 emissions for steam generation in a production process, in 2030. To this end, the operation of hybrid boiler systems was simulated and assessed. The hybrid boiler configurations considered are a hybrid boiler and a hybrid boiler with storage. The performance of the hybrid configurations were compared to alternative technologies. Finally, the performance of the hybrid systems was analysed under different scenarios for 2030. After the discussion of the results and the analysis, the main research question proposed in this thesis is answered:

"To what extent are hybrid boiler systems a cost-effective decarbonisation strategy for steam generation in the industry for 2030?"

This research shows that the operation of hybrid boiler systems in the case scenario analysed, resulted in a reduction of almost 20% of the emissions electrifying part of the heat demand in the production process. In the simulation the hybrid boiler was able to respond to the hourly fluctuation of the electricity prices, switching from natural gas to electricity during hours in which producing the steam from electricity was cheaper. As a result, the hybrid configurations incurred in lower operation costs than alternative options: natural gas boiler, electric boiler and electric boiler with storage. Despite of the fact that the investment costs were considerably higher for the hybrid configurations the price of the steam produced was lower than the alternative options.

It can be concluded that for the case study analysed the hybrid boiler reduced the emissions cost-effectively. However, the incorporation of storage to the hybrid boiler did not improve significantly the performance in terms of emissions reduction and operation costs saved. In the contrary, adding the storage increased the investment costs by 70%. Therefore, for the case study presented the hybrid boiler with storage would not be a cost-effective solution.

In the uncertainty analysis, it was observed that the hybrid boiler could potentially increase the electrification of the steam generation. The electrification could reach up to 87% of the heat generation. In this case the hybrid boiler becomes a baseload electrification for which an electric boiler would be a more cost-effective alternative. In addition, a baseload electrification would not provide flexibility to the system. The flexible operation of the hybrid boilers can link the electricity consumption with hours of abundance of renewable electricity generation and avoid the consumption during peak hours which would benefit the integration of renewable electricity. The potential benefits of hybrid boilers are subjected to other factors and uncertainties. The use of the flexible characteristic of the system depends on the following aspects:

1. The business case influence the performance of the boiler. In this thesis the hybrid system was analysed for the Day-ahead market. However this market might limit the potential of the hybrid boiler for instance due to a lower fluctuation of the prices in comparison with other markets. In addition, a bidding strategy based on the forecast it is required which might be a complex process. Alternatively, price-based demand response programs can provide the opportunity for hybrid boilers to increase the operation costs saved by using its flexibility. Moreover, the use of the flexible consumption of the hybrid boiler under incentive-based demand response programs could be a source of income for the industry. These programs could exploit the potential benefits of the hybrid boiler and increase the electrification at lower costs.

2. The operation of the boiler is subjected to the uncertainty of future prices of the commodities. In this thesis it was concluded that the interaction between the electricity price, the natural gas price and the CO2 strongly impacts the performance of the hybrid boiler. The operation of the hybrid boiler could also be affected by measures from the government to accelerate the energy transition, like taxes and levies.

3. Transmission tariffs based on the capacity consumed can impact the operation of the hybrid boiler reducing the potential use of its flexibility.

In conclusion, hybrid boilers have potential to electrify part of the heat generation in the industry reducing the direct emissions. In addition, the electricity would be consumed during hours of low electricity prices which would benefit the integration of renewable energy. These benefits could be reached exploiting the flexible nature of this technology. Therefore, the right conditions must be set for hybrid boilers to support the energy transition in the industry.

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A MATHEMATICAL FORMULATION

A.1 HYBRID BOILER WITHOUT STORAGE

In this section the mathematical formulation for the hybrid boiler without the storage is presented.

A.1.1 Optimisation

- The objective function

$$\min \sum_{t \in T} c_t^{tot} \tag{A.1}$$

$$\begin{aligned} c_t^{tot} = C_t^{ng} q_t^{d,ng} \Delta t / \eta^{ng} + C^{CO2} q_t^{d,ng} \Delta t / \eta^{ng} + C_{su}^{ng} v_t^{ng} \\ + C_t^{ele} q_t^{d,eb} \Delta t / \eta^{eb} + C_{su}^{eb} v_t^{eb} \end{aligned} \tag{A.2}$$

  The fuel consumed at every hour can be expressed as the energy output of the boiler divided by the total efficiency of the boiler (same approach is used for the electric boiler).

$$Energy_t = q_t^{d,b} \Delta t / \eta^b \qquad \forall t,\ \forall b \tag{A.3}$$

- Heat balance

$$\sum_b q_t^{d,b} = D_t \qquad \forall t,\ \forall b \tag{A.4}$$

- Ramping limits

$$q_t^{d,b} - q_{t-1}^{d,b} \leq R_{up}^b \qquad \forall t,\ \forall b \tag{A.5}$$

$$q_{t-1}^{d,b} - q_t^{d,b} \leq R_{down}^b \qquad \forall t,\ \forall b \tag{A.6}$$

- Logical constraint

$$u_t^b - u_{t-1}^b = v_t^b - w_t^b \qquad \forall t,\ \forall b \tag{A.7}$$

- Minimum downtime

$$\sum_{i=t-TD^b+1}^{t} w_i^b \leq 1 - u_t^b \qquad \forall t \in [TD^b, T],\ \forall b \tag{A.8}$$

- Minimum heat output

$$q_t^{d,b} \geq u_t^b Q_{min}^b \qquad \forall t,\ \forall b \tag{A.9}$$

- Capacity constraints

$$q_t^{d,b} \leq u_t^b Q_{max}^b \qquad \forall t,\ \forall b \tag{A.10}$$

A.1.2 Performance Indicators

- Total operation costs

$$C_{total} = \sum_{t \in T} c_t^{tot} \tag{A.11}$$

- LCOP (see Section 4.2).
- CO_2 direct emissions

$$CO_2 = \frac{\sum_{t \in T}(q_t^{d,ng}\Delta t + E_{SU}^{ng} * v_t^{ng})(MWh) * 3.6(GJ/MWh) * 56.6(kg/GJ)}{\eta^{ng} * 1000(kg/ton)} \tag{A.12}$$

- Total system efficiency

$$E_{Input} = \sum_{t \in T} q_t^{d,ng}\Delta t/\eta^{ng} + q_t^{d,eb}\Delta t/\eta^{eb} + E_{SU}^{ng} * v_t^{ng} + E_{SU}^{eb} * v_t^{eb} \tag{A.13}$$

$$\eta_{hybrid} = \frac{\sum_{t \in T} D_t}{E_{Input}} \tag{A.14}$$

A.2 NATURAL GAS BOILER

The results from the hybrid boiler systems are compared with the performance of a natural gas boiler. To this purpose the performance indicators are formulated for the natural gas boiler case. The formulation of the LCOP is the same as for the hybrid boiler with steam accumulator presented in Section 4.2.

- Total operation costs

$$C_{total} = \sum_{t \in T}(C_t^{ng} + C^{CO_2})D_t\Delta t/\eta^{ng} \tag{A.15}$$

- LCOP (see Section 4.2).
- CO_2 direct emissions

$$CO_2 = \frac{\sum_{t \in T} D_t\Delta t(MWh) * 3.6(GJ/MWh) * 56.6(kg/GJ)}{\eta^{ng} * 1000(kg/ton)} \tag{A.16}$$

- Total energy input

$$E_{Input} = \sum_{t \in T} D_t\Delta t/\eta^{ng} \tag{A.17}$$

A.3 ELECTRIC BOILER

Similarly, the results from the hybrid boiler systems are compared with the performance of a electric boiler. To this purpose the performance indicators are formulated for the electric boiler case. In this case the CO_2 direct emissions are considered to be zero. Moreover, the LCOP is the same as in the previous formulations.

- Total operation costs

$$C_{total} = \sum_{t \in T} C_t^{eb} D_t \Delta t / \eta^{eb} \tag{A.18}$$

- LCOP (see Section 4.2).
- CO_2 direct emissions

$$CO_2 = 0 \tag{A.19}$$

- Total energy input

$$E_{Input} = \sum_{t \in T} D_t \Delta t / \eta^{eb} \tag{A.20}$$

A.4 ELECTRIC BOILER WITH STORAGE

A.4.1 Optimisation

In this section the mathematical formulation for the electric boiler with storage is presented.

- The objective function

$$\min \sum_{t \in T} c_t^{tot} \tag{A.21}$$

$$c_t^{tot} = C_t^{ele}(q_t^{d,eb} + q_t^{s,eb})\Delta t / \eta^{eb} + C_{su}^{eb} v_t^{eb} \tag{A.22}$$

The electricity consumed at every hour can be expressed as the energy output of the boiler divided by the total efficiency of the boiler.

$$Energy_t = q_t^{eb} \Delta t / \eta^{eb} \qquad \forall t, \tag{A.23}$$

- Heat balance

$$q_t^{eb} + q_t^{d,s} = D_t \qquad \forall t, \tag{A.24}$$

- Ramping limits

$$(q_t^{d,eb} + q_t^{s,eb}) - (q_{t-1}^{d,eb} + q_{t-1}^{s,eb}) \leq R_{up}^{eb} \qquad \forall t, \tag{A.25}$$

$$(q_{t-1}^{d,eb} + q_{t-1}^{s,eb}) - (q_t^{d,eb} + q_t^{s,eb}) \leq R_{down}^{eb} \qquad \forall t, \tag{A.26}$$

- Logical constraint

$$u_t^{eb} - u_{t-1}^{eb} = v_t^{eb} - w_t^{eb} \qquad \forall t, \tag{A.27}$$

- Minimum downtime

$$\sum_{i=t-TD^{eb}+1}^{t} w_i^{eb} \leq 1 - u_t^{eb} \qquad \forall t \in [TD^{eb}, T], \tag{A.28}$$

- Minimum heat output

$$q_t^{d,eb} + q_t^{s,eb} \geq u_t^{eb} Q_{min}^{eb} \qquad \forall t, \tag{A.29}$$

- Capacity constraints

$$q_t^{d,eb} + q_t^{s,eb} \leq u_t^{eb} Q_{max}^{eb} \qquad \forall t, \tag{A.30}$$

$$s_t \leq E_{max}^{s} \qquad \forall t \tag{A.31}$$

- Storage operation

$$s_t = s_{t-1} + q_t^{s,eb}\Delta t - S_{loss} q_t^{d,s}\Delta t \qquad \forall t \tag{A.32}$$

$$q_t^{d,s} \leq S_{flow} \qquad \forall t \tag{A.33}$$

$$q_t^{s,eb} \leq S_{flow} \qquad \forall t \tag{A.34}$$

A.4.2 Performance Indicators

- Total operation costs

$$C_{total} = \sum_{t \in T} c_t^{tot} \tag{A.35}$$

- LCOP (see Section 4.2).
- CO_2 direct emissions

$$CO_2 = 0 \tag{A.36}$$

- Total system efficiency

$$E_{Input} = \sum_{t \in T} q_t^{d,eb}\Delta t / \eta^{eb} + E_{SU}^{eb} * v_t^{eb} \tag{A.37}$$

$$\eta_{hybrid} = \frac{\sum_{t \in T} D_t}{E_{Input}} \tag{A.38}$$

B SCENARIO 2030: MODEL FORMULATION

B.1 HYBRID BOILER SYSTEM

Table B.1: Formulation of the hybrid boiler for the Scenario 2030.

Optimisation	
The objective function	$\min \sum_{t\in T} c_t^{tot}$ $c_t^{tot} = (C_t^{ng} + 0.2 * 46.3)\ q_t^{d,ng} 1/0.90 +\ 8.8 * C_t^{ng} v_t^{ng}$ $+ C_t^{ele} q_t^{d,eb}\ 1/0.99$
Heat balance	$q_t^{d,ng} + q_t^{d,eb} = 7.5 \qquad \forall t$
Logical constraint	$u_t^b - u_{t-1}^b = v_t^b - w_t^b \qquad \forall t,\ \forall b$
Minimum downtime	$\sum_{i=t-2+1}^{t} w_i^{ng} \leq 1 - u_t^{ng} \qquad \forall t \in [2, 8760]$
Minimum heat output	$q_t^{d,ng} \geq 0.9\ u_t^b \qquad \forall t$ $q_t^{d,eb} \geq 0.45\ u_t^b \qquad \forall t$
Capacity constraints	$q_t^{d,ng} \leq 9\ u_t^b \qquad \forall t$ $q_t^{d,eb} \leq 9\ u_t^b \qquad \forall t$
Performance Indicators	
Total operation costs	$C_{total} = \sum_{t\in T} c_t^{tot}$
LCOP	See Table 5.4.
CO_2	$CO_2 = \frac{\sum_{t\in T}(q_t^{d,ng}*1+8.8*v_t^{ng})(MWh)*3.6(GJ/MWh)*56.6(kg/GJ)}{0.90*1000(kg/ton)}$
Total energy consumption	$E_{Input} = \sum_{t\in T}(q_t^{d,ng} * 1/0.9 + q_t^{d,eb} * 1/0.99$ $+8.8 * v_t^{ng})$
Total system efficiency	$\eta_{HB} = \frac{7.5 * 8760}{E_{Input}}$

B.2 NATURAL GAS BOILER

Table B.2: Formulation of the natural gas boiler for the Scenario 2030.

Performance Indicators	
Total operation costs	$C_{total} = \sum_{t \in T}(C_t^{ng} + 0.2 * 46.3)\ 7.5 * 1/0.90$
LCOP	$LCOP = \frac{\frac{I + C_{total}}{(1+0.07)^1} + \sum_{i=2}^{25} \frac{C_{total}}{(1+0.07)^i}}{\sum_{i=1}^{25} \frac{7.5*8760/0.74}{(1+0.07)^i}}$
Total energy consumption	$E_{Input} = 8760 * 7.5 * 1/0.90$
CO_2	$CO_2 = \frac{8760*7.5*1(MWh)*3.6(GJ/MWh)*56.6(kg/GJ)}{0.90*1000(kg/ton)}$
Total system efficiency	$\eta = 90\%$

B.3 ELECTRIC BOILER

Table B.3: Formulation of the electric boiler for the Scenario 2030.

Performance Indicators	
Total operation costs	$C_{total} = \sum_{t \in T} C_t^{eb} * 7.5 * 1/0.99$
LCOP	$LCOP = \frac{\frac{I + C_{total}}{(1+0.07)^1} + \sum_{i=2}^{20} \frac{C_{total}}{(1+0.07)^i}}{\sum_{i=1}^{20} \frac{7.5*8760/0.74}{(1+0.07)^i}}$
Total energy consumption	$E_{Input} = 8760 * 7.5 * 1/0.99$
CO_2	$CO_2 = 0$
Total system efficiency	$\eta = 99\%$

B.4 ELECTRIC BOILER WITH STORAGE

Table B.4: Formulation of the electric boiler with storage for the Scenario 2030.

Optimisation	
The objective function	$\min \sum_{t \in T} c_t^{tot}$ $c_t^{tot} = C_t^{ele}(q_t^{d,eb} + q_t^{s,eb}) * 1/0.99$
Heat balance	$q_t^{eb} + q_t^{d,s} = 7.5 \qquad \forall t$
Logical constraint	$u_t^{eb} - u_{t-1}^{eb} = v_t^{eb} - w_t^{eb} \qquad \forall t$
Minimum downtime	$\sum_{i=t-2^{ng}+1}^{t} w_i^{ng} \leq 1 - u_t^{ng} \qquad \forall t \in [2, 8760]$
Minimum heat output	$q_t^{d,eb} + q_t^{s,eb} \geq 0.45 * u_t^{eb} \qquad \forall t$
Capacity constraints	$q_t^{d,eb} + q_t^{s,eb} \leq 9 * u_t^{eb} \qquad \forall t$ $s_t \leq 10 \qquad \forall t$
Storage operation	$s_t = s_{t-1} + q_t^{s,eb} * 1 - 1.05 * q_t^{d,s} * 1 \qquad \forall t$
Performance Indicators	
Total operation costs	$C_{total} = \sum_{t \in T} c_t^{tot}$
LCOP	See Table 5.4.
Total energy consumption	$E_{Input} = \sum_{t \in T} q_t^{d,eb} * 1/0.99$
CO_2	$CO_2 = 0$
Total system efficiency	$\eta_{EBS} = \frac{7.5 * 8760}{E_{Input}}$