The effects of a decrease in gas-fired electricity generation in the Netherlands

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Abstract

The share of natural gas-fired electricity generation in the Netherlands decreased as an effect of national policies and under pressure of a liberalized market, from 57% to 49% between 1998-2018. While coal-fired electricity generation decreased with 1 percent point (29-28%). Further decrease of fossil-fired electricity generation could pose future problems, as this provides the required reliability of electricity input into the grid. Meanwhile, gas-fired electricity generation is more efficient and flexible, and less CO_2-intensive than coal-fired generation. Therefore this research posed the question: 'What are the driving factors behind a change in the share of natural gas in the fuel mix for electricity generation in the Netherlands, and what effects might be expected until 2030?'. The research answered question by reviewing the historic capacity since the start of the liberalization of the electricity market, the costs of electricity generation, and by researching effects on efficiency, CO_2-intensity and flexibility in future scenarios. To find the effects, a range of scenarios with different characteristics for capacity and generation of electricity was researched. A range was researched in order to distillate the effects caused by future changes for natural gas-powered electricity generation. Results found in the research are as follows: newly built gas-fired capacity is cheaper than coal-fired capacity. However, for existing capacity, coal-fired electricity generation is favoured, as the short run marginal costs are lower (25.37-28.60 €/MWh versus 37.38-44.19 €/MWh)**.** Concerning the change in capacity, it was found that the ratio between gas- and coal-fired capacity decreased from 3.6 in 1998 to 2.3 in 2018 and resurges to a range of 2.7-3.3 in 2030. The ratio between gas and coal-fired electricity generation decreased from 2.0 (1998) to 1.8 (2018) and decreases further to a range of 0.6-1.9 (2030). Furthermore, results show a decreasing share of fossil-fired capacity and electricity generation from 86% and 85% (1998) to 67% and 81% (2018), to ranges of 37-63% and 25-61% in 2030, respectively. The shift from natural gas to coal in fossil-fired power generation leads to a decrease in the average energy-efficiency of fossil-fired generation (-3.4 to +0.1 percent point in 2030, relative to 1998), an increase in fossil CO_2-intensity (-4 to +115 tonne CO_2/GWh), and a decrease in flexibility for the majority of the researched flexibility parameters: 'flexible capacity', 'ramp rate', and 'reliable capacity'. The last parameter, 'highly flexible capacity', on the other hand increases with 0-2 percent point to the value of 2018.

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1. Introduction

As the volume of greenhouse gasses has increased exponentially worldwide since the industrial revolution, evidence on a correlation between greenhouse gasses and climate change is stockpiling (IPCC, 2014; KNMI, 2014). The first effects of climate change start to materialize in the form of a worldwide increase in average temperature, which leads to different effects all over the world, e.g. more floods, longer droughts, warmer oceans (KNMI, 2014). As a result of this materialization of effects, worldwide consciousness on the importance of climate change mitigation has emerged. This, in turn, resulted in countries looking for means to lower greenhouse gas emissions.

In this changing political climate, the European Union (EU) has emerged as one of the leading forces in the western world to cope with climate change. It states that 'preventing dangerous climate change is a key priority for the EU'. And seeks to minimalize climate change with policies and targets. The key targets for 2030 are:

- At least 40% cut in greenhouse gas emissions compared with 1990
- At least 32% of total energy consumption from renewable energy
- At least 32.5% increase in energy efficiency (EC, 2019a).

Meanwhile, the contribution of greenhouse gasses from the electricity generating sector in the EU is 27% of total emissions in 2017 (EEA, 2018). As a result of these high contributions, and the goal to become more sustainable, EU policy has emerged to encourage member states to reduce the CO_2-emissions on a national level in the form of 2001/77/EC and the succeeding 2009/28/EC (EC, 2001, 2009a). The directive, and its succeeding directives, were implemented in order to promote the use of renewables for electricity generation and electrification of a country's economy. This is encouraged by requiring countries to publish their yearly fraction of renewable electricity generation. Which should be in line with international treaties such as the Kyoto protocol (EC, 2001). Furthermore the first directive provides an impetus to the formation of a framework for a renewable electricity market (EC, 2001). Apart from these directives targeting the electricity market, other adjacent directives such as the 'renewables directive' and the 'CCS' directive came into power (EC, 2009a, 2009b). Thereby further underlining the green intentions as promoted by the EU. The new European policies require national countries to adapt to these policies. Policies implementing renewable electricity generation have been translated into Dutch policy as a part of the 'Elektriciteitswet' (Rijksoverheid, 2019)

Meanwhile, the extra input of renewables does not necessarily replace the most polluting electricity generation in the national mix. This is generation on the basis of coal, which has an emission factor of 95-107 kg CO_2/GJ (lower heating value, bituminous coal) in comparison to 56 kg CO_2/GJ lower heating value of natural gas (Blok, 2007; RvO, 2018). When generation efficiency differences between coal and natural gas are incorporated, CO_2 emissions per kWh generated are approximately two times higher for coal than for natural gas (Blok, 2007). However, as production prices for electricity generated by coal fired powerplants are lower it is not always coal which is replaced by an increase in renewables (van Santen & van der Walle, 2017). Gas fired power plants are set to a standstill, while the technical conditions are still in order. In Europe this has led to a decrease of active natural gas based capacity (Groot, Crijns-graus, & Harmsen, 2017) . When zooming in to the country level, the fraction of coal powered electricity generation in the Dutch electricity mix was still 34% in the year 2016. Regarding trends over time, the Dutch gross inland consumption of solid fossil fuels has increased with 5.18 percent point between 2010 and 2016, while the natural gas use has decreased with 4.65 percent point (Eurostat, 2018). This decrease is accompanied with a lower load factor and mothballing of gas-fired power plants (van Santen & van der Walle, 2017). In the same period, the amount of renewables in the Dutch electricity mix has increased from 0.09% of primary energy input in 1990 to 4.62% of primary energy input in 2016 (Eurostat, 2019). As the gas fired capacity has unique characteristics which cannot be completely covered by other fuel sources, future problems might arise. These characteristics are (Aalto & Korkmaz Temel, 2014);

- Ramping properties
- Easily shut down
- Controllable output
- Relatively low-carbon emissions for fossil fired power plants, especially as long as carbon capture and storage (CCS) is not widespread, which is not to be expected before 2030-2050 (Aalto & Korkmaz Temel, 2014).

As the last point is even improved with the penetration of renewables, which are considered to have nearly zero end-of-pipe emissions, the first points might be of more importance. The controllable output is not covered by renewables, as wind and solar power are not completely predictable, and cannot be regulated. Therefore, regulatable and reliable capacity is required in an electricity mix to provide a steady frequency and magnitude of output to the electricity net (Gouveia, Dias, Martins, & Seixas, 2014). This stability on the electricity net can be generated from the demand side, by demand-response management, import/export of electricity, and at the delivery side, with fossil fuelled capacity and hydroelectric power plants (ECN, 2017c). This research focussed on the delivery side. As the Netherlands does not house the geography for hydroelectric power plants and storage, fossil fuels still form an important part of regulating the electricity grid (ECN, 2017b). As stated before, coal-fired capacity is still in use in the Netherlands, despite having a higher CO_2 intensity, overall air pollution and a lower flexibility than gas fired capacity. A knowledge gap was found as there is, to the best of my knowledge, no research performed on what problems might arise regarding grid stability and sustainability goals when coal is maintained in the electricity mix instead of natural gas. Other research reviewing future scenarios aim mainly at the total CO_2 reduction and grid stability due to the introduction of renewables, thereby disregarding the differences between natural gas and coal (ECN, 2017c). This research reviews factors which have lowered the gas-fired capacity instead of coal-fired capacity in the Dutch electricity mix, and follows with future scenarios on effects caused in the Dutch market by the change in gas-fired electricity production. Earlier research performed on this subject mainly aims at technical solutions and expansion of the market to cope with increased uncertainty in the electricity mix, whereas this research aims more on how the ratio between coal and gas fired capacity can be influenced in the electricity mix in the coming short future. As natural gas is less carbon intensive, more flexible, and lower in airborne pollution in comparison to coal (Blok, 2007). The research targets the direct future, until 2030-2035, and not 2050 as used by several future energy scenarios, as implementation of carbon capture and storage (CCS) is expected after this period.

The introduction of CCS will change the characteristics of the power plants and merit of order for the production of electricity, as different CCS techniques can be used. As future scenarios do not necessarily provide a implementation rate of CCS, but rather state 'CCS is implemented', researching scenarios after 2030-2035 would pose too much of a uncertainty for the research, and is therefore not performed. Therefore the main research question becomes:

What are the driving factors behind a change in the share of natural gas in the fuel mix for electricity generation in the Netherlands, and what effects might be expected until 2030?

The following sub questions were formulated in order to address the research question:

- How has the built capacity of-, and generation with, natural gas in the Dutch electricity mix developed after the liberalization of the Dutch electricity market (Sub question (SQ)1)
- How is the Dutch electricity market liberalized, and what has been the effect of market liberalization on electricity generation with natural gas-fired power plant in the Netherlands? (SQ2)
- How do different cost components influence the profitability of electricity generation in the Netherlands? (SQ3)
- How will the built capacity and electricity generation by gas fired power plants develop in the Netherlands? (SQ4)
- What effects will a change natural gas capacity in the Dutch electricity mix have on the following factors;
    - The energy efficiency of the electricity mix (SQ5)
    - The CO_2 intensity of the electricity mix (SQ6)
    - The operational flexibility of the electricity mix (SQ7)
    - What are the combined effects of the aforementioned effects (SQ8)

The goal of the research was to gain insight in what problems might arise in the immediate future due to a change in natural gas-fired capacity in the electricity mix. This was found by researching sub question 4-8. Sub questions 1-3 were proposed to create clarity to the mechanisms which have led and will lead to a change in natural gas in the electricity mix. The research contributes to the debate on the energy transition in the Netherlands (Mertz, Meyer, Schöne, & Turkenburg, 2018; van Santen & van der Walle, 2018). It could further provide insight in whether the current addition of renewables in the electricity mix is as effective as preferred, while this is not the main research question.

2. Theoretical background

2.1 Gas fired power plants

As the research reviews gas fired power plants, it is important to create a distinction and describe the general types in gas fired power plants and the uses for electricity generation. Andrews & Jelly (2017) describe three main types of gas fired power plants:

1. The ‘simple’ gas turbine
2. Combined cycle gas turbines (CCGT)
3. Combined heat and power generation turbines (CHP)

These will be the main categories for the research, as these are also in line with the Platts Wepp database which is used in this research.

The simple gas turbines make use of a Brayton cycle to generate power to rotate a generator and generate electricity. These turbines have relatively low capital costs, and can reach an efficiency of up to 40% (Andrews & Jelley, 2017). The combined cycle gas turbines, make use of both an open Brayton cycle and the closed Rankine cycle to power the generator. Due to the use of two different cycles, efficiency can be higher, up to 60%, but costs are also increased compared to the simple gas turbine. The last category are CHP turbines, these generate both heat and electricity with the same fuel input, resulting in a lower electric efficiency of the power plant, but a higher total efficiency of the plant. When the production of heat is accounted for in the efficiency, efficiency can be up to 80%. As heat needs to be transported from the power plant, costs are higher due to investment in pipework and other infrastructure (Andrews & Jelley, 2017).

Next to differences in generating technology, differences in type of powerplant are also important to address. Regarding types of power plants, there are two main types: centralized-, and decentralized power plants. The majority of fossil capacity in the Netherlands is centralized capacity (76%); electricity is generated on a different site than the location of the end user, therefore transportation of electricity is required (CBS, 2019e). This research also includes the decentralized capacity in the Netherlands, for which the majority of gas fired installations is installed at greenhouses (Platts, 2018). While this part of capacity is smaller, it cannot be seen as insignificant as it consists of 3.4% of gas fired capacity (36% of gas fired electricity generation), and make up the majority of solar PV capacity (Platts, 2018). For production of electricity by fossil fuels both centralized and decentralized values were available (CBS, 2019b). But as future scenarios include decentral generation, and capacity is not insignificantly small, it has been chosen to include this in the research too (ECN, 2017a, 2017c).

2.2 Costs of electricity production for utilities

In order to create a more competitive electricity market, the European Union has implemented the option of liberalization of the electricity market (EC, 1997, 2003b). As microeconomics suggest that liberalization will lead to an increase in competition, and thus higher internal and external efficiencies. In turn leading to cheaper delivery of goods to the end consumer (Jamasb & Pollitt, 2005). The costs for producing electricity consists of the following factors (Kang & Rohatgi, 2016);

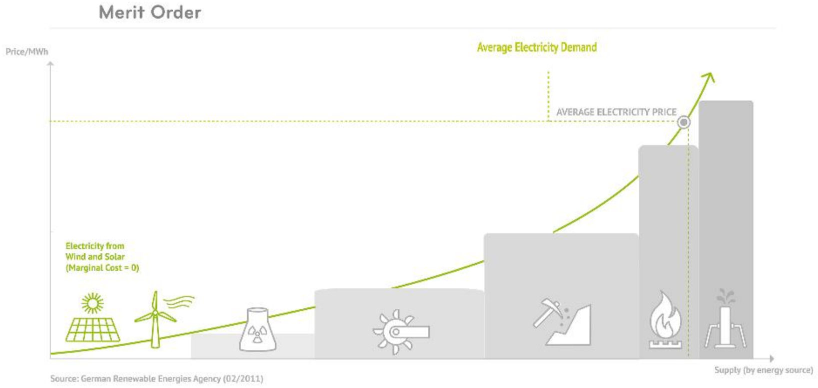
- Initial power plant investment
- Annual costs
    - Operation and maintenance
    - Fuel costs
    - Costs of CO_2 emittance

The benefits of producing electricity are harvested when selling electricity to the market. This can be to the wholesale market, or the spot market. The wholesale market prices are lower but the sales are guaranteed, while the spot market only opens up when shortages arise, and prices are higher (EPEXSpot, 2019).

2.3 Merit order effect

The merit order is the order which determines which power plants will deliver electricity to the grid, and which will not, as the price is too high. An example of the merit order for electricity production can be found in Figure 1. As visible, the electricity price follows a more or less set curve so the electricity price. The figure depicts the average electricity demand, which intersects the price curve at a certain point.

Following the free market principles, everything under curve produces electricity as these are in the position to generate revenues.



Source: German Renewable Energies Agency (02/2011)

Figure 1: Example of the merit order for electricity generation, adapted from (Next Kraftwerke, 2019)

The merit order is based on bids for electricity production, which in turn depend on the short run marginal costs (SRMC) of a power plant. These SRMC include costs of operation, costs of emissions, and fuel costs. As renewable resources have nearly zero SRMC, as ‘fuel’ input is taken freely from the environment, renewable energy sources will be on the left side of the merit order (Figure 2) (Luňáčková, Průša, & Janda, 2017). This effect shifts the supply curve of the complete market, and thus pushing more expensive units out of production. In general, it can be assumed that the marginal units are oil and gas-fired power plants (Luňáčková et al., 2017). During periods when there is no or too little input from renewable resources, these power plants are able to produce electricity for the required price, and will be put into the mix again. Therefore, existence of these marginally-run power plants is of major importance for the current electricity network to guarantee electricity deliverance (Aalto & Korkmaz Temel, 2014). As a result of the introduction of more renewables to the electricity system and the merit order effect, gas fired power plants will run less often, or might even be completely shut down. When running less often, the capacity factor of the power plant decreases. Thereby increasing the share of investment costs and the fixed operation and maintenance costs in the yearly costs, and lowering the benefits of electricity production (Blok, 2007; Kumar, Besuner, Lefton, Agan, & Hilleman, 2012).

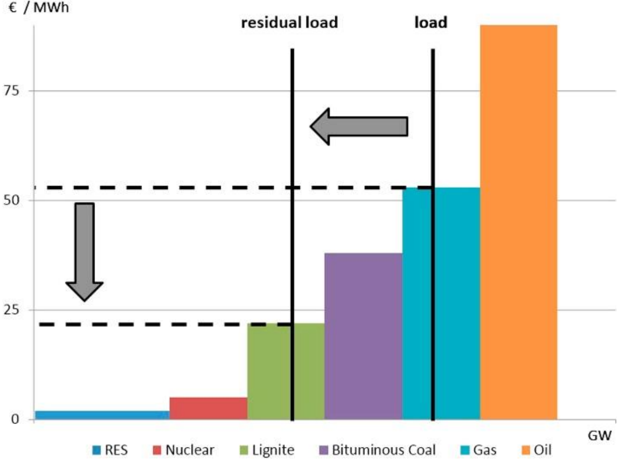


Figure 2: Illustrative figure on the effect of addition of RES on the market clearing price (Luňáčková et al., 2017)

2.4 Energy efficiency of the electricity mix

Energy efficiency of the electricity mix can be defined as the overall electricity generated by the complete energy sector in a country or region, divided by the energetic value of all fuel input into this sector (Blok, 2007). The efficiency of a national or regional electricity mix can be attributed to the following main factors (Joskow, 2003; Luňáčková et al., 2017).

- Composition of the generating capacity
- Age of the generating capacity
- Merit order effect in the generating capacity

The composition of the generating capacity is an overview of what types of capacity is installed, and what technologies are installed. A different composition will lead to different efficiencies, as the main two types of fossil fuels produce electricity at a different efficiency (coal: 39-45% , natural gas: 40-59%) (IEA, 2016b). When including combined heat and power generation, the efficiency of a gas fired powerplant can go up to 82% (IEA, 2016b). However, as the combined generation of heat and power leads to a loss in the efficiency of electricity generation, correction for this efficiency loss is required when the electric efficiency is calculated (Groot et al., 2017). Considerable differences between countries can occur, e.g. France depends for 3.5% on natural gas for electricity production in 2015, while the Netherlands powered 42.2% of its electricity production with natural gas (World bank, 2017).

The age of the fleet determines for a part what type of technology is installed as capacity, and therefore also affects the composition of the fleet. Furthermore, power plants tend to become less efficient during its lifespan, as fatigue of materials increases (Kumar et al., 2012).

As discussed before the merit order effect pushes the marginal electricity producers out of the electricity mix during times of high renewable generation.

2.5 Operational flexibility

Operational flexibility is an important property of a power system and crucial for phasing out disturbances in a power network. Disturbances can consist of deviation in power feed-in, or load demand, compared to the prediction, or due to failure of components of the power system, resulting in shortage in the grid (Ulbig & Andersson, 2015). Last decades, operational flexibility has become increasingly important as a result of increasing penetration of renewables, an increase in power-market activity, and the emergence of smart grid, as a vision for the future (Ulbig & Andersson, 2015). Operational flexibility is defined by Ulbig & Anderson (2015) as "The technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out- feed from the grid over time." This operational flexibility can be obtained on several levels, as shown in Figure 3. This research will mainly look at operational flexibility gained by conventional power units.

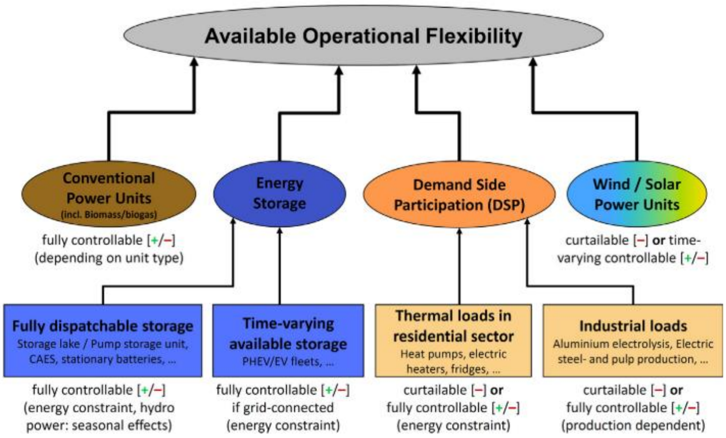


Figure 3: Input factors for operational flexibility of a power system (Ulbig & Andersson, 2015).

In order to measure and compare operational flexibility of a power grid, the following parameters are proposed (Denholm & Hand, 2011; Denholm, Ela, Kirby, & Milligan, 2010; Ulbig & Andersson, 2015)

- Power provision capacity π [MW]
- Power ramp capacity ρ [MW/min]
- Energy provision capacity ε [MWh]

3. Research overview

As the research consists of multiple layers, it is divided into two parts, where the first section aims to explain why natural gas-fired capacity has lowered over the past years, and the second part explored future scenarios and described the results of a change in natural gas in the electricity mix. Figure 4 provides an illustrative overview on the interlinkage between sub questions within the research. Furthermore, the research alternates methodology and results per sub question, as this led to an increased readability of the report. Uncertainties of results and discussion of uncertainties will be treated in one chapter at the end of the report.

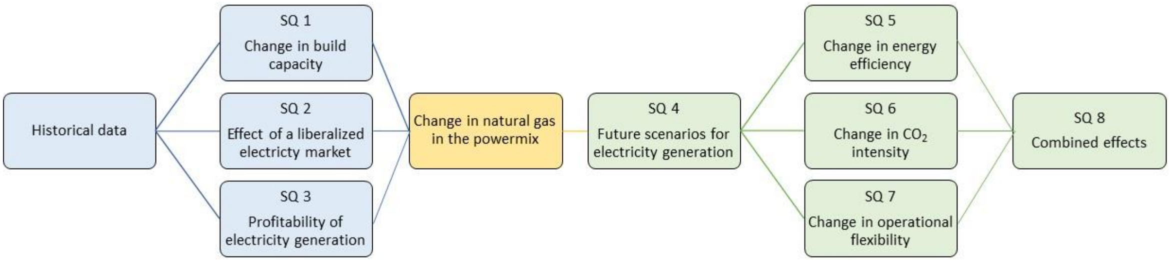


Figure 4: Schematic overview of the interlinkage between sub questions in the research

4. Historic build-up of capacity and generation

4.1 Methodology

This section will quantitively describe the historical change in built capacity of natural gas based power plants in the Netherlands to find an answer to the first sub question: *"How has the built capacity of-, and generation with, natural gas in the Dutch electricity mix developed over time"*.
The change in built capacity was researched by reviewing the built capacity from 1996, when data was available, and onwards. As this is the moment when the first steps were made to liberalize the European electricity market (EC, 1996). From then on, profitability became the major decision factor to start construction of a power plant, instead of governmental decrees (Serena, 2014). When older data was available, trends before and after liberalization were reviewed to provide insight into the effects of liberalization. In addition to the capacity, electricity generated and the load factor of natural gas- and coal-fired power plants were reviewed. In order to correct for an increased electricity use over the years, not only absolute numbers were calculated, but the numbers were also calculated as a fraction of the total capacity and electricity generation in the Netherlands.

4.1.1 Development of built capacity

To reconstruct the development of built capacity over time, the Platts WEPP database was used. However, as the last available output originated from October 2017, the database was checked and updated with external sources. Starting with the "Energietrends 2016" by ECN (ECN, 2016). Further updating was performed by reviewing online sources and newspaper databases such as Lexisnexis for data on new power plants or shutting down of power plants. A total built fossil capacity of 18.5 GW in June 2018 was found. This is a deviation of 3.1% from the fossil built capacity as provided by TenneT (19.1 GW) and The Joint Research Centre Power Plant Database from the EU, and is therefore deemed useful for research purposes (Kanellopoulos, Hidalgo González, Medarac, & Zucker, 2017; TenneT, 2019b). Mothballed capacity is not deemed as readily available for the market due to lack of incentive to restart mothballed capacity, and was therefore not included into the current capacity figure (Peichert, 2018). A table with mothballed capacity and the year of mothballing can be found in Table 1. The research defines the start of the year as the moment when capacity is mothballed. Total mothballed capacity is 9.8 percent of the total capacity. Addition of this mothballed capacity would lead to a lower load factor for gas fired capacity. However, it has not been added, as different companies have different incentives to restart the capacity, thereby leading to extra uncertainty in the research (de Boer, 2019; Rigter, 2019). Interviews suggested that there are only plans to take the reactivate Claus C in the short future, this is expected in 2020, but enquiry at RWE suggested that this is still speculative (Bouwmeester, 2019; Sedee, 2018)**.**

Table 1: Mothballed capacity in the Netherlands

Powerplant	**Date of mothballing**	**Capacity [GW]**
Rijnmond GT	2017*	0.8
Eemshaven	2017	0.7
Claus C	2014	1.5
Moerdijk I	2018	0.3
Total	**-**	**3.3**

* Restarted at the start of 2019

The Platts WEPP database lists 4 power plants with a status 'unknown'. As these power plants have a total combined capacity of 5 MW, the contribution is deemed insignificant and the power plants are not incorporated in the research. After reconstruction of the built capacity, the gas-fired capacity as a fraction of the total built capacity was found by dividing the gas-fired capacity as found in the Platts WEPP database by the total installed capacity. To calculate the gas fired capacity from the Platts WEPP database, a distinction was made between natural gas (category: GAS) and other types of gas, BGAS (biogas), LGAS (landfill gas), CGAS (coal gas), DGAS (digester gas), and RGAS (refinery gas).

Furthermore, the fraction of coal-fired capacity (type COAL) and fossil fired capacity (aforementioned types and NUCLEAR & OIL) were reviewed in a same manner as the gas-fired capacity. While Platts WEPP database was sufficient for fossil capacity and large installations, a difference of 7 GW installed capacity was found in comparison to the total capacity as published by TenneT (TenneT, 2019a). This deviation was found to be in the built solar capacity, as the majority is installed in small installations and therefore not included in the Platts database. Therefore for the solar capacity and electricity generation was added via CBS thereby resulting in a 0.5 GW deviation from the total capacity as reported by TenneT, which is deemed acceptable (CBS, 2018d).

4.1.2 Development of electricity generation

Electricity generation was found by reviewing data from CBS Statline (CBS, 2019e). For this research, both central and decentral generation was included, as the data in the Platts WEPP database also includes decentral installations at industrial companies. The electricity generated was calculated per energy carrier, and thus for natural gas and coal. While biomass is starting to emerge as a co-firing source, it is not deemed as a relevant source up to today and therefore not treated as a separate category in the results. Enquiry at RWE learned that current capacity is in the process of transformation to become able to co-fire biomass, thereby explaining the small amount of 8.7 PJ electricity generated with biomass in 2018 (2.1% of the total electricity production) (CBS, 2018a; Rigter, 2019). Data was plotted into a figure, where the change in absolute electricity generation in total and the change for both gas- and coal-fired electricity production is made visible. The fraction of electricity generation was calculated in a same manner as the fraction of capacity as described in section 4.1.1, thereby using ‘natural gas’ and ‘coal and coal products’ as the energy carriers researched from Statline (CBS, 2018c).

4.1.3 Load factor

The load factor was calculated by division of the electricity generated per fuel type as described in section 4.1.2, divided by the yearly capacity as found in section 4.1.1. The load factor is then calculated using the formula as described by Blok (2007).

$$Load\ factor\ = \frac{E}{C * 8760} \qquad (1)$$

Where E = electricity generated [GWh]
C = Electricity generating capacity [GW]
8760 = amount of hours in a year

4.2 Results

4.2.1 Development of built capacity

Total generation capacity has increased between 1996 and 2018 by 103% (from 15.0 to 30.4 GW) as visible in Figure 5. Capacity is split up into five categories, natural gas fired capacity, other gas fired capacity (gas based capacity not fired by natural gas), coal capacity, other fossil capacity (fossil based capacity, not based on coal or any form of gas) and other capacity, including waste as an energy source, and renewable energy sources. Starting in 2012, the increase in built fossil capacity levels off, or decreases. Where in this period, the gas fired capacity starts to decline, the fraction of gas-fired capacity to the total remains fairly high (45% in 2018) in comparison with surrounding countries, e.g. 15% in Germany. When looking at the total capacity the overall increasing trend continues, due to a higher increase of other capacity than the decrease of fossil capacity.

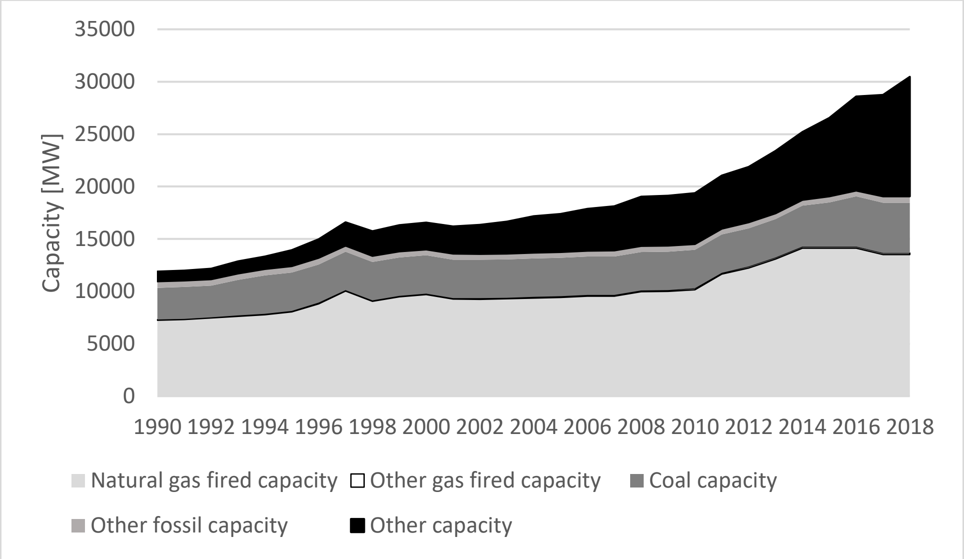


Figure 5: Electricity generating capacity in the Netherlands (CBS, 2018d; Platts, 2018)

The difference between gas- and coal-fired capacity is shown in Figure 6, it shows that the difference between gas fired and coal fired capacity has increased from 5255 MW to 8848 MW in the researched period. The increase could be explained partially by the total increase in built capacity; when the ratio remains the same, the difference in MW will increase.

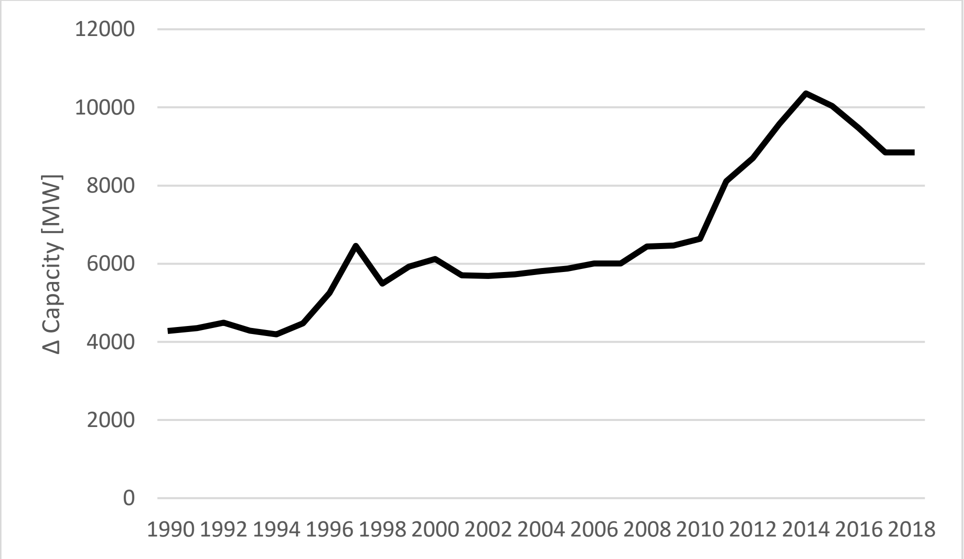


Figure 6: Difference between gas- and coal-fired capacity (based on Platts, 2018)

When the development of capacity as a share of the total capacity in the Netherlands (Figure 7) is reviewed it becomes visible that the coal fired fraction of capacity remains relatively stable in the period between 1990 and 2018. A peak in coal fired capacity can be found in the year 2012, when several large coal fired powerplants were delivered. From 1998 and onwards a general trend of increase in 'other capacity' is visible, this can be explained by the increase in renewable capacity as the result of both European and Dutch policy to increase the amount of renewable electricity generation.

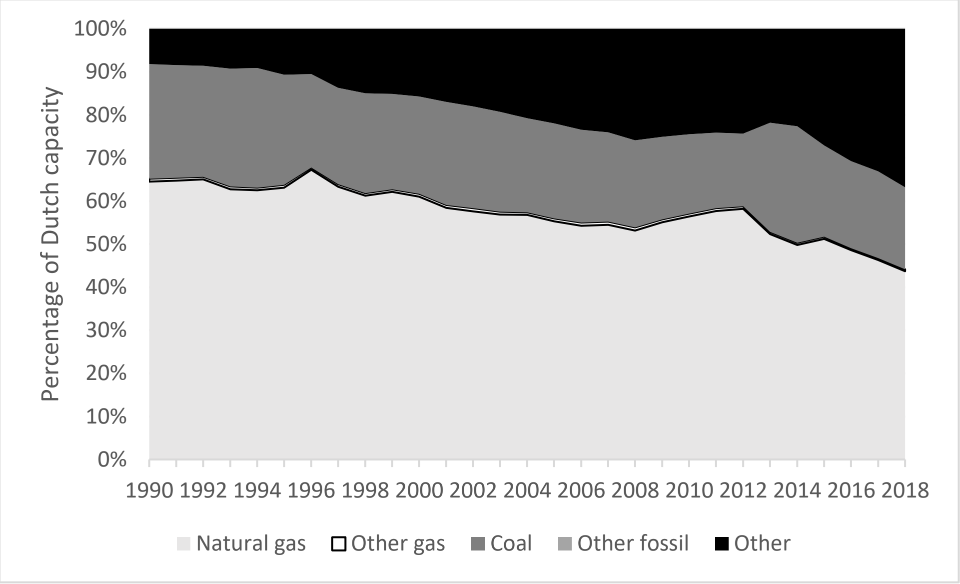


Figure 7: Composition of electricity generation capacity in the Netherlands (CBS, 2018d; Platts, 2018)

Table 2 shows a snapshot of the current state of the electricity market. It was created to provide extra insight in the composition of the built capacity. The table shows the period in which the capacity was built (and thus the age of the capacity), and the size of the capacity. From this table it becomes apparent that currently the majority of installed megawatts is installed after 2000, and that coal fired capacity is newer than the gas fired capacity (73% (of MW) is built after 2000 relative to 53% for gas fired capacity). This could pose future implications, due to the current overcapacity in the market. It could result in demolition of old gas fired capacity, without construction of new gas fired capacity. Thereby shifting the fraction between gas and coal fired capacity in the direction of the coal fired capacity. The category 'other' shows a large increase in number of built installations between 1980-2000, this is due to the fact that there was a surge in building of new wind turbines. In this period most wind 'parks' consisted of 1-10 wind turbines, thereby disturbing the number of newly built installations. It must be noted, that as data is solely from Platts database, solar PV panels on rooftops for individuals are not included in this table. Inclusion would lead to a distorted number of installations for the 'other' category, but would lead to a more precise value for the capacity (87 MW of installed PV in Platts, 4414 MW according to CBS) (CBS, 2018d; Platts, 2018).

Table 2: Snapshot of built capacity for electricity generation in the Netherlands in 2018 (Platts, 2018)

Type	**Coal**	**Natural gas**	Combined cycle	Simple cycle	Internal combustion	**Other gas**	**Other fossil**	**Other**
Number of installations	6	1003	21	198	784	131	61	697
Built before 1980	0	29	0	29	0	0	2	7
Built between 1980-2000	2	877	8	147	722	43	55	450
Built after 2000	4	97	13	22	62	88	4	240
Built with capacity: <100MW	0	970	2	184	783	131	60	683
Built with capacity: >100MW	6	33	19	14	1	0	1	14
Capacity (2018) [MW]	4796	13547	7828	5276	443	141	879	6753
Built before 1980 [MW]	0	514	0	514	0	0	536	140
Built between 1980-2000 [MW]	1280	5857	2185	3429	243	93	275	2292
Built after 2000 [MW]	3516	7176	5643	1333	200	48	68	4321

4.2.2 Absolute electricity generation

Absolute electricity generation has increased between 1998 and 2017 from 92 to 117 TWh per year. The amount of electricity produced by coal and natural gas is nearly similar when comparing 1998 and 2017, however fluctuations per energy carrier did occur. The drop in electricity generation in the year after 2009 could be explained by the worldwide economic crisis. Despite an increase of generation after this crash, the electricity production was still not at the same level at the end of 2017. This economic crisis led to a high production in 2009 and 2010 due to previously settled contracts. This led to a minimization of the import of electricity. After fulfilment of these contracts, new contracts were signed based on the new electricity need. This has led to a renewed period of electricity imports. The increase in overall electricity production can be explained by the increase of 'other' energy carriers, and not by a change conventional energy carriers such as natural gas or coal. While the share of 'other' electricity generation has increased, the fractions of different categories enclosed in the other category have changed too. In 1998, the largest share was taken up by nuclear power generation, with 27%. In 2007, this was still the largest share (21%), but closely followed by biomass (20%) and wind power with 18%. In 2017, renewables have become the largest share, with wind energy providing 38%, biomass 16%, and solar power 8%. Nuclear power generation has fallen back as a fraction to 12% (CBS, 2019e). These shares have not been presented in Figure 8, as the shares to the total are much smaller and therefore not well visible in the figure, with 9 percent for wind generation as the largest share found.

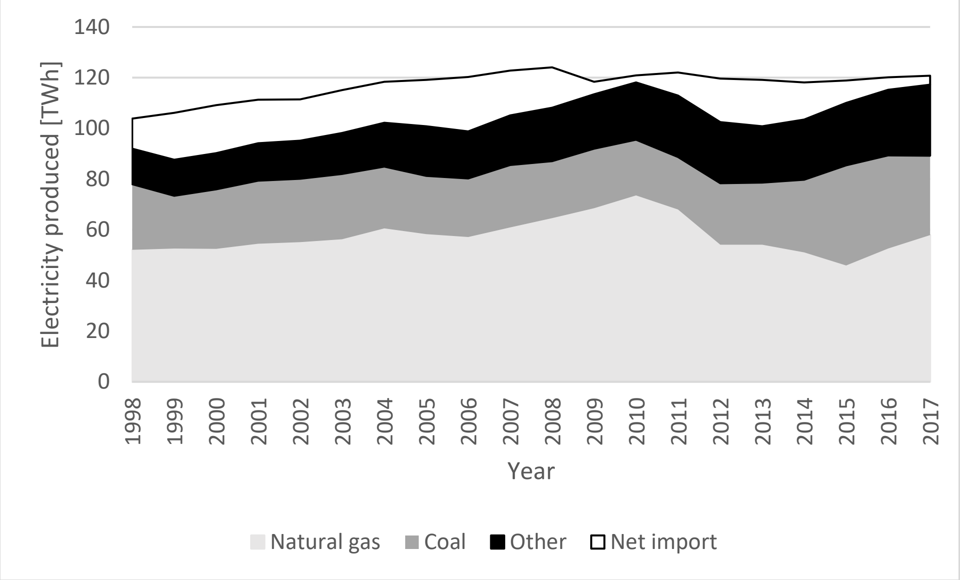


Figure 8: Electricity produced per energy carrier in the Netherlands (CBS, 2018c)

Figure 9 plots the difference in generation of electricity by coal and gas. As visible, the difference increases between 1998 and 2009, and crashes until 2015 which is followed by a new increase. Remarkable is the difference between generation and built capacity for a fuel, therefore the built capacity is plotted on a secondary y-axis. As visible, both keep the same pace until 2004, where the difference in capacity remains relatively stable until 2008, while the use of gas as an energy carrier increases in comparison to coal. Several factors could explain this difference, among which governmental policy and costs of production (Chapter 2), both factors will be reviewed later on in the research.

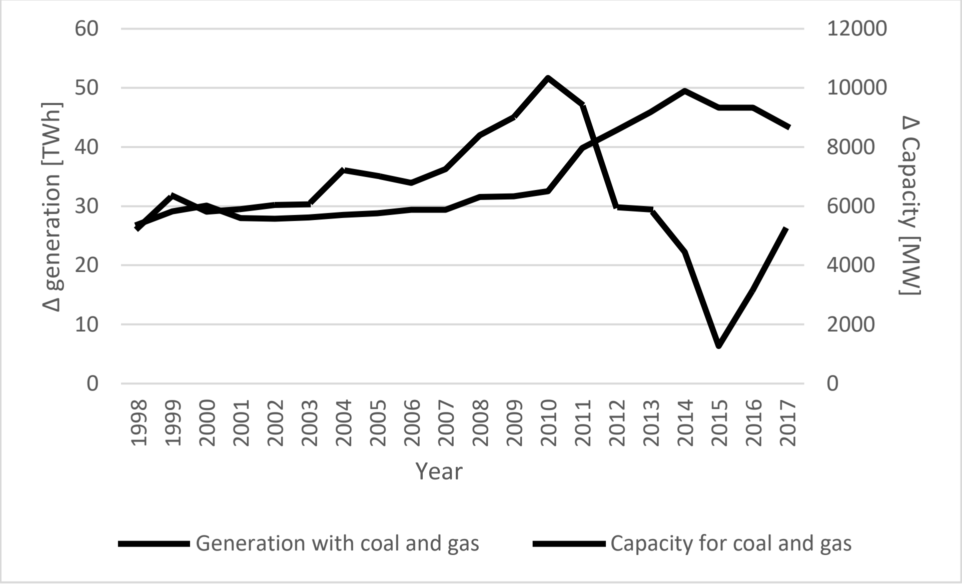


Figure 9: Difference between gas- and coal-fired generation and capacity (CBS, 2019e; Platts, 2018)

Figure 10 shows the contribution of several energy carriers to the total electricity generation per year. As visible, the use of coal increases between 2011 and 2015 and declines afterwards to 28%, as it was at the start of 1998. So while the generation fuelled by coal fluctuates, it is always around 30%. The increase in electricity generation by the category 'rest', which mainly consists of renewables increased continuously and has led to a decrease in gas fired electricity generation from 57% in 1998 to 49% in 2017.

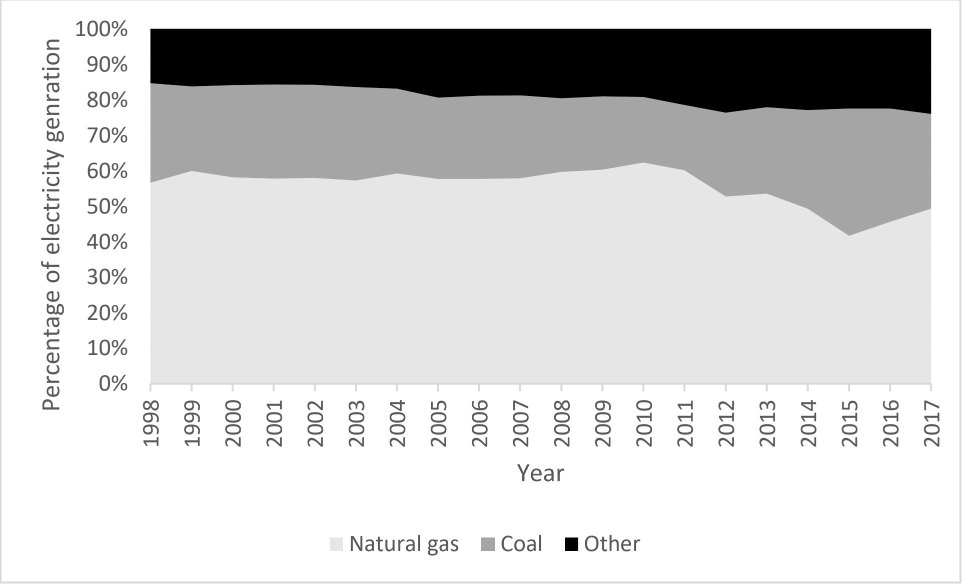


Figure 10: Composition of electricity generation per energy carrier in the Netherlands (CBS, 2018c, 2019c)

4.2.3 Load factor per fuel

As visible in Figure 11, the load factor of both gas and coal fired capacity are both relatively high and do not differ much between 1998 and 2011. From 2011 onward, the load factor for gas fired capacity drops to 37% in 2015, after which it increases to 49% in 2017. In the same period the load factor for coal fired capacity increases from the lowest point which it had in 2011 (65%) to 74% in 2017. As visible in the figure, the load factor for both gas and coal fired capacity has decreased in the period between 1998 and 2017. This can be explained in combination with the results from section **2.1.3**, where it becomes apparent that the increase in electricity generation is mainly covered by an increase in other fuels than natural gas and coal. Furthermore it could be hypothesized that, next to the general decrease for these two fossil energy carriers, a sudden decrease in the load factor of one fuel should lead to an increase of the load factor for another energy carrier.

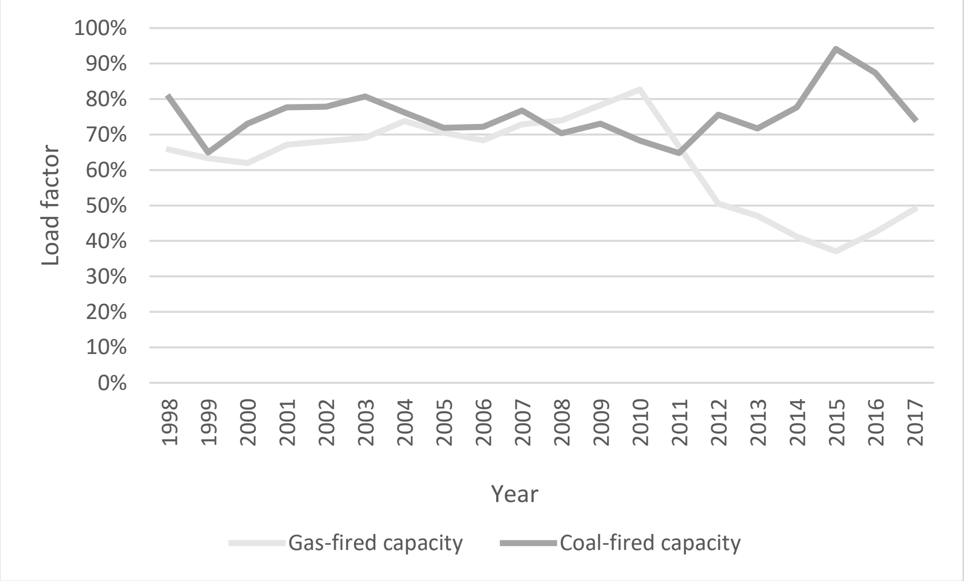


Figure 11: Load factor of gas-fired and coal-fired capacity in the Netherlands

4.3 Section conclusion

The sub question aims to answer how the Dutch electricity mix has developed since the liberalization of the market. From the results we can conclude that the total capacity has increased over the researched period. But this is not necessarily a result of the liberalization, as this increase was already visible in the period before liberalization. It was found that the fossil capacity increased with 43% between 1998 and 2017, and with 75% between 1990 and 2017. In the same time span, the capacity of other has increased with 382% for 1998-2017, and 1116% between 1990 and 2017. Within the fossil capacity, the natural gas fired capacity has increased with 3 percent point, while the coal fired capacity decreased with 2 percent point between 1998 and 2017. The generation by the installed capacity, show another figure, whereas the natural gas fired generation as a share of the total fossil generation has decreased with 1 percent point (62-61%) between 1998 and 2017, the coal fired electricity generation increased with 3 percent points (31-34%). This has led to changes in load factors, whereas the sector-wide natural gas load factor decreased with 17 percent points (66-49%) between 1998 and 2017, the coal fired load factor decreased with 6 percent point (80-74%) in the same period. The following two chapters will look further into the mechanisms behind these observed changes.

5. Liberalization of the electricity market

5.1 Methodology

To answer the sub question: “What has been the effect of market liberalization on the built capacity for electricity generation with natural gas-fired power plant in the Netherlands”, the effects of market liberalization on the profitability were described in a qualitative manner.

Firstly, the original state of the electricity market before the liberalization is described. Followed by a description of the sets of rules and ordinances for liberalization of the electricity market ordered by the European commission. These rules and ordinances are transposed to Dutch national law, which was treated next. As a concluding step to find an answer to this research questions, the changes made due to the liberalization of the market in comparison to the original state were described. The profitability of electricity generation by a power plant was leading for this comparison. This was chosen as the free-market principle which is introduced by liberalization of a market, always seeks to maximise profits, and from that point improvements may arise (Serena, 2014). It is important to shed light on this open market principle, as it alters the behaviour of the electricity market strongly. Countries with one state-owned electricity producer, or a ‘state-champion’ like EDF in France was, had a strong influence on what capacity will be build (Serena, 2014). The research reviewed published papers and articles and bundled these into a general overview of the found effects of market liberalization.

5.2 Results

5.2.1 Old state of Dutch electricity market

Before the initiation of liberalization of Europe’s electricity market, energy (both gas and electricity) was delivered by state-owned or champion utilities (Serena, 2014). The electricity market consisted mainly of heavily regulated, vertically integrated monopolies, in order to ensure nation-wide access to what was considered as a public good; electricity (Domanico, 2007). This could be explained by the peculiar structure of the electricity market. First off, electricity production requires transportation to consumers to become profitable. Investments in ways of transportation are substantial, even before any profits can be generated. Further reasons for one vertically integrated state-champion are the homogeneity of the product presented to end-consumers, the heterogeneity of production methods and costs for a similar end-product, and an inelastic demand (Domanico, 2007). However, competition from new industrializing countries and the feel that the electricity market should be transformed to keep a competitive national industry, led to the start of liberalization of the energy market (Serena, 2014).

5.2.2 EU regulations on Europe’s electricity markets

The first attempts to create a liberalised electricity market were on the basis of free movement of capital, goods, services and inhabitants in the EU. This process of liberalization started with directive 96/92/EC in 1996 and was followed by new directives in order to adjust to shortcomings of earlier directives or changing circumstances.

5.2.3 Directive 96/92/EC: first legislation on liberalization of the electricity market

The first directive introduces concepts and a framework on how the future European electricity market should be shaped. It ensures vital requirements, such as the security of supply, competitiveness of the European electricity sector and economy, and protection of the environment. The directive introduced open wholesale and retail markets to encourage trading in electricity, and allowing new competitors to enter the newly opened market. Furthermore, vertical integration as previously described was ended, leading to a division between utilities and the national network operator (in the Netherlands, TenneT) (Rijksoverheid, 2019; TenneT, 2019b). Network operators were expected to grant access to every company demanding it and meeting the requirements of access.

To grant this access, three methods were created (EC, 1996):

- negotiated third party access, producers negotiate for a framework for access with the network operator
- regulated third party access; producers are allowed to the network on the basis of previously published rates
- Single buyer option; a single buyer previously designated by the member state purchases all required electricity for a country, and determines which plants are required for production (EC, 1996).

5.2.4 Directive 2003/54/EC: improvements on liberalization of the electricity market

The second European energy directive aimed at improving on the flaws of the first energy directive, complete opening of the market, and further strengthening of the European electricity market. The first change made to the former directive is that only regulated third party access remained as the allowed method for new competitors to use the electricity network, thereby creating one levelized cost for all electricity producers (EC, 2003a). The second major change is the addition of generation, or capacity procedures for new capacity. The directive states that authorisation of new capacity should be the standard procedure, but in case of too little capacity, tendering offers may be set out (Jakovac, 2012). This results in a more market based strategy for capacity building. Only when it is viable, producers will invest in new capacity and try to get the plans authorised.

5.2.5 Elektriciteitswet 1998: Dutch transposition of EU directives

Dutch transposition of EU directives started in 1998 with the 'Elektriciteitswet 1998'. This law has been updated over time and is still the leading law for the Dutch electricity market in the present. The law describes the Dutch electricity market as it is intended to be and states the requirements for the electricity network. It describes the required institutions in the market and their obligations and power (Rijksoverheid, 2019).

5.2.6 Effects of new regulations

The effects of a liberalised market are a subject of discussion, however, general trends can be found in all liberalised markets. In liberalised markets, the risks are shifted from consumers to producers of products, thereby providing a disadvantage to capital intensive technologies with long payback periods. Short lead times and modular technologies are preferred, to create a risk as low as possible for investors (IEA, 2015). Furthermore, costs have become the dominating factor for decision making, whereas before the liberalization, governmental policy was dominant. Policies could have aimed for low costs, but other factors such as employment could also be a major factors (IEA, 2015). This was exactly the goal, as lowering of costs and higher efficiency were the main goals of the liberalization (Rathke, 2015). However, electricity prices for end-users are currently increasing in Europe. This increase could also be attributed to increasing fuel costs and addition of CO_2 taxes (Serena, 2014). Electricity prices are therefore not a suitable indicator to review the effects of the liberalization of the electricity market. Production prices, on the other hand are an important factor to determine built capacity and production of power plants as stated before. The change in built capacity and electricity generation can be found in Chapter 4 **(**Figure 5 and Figure 8). Sub question 3 analyses how the prices for electricity production prices are build up and contribute to the current electricity mix in the Netherlands.

A final remark on the importance of legislation is vital for the continuation of the research. As costs and margins became increasingly important due to liberalization of the electricity market, legislation can overrule the market forces which are in place (Bouwmeester, 2019)**.** As of the date, Dutch government prepares legislation to cut out coal as a fuel for electricity generation (Rijksoverheid, 2018). Looking at built capacity in the Netherlands, this might strike as odd, due to the recent building surge of coal-fired power plants. As construction of new power plants is not realistic in the near future due to overcapacity on the Dutch grid (Bouwmeester, 2019; Tijdink, 2019), it is of importance to review which power plants will produce electricity under current circumstances. This was reviewed by sub question 3.

5.3 Section conclusion

The Dutch electricity market has been liberalized guided by European directives in order to create an open European electricity market to increase competitiveness under electricity generating companies in Europe. This is still an evolving process which does not seem to be finished yet, when looking at the number of countries which still support a ‘national champion’. Effects of the liberalization on electricity prices are yet unclear, as electricity prices for the end-user have risen since the start of market liberalization. However, it is undetermined if this increase would have been higher without market liberalization. Therefore production prices are proposed as a parameter. Interesting to see is the combination of the shift of risks from consumers to producers as described in section 5.2.6, and the high amount of newly build small scale capacity in the category ‘other’ as described in Table 2. It is, however, unclear whether this is a result of liberalization or other policy and trends in renewable electricity generation.

6. Costs of electricity generation

6.1 Methodology

This section aims to answer the sub question: “How do different cost components influence the profitability of electricity generation in the Netherlands?”. Firstly the types of researched powerplants are discussed, followed by the economic indicators and the used formulas.

6.1.1 Powerplants and cost build-up

The research has reviewed both hypothetical new installations which could be built in the future, and the last built powerplant of every major technology for coal- and gas-fired powerplants. It is important to consider that for future powerplants, parameters from the last build powerplants for every technology were used, concerning load factor and efficiency. The researched powerplants and their efficiencies can be found in Table 4. The efficiencies used in this research were the efficiencies as reported by the utility company owning the power plant. These values are the maximum possible efficiency for these installations. However it is expected that this will not disturb the results, as the maximum efficiencies for all powerplants were used.

Table 3: Researched powerplants

Energy carrier	Type	Plant	Electric efficiency
Coal	ST	Eemshaven	0.46
	ST/S	Mpp3	0.47
Natural gas	CCSS	Flevo Maxima	0.59
	CCSS/CP	Diemen 34	0.59
	GT/CP	Rijnmond	0.52
	GT/C	Diemen 33	0.54

The cost of construction and its related economic parameters are more of a theoretical concept for future investments in the market, as interviews with utility companies and network operators have acknowledged that no new fossil capacity will be built in the near future (Bouwmeester, 2019; de Boer, 2019; Tijdink, 2019). The current electricity network copes with an overcapacity and mothballs fossil capacity, as it structurally falls out of the order of merit. However, investment and thus cost of construction are a vital part of indicators which are able to show the economic feasibility and the areas which require the largest investments of new technologies and therefore will be included in the research. Both theory and interviews suggested the use of the net present value (NPV) and internal rate of return (IRR) as economic indicators. For both indicators the different types of costs and benefits generated over the lifetime of the installation are important. Therefore the used cost concepts are elaborated on next.

The costs for newly built capacity are build up out of the following components (Tidball, Bluestein, Rodriguez, & Knoke, 2010);

- Investment costs
- Fixed O&M costs (Insurance, taxes, land lease payments and other fixed costs) (NREL, 2015)
- Variable O&M costs (Scheduled and unscheduled maintenance of power plants, and other technical components of the power plant, salaries) (NREL, 2015)
- Fuel costs
- Emittance costs

The benefits consist of the sales of electricity. Prices are established by gathering an average value of the electricity sales price over the past 5 years (ENTSOE-E, 2019). Both yearly costs and benefits are dependent on the amount of electricity produced per year. Therefore the place in the order of merit has to be determined on the basis of its short run marginal costs, which circle back to the efficiency, fuel costs, and variable O&M costs. As O&M costs consist of both variable and fixed O&M costs, it is important to find both separately and not a single value, because this already accounts for a predestined load factor. Therefore the research looked into the most modern installations of different technologies, and determined these parameters and the load factor for these installations.
These values can be found in Table 5.

Table 4: Economic parameters used for powerplants

Powerplant type	**ST**	**ST/S**	**CCSS**	**CCSS/CP**	**GT/CP**	**GT/C**	**Source**
Powerplant fuel	**Coal**		**Natural gas**				-
Powerplant	Eemshaven	Mpp3	Flevo Maxima (total)	Diemen 34 CC2	Rijnmond GT1	Diemen 33 CC1	-
Capacity of installation	1200	1600	880	435	260	150	(Platts, 2018)
Investment cost [€2019/MW]	2916000	2916000	714000	714000	1012000	1012000	(BLS, 2016; EIA, 2016, 2019; Wisselkoers.nl, 2019)
Fixed O&M [€2019/MW/year]	30098	30098	27321	27321	16673	16673	(BLS, 2016; Newell, Hagerty, Pfeifenberger, Spees, & Liao, 2014; Tidball et al., 2010)
Variable O&M - high [€2019/MWh]	5.02	5.02	1.30	1.30	2.16	2.16	(BLS, 2016; Newell et al., 2014; Tidball et al., 2010)
Variable O&M - low [€2019/MWh]	2.29	2.29	0.34	0.34	0.72	0.72	(CAISO, 2018)
Electric efficiency	46%	47%	59%	59%	52%	54%	Plant owners sites
Emission [tonne CO_2/year]	7587	7282	1165	447	530	178	(NEA, 2018)
Load factor	60%	97%	44%	34%	13%	34%	-

These values were then used for cost calculation of a newly to build installation. Uncertainty in the found values must be searched mainly in the price values for installations. Variations were especially big for variable operation and maintenance costs, therefore, a set of two different values was used. Variation in investment costs and fixed O&M costs were also found, but never as large as the variable O&M costs (up to 382%) Furthermore, the electric efficiency values are high, as these are the (maximum) values as reported by the owning companies. Load factor was found by division of the yearly CO_2 emittance by the emission factor of the input fuel, resulting in the amount of fuel input. This was divided by the average efficiency of the installation to find the electricity output. The load factor was then calculated as described in section 4.1.3. For the 'Diemen' installations, a total amount of CO_2 emittance was found, leading to difficulties as the installation consists of both gas and coal fired power plants. In this research it was decided to spread the CO_2 emissions as a ratio over both installations, taking the capacity times the emission factor of input fuel as the ratio. The used values for the economic parameters can be found in Table 6. Uncertain values in the table are the sales price of electricity, the fuel prices and the emission costs. Future electricity sales prices depend heavily on future electricity scenarios. Therefore the current electricity price, is frozen for the future.
Coal price; the research tried to cope with the uncertainty by taking the average price in the last 5 years. A decrease might be expected in Australia, no data for Europe yet found (World bank, 2019)

Gas price; the research tried to cope with the uncertainty by taking the average price in the past 5 years, similar to the method for the coal price. No large increase in price is expected in Europe before 2030, even a decrease can be expected when looking at constant dollar prices (World bank, 2019).
Emission cost; For this category, the research tried to cope with the uncertainty this by taking the average over the last five years. As the current emission cost is very low (5€/tonne), but prices can be expected to rise again under the framework of the European emission trading scheme (EC, 2019b).

Table 5: Economic parameters used for the research

Parameter	**Value**	**Source**
Electricity sales price [€/MWh]	41.43	(ENTSOE-E, 2019)
Fuel price - coal [€/GJ]	2.31	(Blok, 2007; CLO, 2019)
Fuel price - gas [€/GJ]	5.65	(Blok, 2007; CLO, 2019)
Emission cost [€/tonne]	11.40	(CBS, 2018b)
Emission factor – coal [tonne CO_2/GJ]	0.094	(RvO, 2018)
Emission factor – natural gas [tonne CO_2/GJ]	0.0565	(RvO, 2018)
R-low	0.05	(Blok, 2007)
R-high	0.12	(Blok, 2007)
Lifetime [years]	40	(Platts, 2018)
α-low	0.06	Own calculations
α-high	0.12	Own calculations

6.1.2 Economic indicators

The NPV was calculated as follows:

$$NPV = -I + \sum_{i=1}^{L} \frac{B-C}{(1+r)^i} \qquad (2)$$

Where I = initial investment
L = lifetime of the investment
B = annual benefits in year i, consists of heat and electricity sales
C = annual costs in year i, consists of O&M and fuel costs
i = year
r = discount rate, tested for both a social discount rate (5%) and private discount rate (12%) (Blok, 2007)

As the values of the NPV were very negative for both calculated r-values, the IRR was not calculated. These values are in line with the interviews conducted during the research, referring to the overcapacity in the current market.

Fuel costs were calculated as follows:

$$C_f = \left(\frac{Cap \times LF \times 8760}{\eta}\right) \times F \qquad (3)$$

Cap = capacity [MW]
LF = load factor
η = efficiency
F = fuel price [€/MJ]

Emission costs have been calculated as follows;

$$C_e = \left(\frac{Cap \times LF \times 8760}{\eta}\right) \times EF \times EP \quad (4)$$

EF = emission factor [tonne CO_2/MJ]
EP = price of CO_2 [€/tonne CO_2]

Benefits have been calculated as follows:

$$B = (Cap \times LF \times \eta_E) \times P_E + (Cap \times LF \times \eta_H) \times P_H \quad (5)$$

η_E = efficiency of electricity production
P_E = price of electricity sales [€/MWh]
η_H = efficiency of heat production
P_H = price of heat sales [€/MJ]

The second step of economic indicators aimed at the cost of electricity production. It calculated lcoe values with Formula 6 and the short run marginal costs of installations. A low and a high scenario for the lcoe were calculated, thereby using the low and high r-value to calculate alpha, and the low flexible yearly operation and maintenance costs.

$$lcoe = \frac{\alpha \cdot I + OM_{ann} + F_{ann}}{E_{ann}} \quad (6)$$

where α = capital recovery factor, depending on lifetime and discount rate
I = initial investment [€]
OM_{ann} = annual operation and maintenance costs [€/year]
F_{ann} = annual fuel costs, depending on fuel costs, carbon price, energy efficiency [€/year]
E_{ann} = annual electricity production [MWh/year]

Furthermore, the SRMC costs were calculated with Formula 7

$$SRMC = \frac{E_{out}}{\eta_E} \times F + \frac{E_{out}}{\eta_E} \times EF \times EP + OM_{flex} \quad (7)$$

Where E_{out} = 1 MWh
η_E = efficiency of electricity production
F = Fuel price [€/MWh]
OM_{flex} = flexible O&M costs [€/MWh]

6.1.3 Correlations

In addition to the calculation of cost parameters, the research looked for correlations between several factors supposedly influencing the load factor of the powerplants. Most important is the SRMC, which could be an indicator for the load factor.

Furthermore, the required CO_2 emission price for a merit order change was calculated for the best practice installations currently in the market (Coal: MPP3, Natural gas: Flevo Maxima power plant). Currently the coal fired capacity has lower SRMC, and is therefore earlier in the merit order than natural gas (see Chapter 2.). The research compared both equations for short run marginal costs (Formula 7), and looked for the required EP, as found on the intersection of the formula for $SRMC_{coal}$ and $SRMC_{naturalgas}$.

6.2 Results

6.2.1 Economic parameters

The results of the aforementioned methods are summarised in a table (Table 7) to provide the exact values and a figure to provide more insight in the overall values. The table provides an overview of the different parameters calculated for all the installations. As visible, the lcoe is higher than the average price for electricity found via ENTSO-E (41€/MWh) for all cases, both with the current load hours (calculated in ‘future capacity’), and with a pre-set load factor of 80% (ENTSOE-E, 2019). This a clear sign in the direction of the current situation of the electricity market which does not leave room for newly built fossil fuel projects. In the low r-scenario, the lowest lcoe is still a factor 1.06 higher than the average electricity price. Furthermore it becomes clear that the type of energy carrier does not necessarily correlate to the value of the lcoe.

The value of the NPV is strongly negative for all installations, again in line with the current situation in the Netherlands. It is noteworthy that gas-fired power plants on average provide a better NPV value than coal-fired power plants. This is due to the high investment costs in coal fired power plants, as will become visible in Figure 12. The first two rows present the short run marginal costs, which is an indicator for the order of merit. It is visible that when coal fired power plants are built, and the investment costs are not a factor anymore, these become cheaper to produce electricity, and are thus lower in the order of merit, resulting in a higher load factor.

Table 6: Economic parameters for power plants in the Netherlands

Fuel type		**Coal**		**Natural gas**			
Powerplant type		ST	ST/S	CCSS	CCSS/CP	GT/CP	GT/C
Plant		Eemshaven	Mpp3	Flevo Maxima	Diemen 34	Rijnmond	Diemen 33
Current capacity	**Short run marginal costs - low [€/MWh]**	25.88	25.37	37.38	37.38	42.75	41.20
	Short run marginal costs - high [€/MWh]	28.60	28.10	38.35	38.35	44.19	42.63
Future capacity	**NPV-low [Million€]**	-533	-232	-222	-246	-367	-336
	NPV-high [Million€]	-725	-533	-252	-270	-383	-377
	LCOE-low [€/MWh]	58.31	43.54	52.73	57.93	105.71	63.78
	LCOE-high [€/MWh]	93.16	65.17	64.43	73.03	161.26	85.18
Pre-set value of 80%	**NPV-low [Million€]**	-378	367	-133	-133	-327	-284
	NPV-high [Million€]	-634	-615	-189	-189	-428	-381
	LCOE-low [€/MWh]	48.93	48.54	44.64	44.64	50.63	49.18
	LCOE-high [€/MWh]	75.16	74.77	51.06	51.06	59.74	58.29

Figure 12 shows the costs per installation. It becomes visible that the investment costs are much higher for coal-fired power plants, and investment costs are contribute to nearly half of the yearly costs of gas fired power plants. In the high alpha scenario (using a commercial r-value) the costs are even higher. For both cases the NPV was negative, as was visible in Table 7. Therefore, the installations only become profitable after the economic lifetime under current circumstances and assumptions. Emission costs only contribute to a very small amount of the total costs per year, thereby keeping the short run marginal costs of coal fired power plants low.

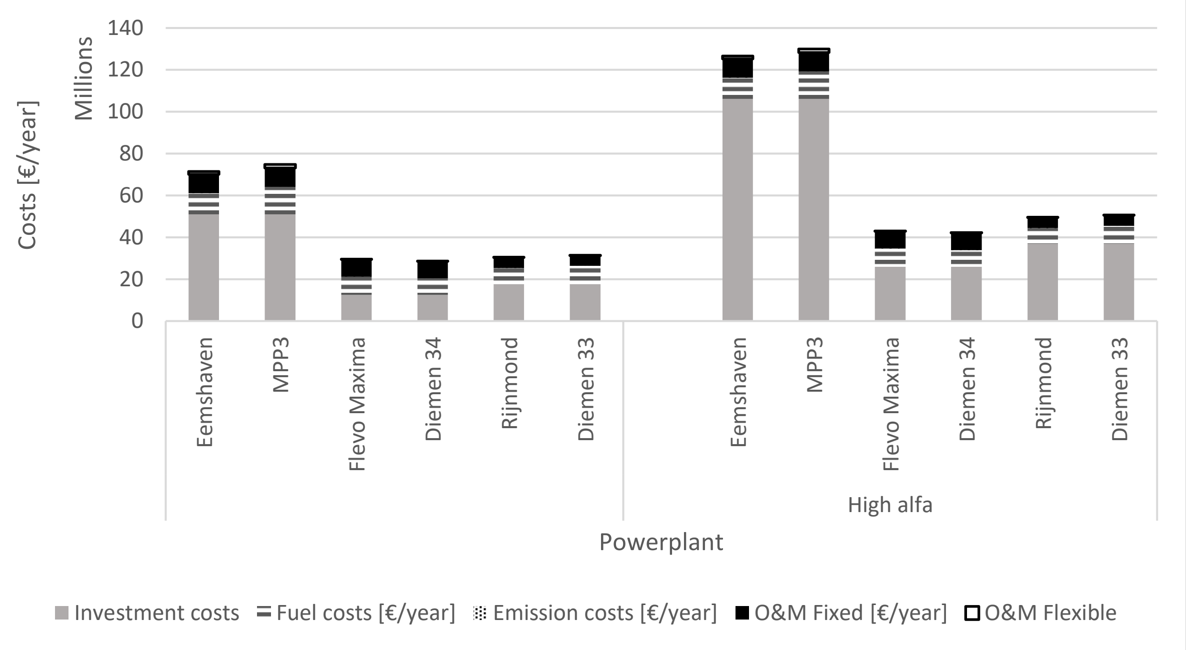


Figure 12: Cost breakdown of newly build power plants

6.2.2 Correlations

The research tried to assess whether fuel price, emission costs and the variable O&M costs (together the SRMC) correlated to the load factor of the installations. Figure 13 and Figure 14 provide the fuel price, emission costs and load factors for the complete sector of natural gas fired and coal fired electricity generation. Variable maintenance costs were not represented in the graph, as these remained constant over time and could not be converted into €/primary fuel. As conversion would lead to a lower cost per primary fuel for a less efficient installation with the same variable O&M costs as a similar installation with higher efficiency. Figures presenting the SRMC and load factor over the years can be found in appendix A. As visible in Figure 13 and Figure 14, there is no price data for CO_2 emissions before 2007. This is due to the fact that there was no trading in allowances before this period. The emission trading scheme started in 2005, but allowances were handed out freely until 2007, which marked the start of the second period of the European emission trading scheme (EC, 2018)**.**

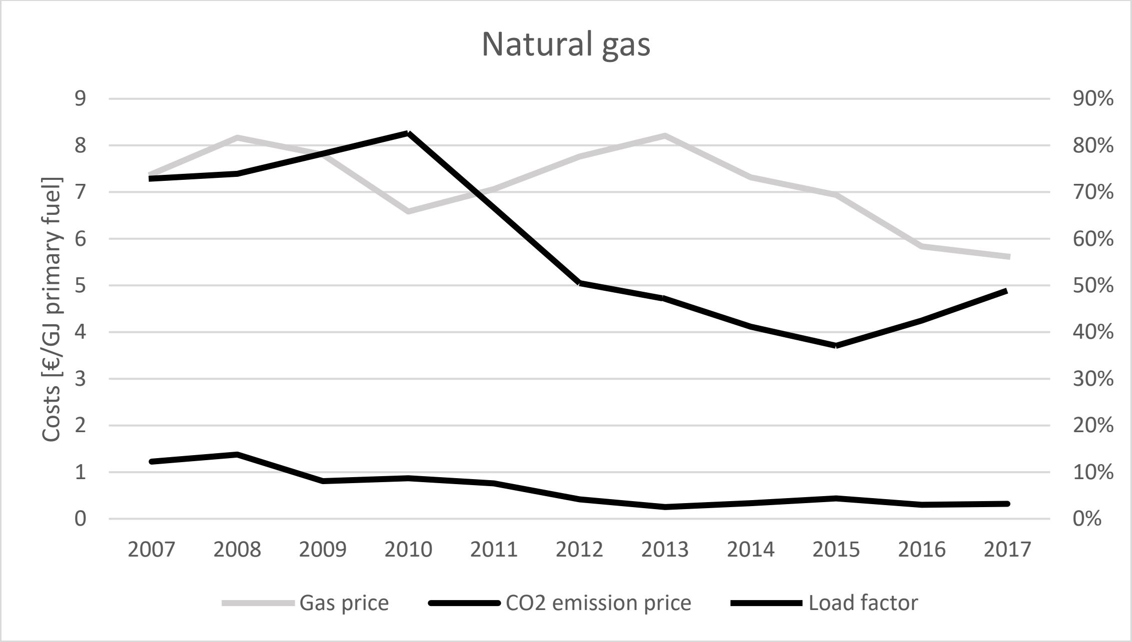


Figure 13: Development of natural gas price, CO_2 emission price and load factor (CBS, 2018b, 2019a)

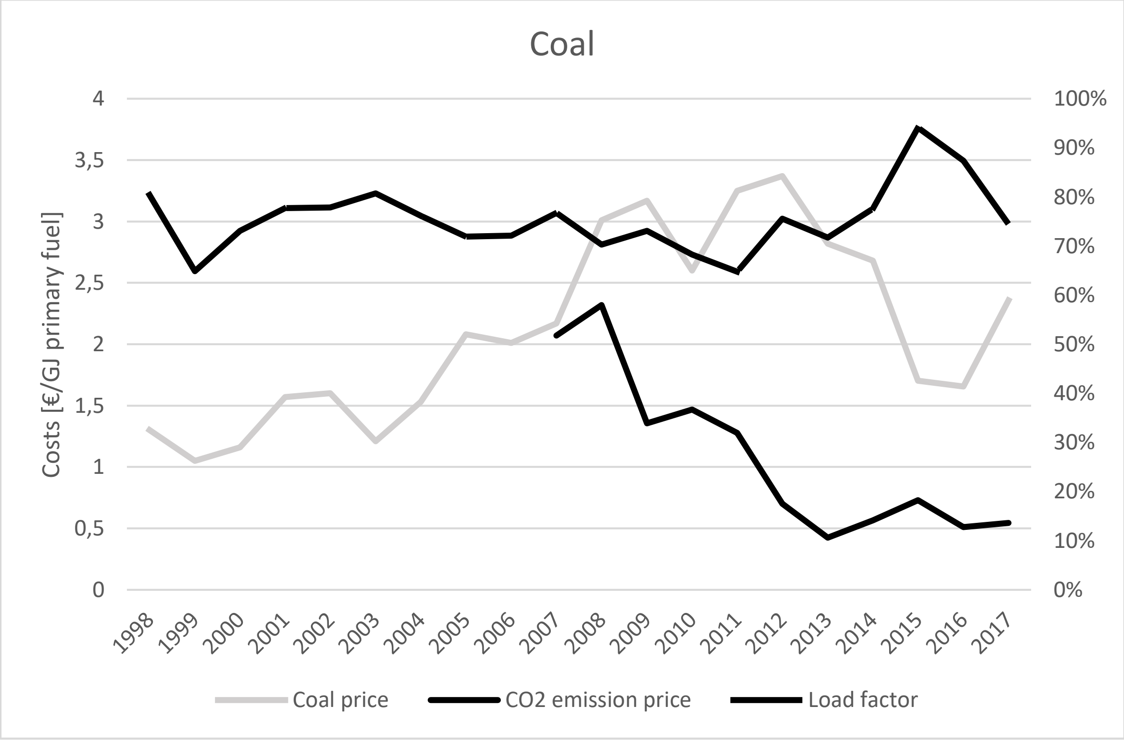


Figure 14: Development of coal price, CO_2 emission price and load factor (CBS, 2018b; CLO, 2019)

The research further looked into the required price of CO_2 allowances to turn around the merit order between coal- and gas-fired capacity, in order to preserve gas fired electricity generation in the electricity mix, and thereby gas fired capacity in the future. This was performed for both the low, and the high flexible O&M costs. It was found that for a low flexible O&M costs scenario, a price of 142.03 €/tonne CO_2 was required, and for the high flexible O&M a price of 125.04 €/tonne CO_2 was required. The latter is a lower value, as the difference between O&M costs is smaller in this scenario.

In the search for correlations, firstly scatterplots were formed to look for a general trend (Figure 15, Figure 16). As visible the trend lines for both figures have a different direction, which should not occur. The trendline for natural gas fired capacity shows an increase in load factor for higher SRMC, which contradicts with liberal market principles.

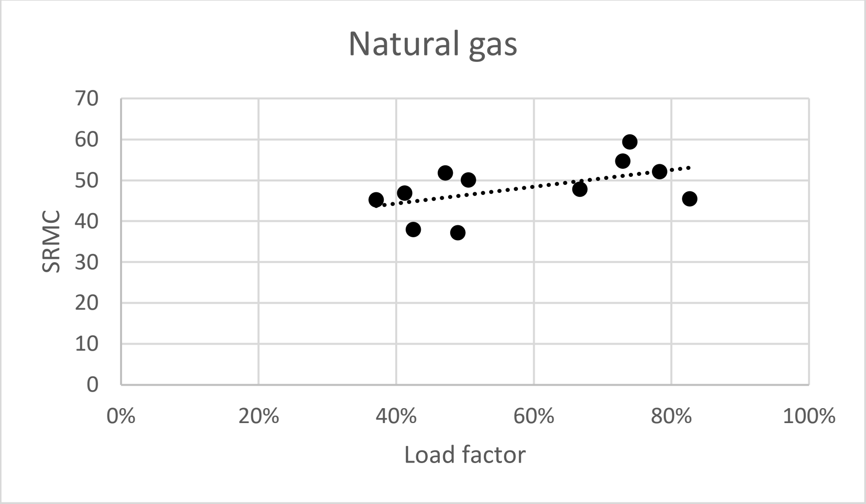


Figure 15: Scatterplot of SRMC and load factor of gas fired powerplants in the Netherlands between 2007-2017

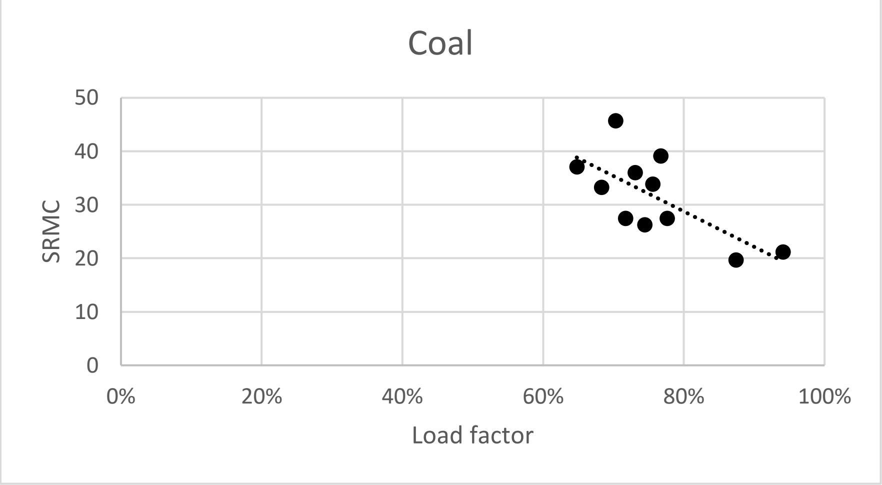
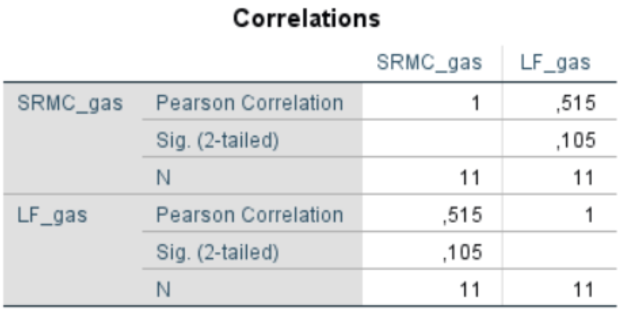


Figure 16: Scatterplot of SRMC and load factor of coal fired powerplants in the Netherlands between 2007-2017

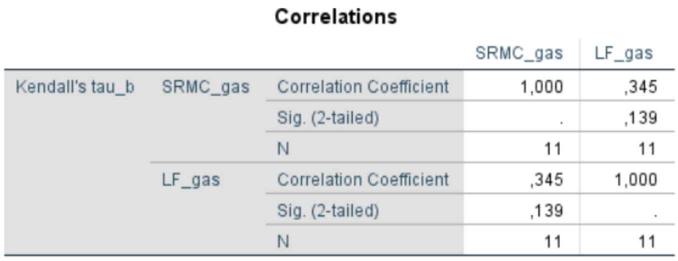
For both possible correlations statistical tests have been performed to review these correlations. As visible in the histograms as provided in Appendix A, SRMC for both energy carriers could be considered to have a normal distribution. However, load factor, especially for gas fired capacity, does not. Therefore Pearson's R can only be used for the coal fired capacity, and Kendall's Tau must be used for the gas fired capacity. As the power of Pearson's R is larger, both tests are still performed for both parameters, to provide a comparison between both correlations (Figure 17-20). As visible, the significance for Pearson's R is higher than for Kendall's Tau, due to its higher power as stated before. However, the correlation between SRMC of gas and the load factor is not significant, as it becomes significant when it is lower than 0.05. Regarding coal fired power plants, no significant relationship could be found either, however, the R^2 of the relation does have the right coefficient, and significance is much closer to 0.05.



Correlations

		SRMC_gas	LF_gas
SRMC_gas	Pearson Correlation	1	,515
	Sig. (2-tailed)		,105
	N	11	11
LF_gas	Pearson Correlation	,515	1
	Sig. (2-tailed)	,105	
	N	11	11

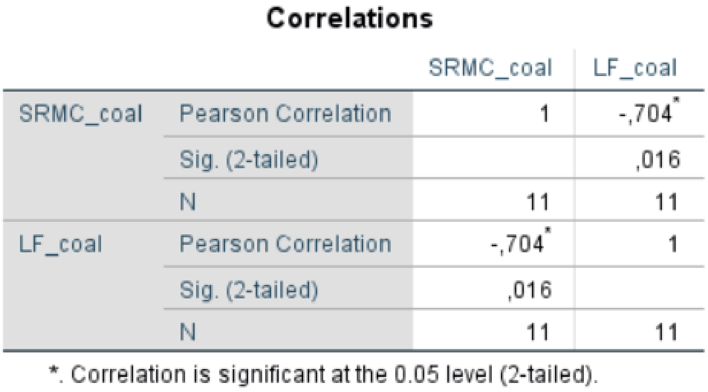
Figure 17: Pearson's R for correlation between SRMC and load factor for gas fired capacity in the Netherlands between 2007-2017



Correlations

			SRMC_gas	LF_gas
Kendall's tau_b	SRMC_gas	Correlation Coefficient	1,000	,345
		Sig. (2-tailed)	.	,139
		N	11	11
	LF_gas	Correlation Coefficient	,345	1,000
		Sig. (2-tailed)	,139	.
		N	11	11

Figure 18: Kendall's Tau for correlation between SRMC and load factor for gas fired capacity in the Netherlands between 2007-2017

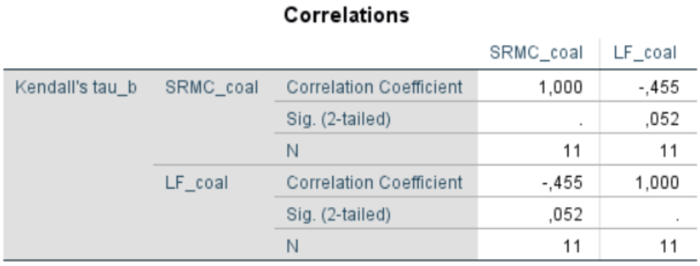


Correlations

		SRMC_coal	LF_coal
SRMC_coal	Pearson Correlation	1	-,704*
	Sig. (2-tailed)		,016
	N	11	11
LF_coal	Pearson Correlation	-,704*	1
	Sig. (2-tailed)	,016	
	N	11	11

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 19: Pearson's R for correlation between SRMC and load factor for coal fired capacity in the Netherlands between 2007-2017



Correlations

			SRMC_coal	LF_coal
Kendall's tau_b	SRMC_coal	Correlation Coefficient	1,000	-,455
		Sig. (2-tailed)	.	,052
		N	11	11
	LF_coal	Correlation Coefficient	-,455	1,000
		Sig. (2-tailed)	,052	.
		N	11	11

Figure 20: Kendall's Tau for correlation between SRMC and load factor for coal fired capacity in the Netherlands between 2007-2017

Further correlation tests have been performed in order to review possible correlations between load factor and fuel price or load factor and SRMC difference (dSRMC). To search for this correlation, Pearson's R was not suitable, as price data and dSRMC data did not show a normal distribution (Appendix A). Conversion of fuel prices did not produce any data with a normal distribution either. Therefore Kendall's Tau was used, as this is an acceptable method for non-normal data. No correlation between either of the variables and the load factor could be found for the researched period (2007-2017). Reasons for the lack of correlation could be the short period of available data (N=11). Furthermore this data could be distorted due to inclusion of the economic crisis in this period, which might have led to a disconnection between possible benefits and the load factor. As the significance and coefficient of all correlations is too small (Appendix A), it is assumed that the price is not the only determining factor of electricity production, even in the liberalized market. This is in line with reasons for electricity production as stated by utilities (de Boer, 2019).

6.3 Section conclusion

It has become clear that investment in both coal and gas fired capacity is not advised under current conditions. This is visible in the negative NPV for all powerplants, both for a low and high depreciation rate. The NPV is dominated by the investment costs, which can contribute up to 80% of the total costs of a powerplant. Under current circumstances production by coal fired capacity is cheaper than gas fired capacity, when the capacity is already installed. This was found after comparison of the short run marginal costs, which are around 10€/MWh higher for gas fired electricity generation. This difference in short run marginal costs could be overcome by increasing the required price for CO_2 emittance. A price in the range of 125-142 €/tonne CO_2 (depending on the variable operation and maintenance costs) would alter the merit order, and give gas fired electricity generation an edge over coal fired electricity generation, concerning the short run marginal costs.

7. Future generation scenarios

This section in the research aims to answer the sub question: *"How will the built capacity and power generation by gas-fired power plants develop in the Netherlands?"*. The research looked into energy scenarios, which will represent future extremes as long as they will be in reason. On the basis of these found scenarios, sub questions five, six, and seven were researched.

7.1 Methodology

For the use of scenarios, it was chosen not to create an own scenario for the future electricity use and generation of electricity, as this is a study area of its own, and would be out of the scope for this research. As the results of the correlation tests were not deemed useful to produce educated guesses for this research, scenarios from other sources are used to provide insight in possible future electricity generation. The scenarios used were selected to create a wide range of scenarios, therefore, one scenario from the European commission was chosen (EC, 2013a), one scenario developed by an external company (Frontier economics, 2015), and two scenarios (ECN, 2017a, 2017c) developed by the Dutch Energy research centre (ECN) were chosen as scenarios by this institute are a vital part of Dutch future energy policies.

7.2 Results

The research used five different scenarios, originating from 4 sources. As visible in all scenarios, the capacity for electricity generation will continue to grow, however in different amounts of growth. Resulting in a total capacity range in 2030 between 38.3 and 46.2 GW. However, the generation mix is different for the scenarios, whereas the scenarios proposed by the Dutch energy research centre (ECN) provide a higher penetration of renewables than the older and international proposed scenarios. Another interesting factor is that in times of discussion about CO_2 emissions by electricity generation, all scenarios do not provide a big role for nuclear generated electricity, with a 4.6% share to the total as the largest in the scenario by Frontier Economics.

Table 7: Future capacity for electricity generation in the Netherlands

		Capacity [GWe]					
Scenario	Fuel Year	Coal	Oil	Gas	Renewables	Nuclear	**Total**
(Platts, 2018)	**2010**	3.6	0.0	10.0	5.3	0.5	**19.4**
	2018	4.8	0.1	13.6	11.5	0.5	**30.5**
R-scenario & A-scenario (ECN, 2017c)	**2020**	5.4	0.0	15.2	14.3	0.5	**35.4**
	2025	4.6	0.0	13.3	22.3	0.5	**40.8**
	2030	4.6	0.0	12.4	28.7	0.5	**46.2**
(EC, 2013)	**2020**	6.0	0.7	18.4	10.5	0.5	**36.0**
	2025	6.0	1.0	18.3	12.9	0.5	**38.6**
	2030	5.6	1.0	17.7	13.4	0.6	**38.3**
(Frontier Economics, 2015)	**2020**	4.1	0.0	10.4	13.1	1.8	**29.3**
	2025	4.1	0.0	11.8	16.4	1.8	**34.1**
	2030	4.1	0.0	13.2	19.8	1.8	**38.9**
(ECN, 2017a)	**2020**	3.5	0.0	14.8	10.1	0.0	**28.4**
	2025	3.5	0.0	13.2	17.4	0.0	**34.1**
	2030	3.5	0.0	11.4	25.5	0.0	**40.5**

For the electricity generation, a similar image is visible with different total amounts of electricity generation and different build ups of how the electricity is generated. It is interesting to see that different scenarios come to rather different load factors for their respective capacities. As the ECN, 2017a scenario produces 3820 load hours/GW renewable capacity, and the ECN, 2017c only 2230 load hours/GW, a difference of 71%. For gas fired capacity, these changes become even larger, with 3900 load hours/GW for ECN, 2017 A-scenario and 1100 load hours/GW for the ECN, 2017a scenario, a difference of 254%. These differences between the scenarios could be explained by the goal the scenario serves, or the company or institute which created the scenario. Table 9 shows current and future electricity generation in different scenarios in the Netherlands. The value for 2017 is shown, and not 2018 as in the previous table, as this was the most recent data available.

Table 8: Future electricity generation in the Netherlands

		Production [TWh]					
Scenario	fuel year	Coal	Oil	Gas	Renewables	Nuclear	**Total**
(CBS, 2019e)	**2010**	21.9	0.0	77.9	11.2	4.0	**115.0**
	2017	31.3	0.1	57.9	17.4	3.4	**110.1**
R-scenario (ECN, 2017c)	**2020**	31.5	0.0	49.0	35.5	4.0	**120.0**
	2025	32.1	0.0	47.3	53.3	4.0	**136.7**
	2030	30.0	0.0	43.0	64.0	4.0	**141.0**
A-scenario (ECN, 2017c)	**2020**	32.1	0.0	50.9	35.5	4.0	**122.5**
	2025	33.7	0.0	50.9	53.3	4.0	**141.9**
	2030	33.0	0.0	48.0	64.0	4.0	**149.0**
(EC, 2013)	**2020**	37.7	1.2	46.6	41.1	4.0	**130.5**
	2025	38.3	1.3	40.2	47.3	4.1	**131.1**
	2030	32.0	1.5	48.3	48.4	5.0	**135.2**
(Frontier Economics, 2015)	**2020**	29.0	0.0	49.5	38.5	2.6	**119.5**
	2025	27.3	0.0	49.4	49.0	2.6	**128.2**
	2030	25.6	0.0	49.2	59.5	2.6	**136.9**
(ECN, 2017a)	**2020**	27.5	0.0	26.3	40.0	2.5	**96.3**
	2025	28.8	0.0	23.8	72.5	2.5	**127.5**
	2030	21.3	0.0	12.5	97.5	2.5	**133.8**

7.3 Section conclusion

This section searched for an answer to the research question: “How will the build capacity and power generation by gas-fired power plants develop in the Netherlands?”. It was designed to create clarity on the different future scenarios for the next sub questions and how they align with current values in the Netherlands. When looking at the main focus of the research, coal and gas fired capacity and generation, the numbers of future do align with the historic numbers. Large differences in the shares of generation by gas fired capacity were found (9-36% to the total electricity generation), while differences between shares of coal fired electricity generation to the total are smaller between the scenarios (16-24%). In future scenarios, gas fired capacity projects to be replaced mainly by renewable capacity. It should be noted, that future scenarios provide a range of projections for the future electricity total electricity use with a difference of 11% between both extremes. Thereby influencing future use and requirement of new capacity and adding to the uncertainty of future electricity mixes.

8. Future efficiency of electricity generation

8.1 Methodology

To calculate the change in efficiency over time in the different scenarios, the efficiency per fuel type was researched, and used in the future scenarios in order to calculate the overall and fossil efficiency of future electricity generation scenarios.

8.1.1 Electric efficiency per energy carrier

Efficiency per fuel type was calculated to be the an average of the energy input divided by the energetic value of energy input over the past five years. Data input from CBS (CBS, 2019e) only provides a total of energetic value for both electricity generation and heat generation. For the majority of categories this does not provide significant changes, however for biomass and natural gas this needs to be addressed. As future scenarios did not address how the structure of the renewables category will change over time, it is assumed that the change in structure comes to a standstill as it is not viable to continue the trend of the last five years for the complete scenario. This would result in a near complete dominion of electricity generation by wind and solar power, which would presumably hit a natural maximum in a densely populated country as the Netherlands and a densely used sea as the North Sea.

As the Netherlands currently houses CHP plants, the electricity output of a CHP plant cannot be simply regarded as the electricity generated divided by energetic value of the fuel input. This would discard the heat produced by the CHP plant. Discarding this produced heat leads to a skewed image of electric efficiency, as the total efficiency of the installation increases at the costs of a margin of the electric efficiency. Therefore, the heat output from CHP plants is included into the equation for the total efficiency too, by including a correction factor for the power efficiency lost due to heat generation (Graus & Worrell, 2009; Hemmer & Klaassen, 2012).

The use of national data was preferred as it is deemed more accurate as international data. However, as data on CHP generation was only presented as an aggregate, this was not preferred for efficiency calculation of gas fired capacity. Therefore, data from the international energy agency (IEA, 2016a) was used to calculate efficiency by gas fired capacity, as this presented CHP output as a separate value.

The formula for efficiency of the total mix results in:

$$\eta_x = \sum \frac{(\mathrm{P_x} + \mathrm{H_x} \cdot \mathrm{s})}{\mathrm{F_{tot}}} \tag{8}$$

Where η = the efficiency of the electricity generated by fuel x
P_x = power produced by energy carrier x [TJ]
H_x =heat produced by energy carrier x [TJ]
s = correction factor
F_{tot} = fuel input [TJ]

Filling in Formula 8 leads to the efficiencies as stated in Table 10. As visible, the results are lower than the values stated in Table 3. Values in Table 3 are based on the maximum possible efficiency as supplied by the owner. Values in Table 10 also include efficiency losses due to less than optimal use of the power plant e.g. due to cycling and starting-up.

Table 9: Efficiency of electricity generation per fuel type; based on market wide fuel input and electricity generation

Fuel type	**Electric efficiency**
Coal	43 %
Oil	37%
Gas	55%
Wind, Solar PV, Hydro	100%
Nuclear	37%
Biomass	37%

8.1.2 Reporting

The research reported on both the efficiency of the total capacity. This was performed on the basis of three different types of scenarios, the future scenarios (the electricity generated divided by the electricity generated per fuel times the fuel efficiency), a theoretical best practice scenario, and an theoretical equal loads scenario where all capacity produces electricity with the same load factor (the average efficiency of the capacity).

8.1.3 Best practice scenario

For the best possible efficiency scenarios, no new efficiencies for single powerplants were used. This scenario was calculated by filling the electricity needs with an order of merit, based on the efficiency of generating technologies. To fill electricity demand, the availability factor of generating technologies was taken into account in order to find the maximum yearly electricity production per technology. The availability of powerplants is only determined by outages of the installation due to maintenance or unexpected outages. Availability declines during the lifetime of an installation due to an increased number of outages. However, as the age of the electricity generating capacity is deemed to be homogenous for the Dutch power system, the average value is used for power plants. The availability of solar power and wind power is not only determined by outages, but also by the availability of the energy source, therefore these values are lower than for conventional installations. Values for availability factors can be found in Table 11. These availability factors were also required for division of the category ‘renewables’ as reported in the future scenarios into separate renewable categories. As no division is provided, it is assumed that the initial ratio of wind powered, solar powered, hydropower and biomass remains similar to the value of 2018 (48.48%, 48.70%, 0.44%, 2.38%). However, this would lead to impossible load factors required from the built capacity. Therefore it is assumed that the built capacity produced electricity on the basis of the availability factors as reported in Table 11, and the remaining electricity in the scenarios required by ‘renewables’ is produced by biomass.

Table 10: Availability factors for electricity generating technologies

Type	**Availability factor**	**Source**
Coal	83.28%	(World energy council, 2010)
Gas	79.40%	(World energy council, 2010)
Solar power	875kWh/kWp/year	(van Sark, 2014)
Wind power	23.31%	(CBS, 2019d).
Hydropower	82.3%	(Oak Ridge National Laboratory, 2018)
Biomass	90.0%	(Bouwmeester, 2019)
Oil	83.78%	(World energy council, 2010)
Nuclear	80.6%	(IAEA, 2019)

8.1.4 Equal loads scenario

The equal loads scenario is a theoretical scenario designed to, in combination with the actual future scenarios, provide an insight in how the installed capacity will be used. When the reported efficiency is higher than for the actual scenario, more efficient installations are used than the average of all installations. The scenario does not take into account the fulfilment of electricity demand at a certain moment, and minimum load factors for power plants which cannot be shut down easily. Therefore the scenario is not refined enough to be considered a realistic future scenario, but only aims to provide insight in whether more or less efficient capacity than the average efficiency is used.

8.2 Results

8.2.1 Future scenario efficiency

When reviewing Figure 21 it becomes clear that the total efficiency is expected to increase in all scenarios. As visible when Figure 21 and Figure 24 are compared, the future scenario load factors all provide a lower efficiency than the equal load scenarios (a range of 56-62% versus a range of 57-62%). This implies that the actual use of the build capacity tends to use capacity with a lower efficiency first in comparison to capacity with a higher efficiency. This can be explained that renewables, which have the highest efficiency are not always available, and fossil powered electricity generation, with a lower efficiency, is.

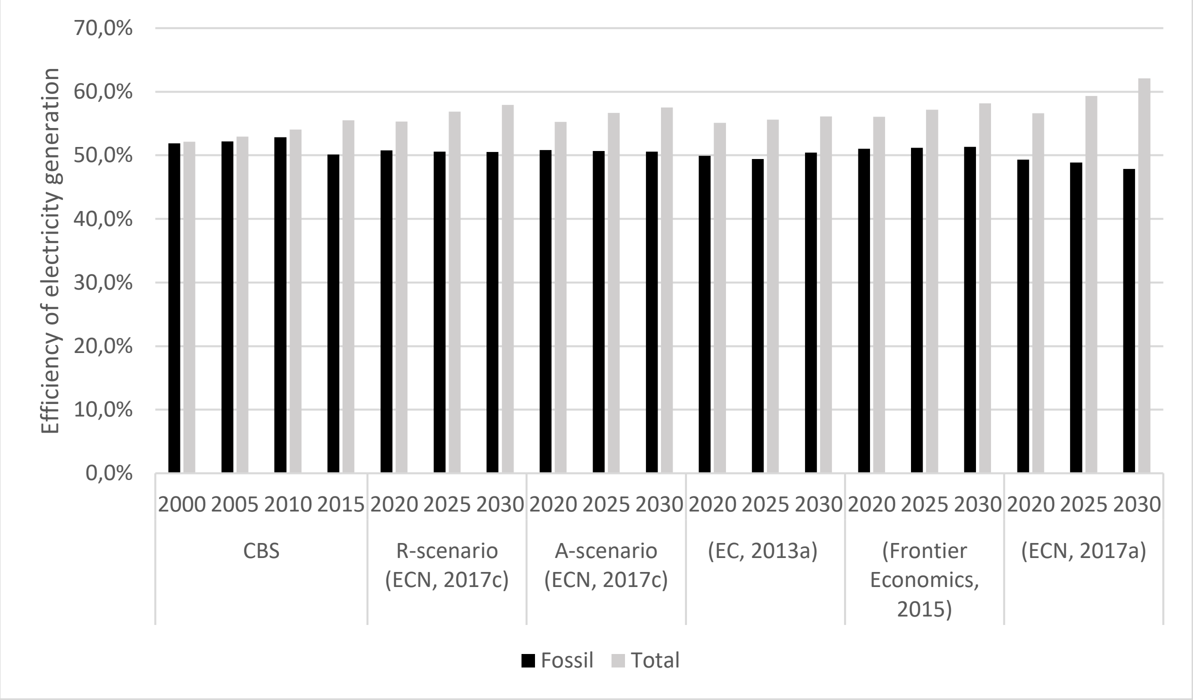


Figure 21: Past and future efficiency of electricity generation

However, when Figure 22 is taken into account, it becomes apparent that the efficiency of fossil generated electricity follows a negative trend for three out of five scenarios, and a negative result compared to the value of 2015. This is a result of the changing ratio between coal- and gas-fired capacity. Current practice houses a larger fraction of natural gas fired electricity generation, thereby ensuring a higher efficiency. The drop in efficiency in 2015 can be explained by a large drop in the ratio between gas and coal fired electricity generation, in 2010 this was 3.6, which dropped to 1.3 in 2015. However, this data point is an outlier, as the value restored to 1.9 in 2017, which was the latest data available.

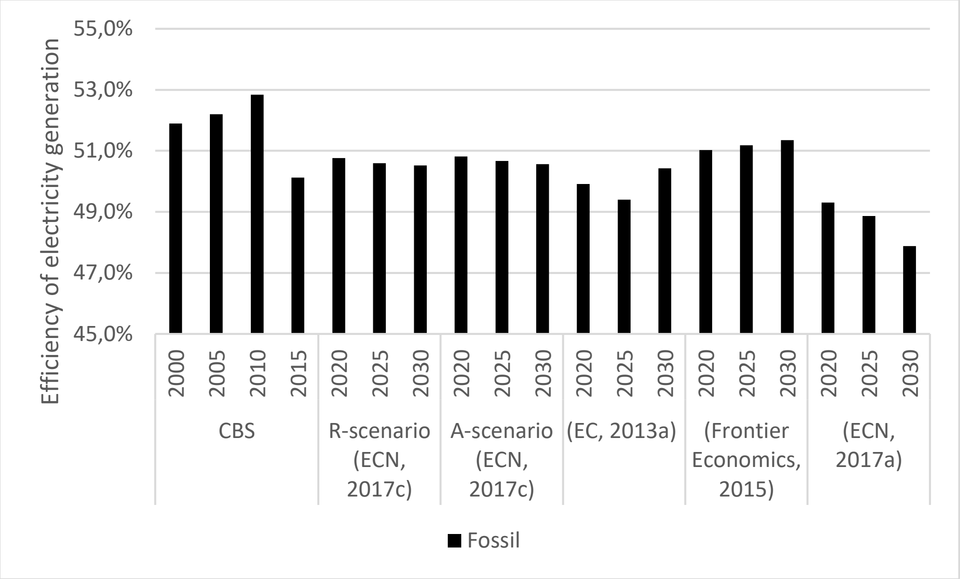


Figure 22: Past and future efficiency of electricity generation, fossil fuels only

8.2.2 Best practice

For the best practice scenario, only the total efficiency has been calculated, as renewables and gas fired capacity are able to supply all of the future electricity generation. Coal fired capacity is only required for the historic electricity generation. As visible, an efficiency improvement of 8-17 percent point in comparison to the future electricity generation scenarios could be achieved, by using the most efficient technologies first.

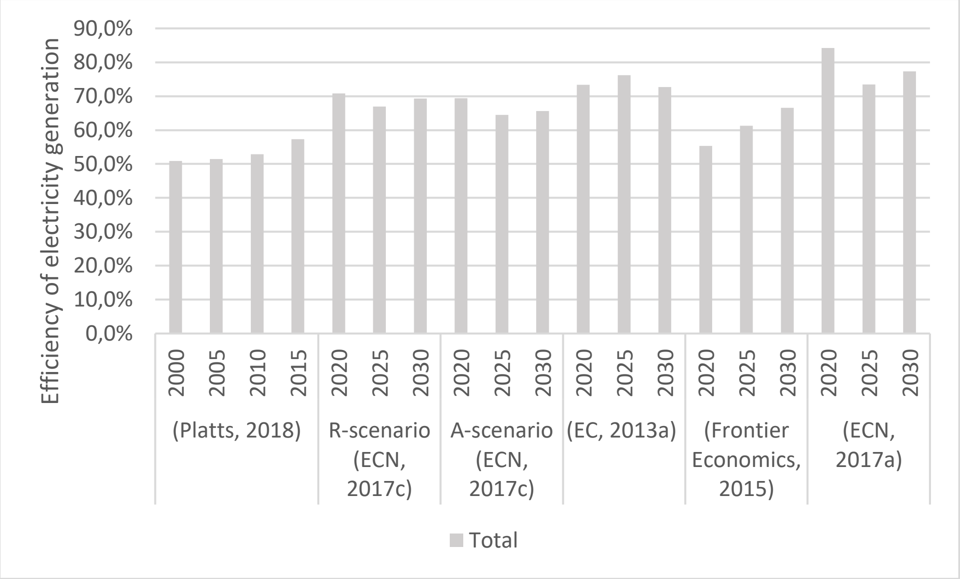


Figure 23: Past and future efficiency in a best practice scenario

8.2.3 Equal load factors

When only the total efficiency is considered, an increase is to be expected in all future scenarios. However, efficiency of fossil fired capacity shows a different trend. As Figure 24 does not provide insight in these changes due to a different scale, another figure was created displaying solely fossil generated electricity.

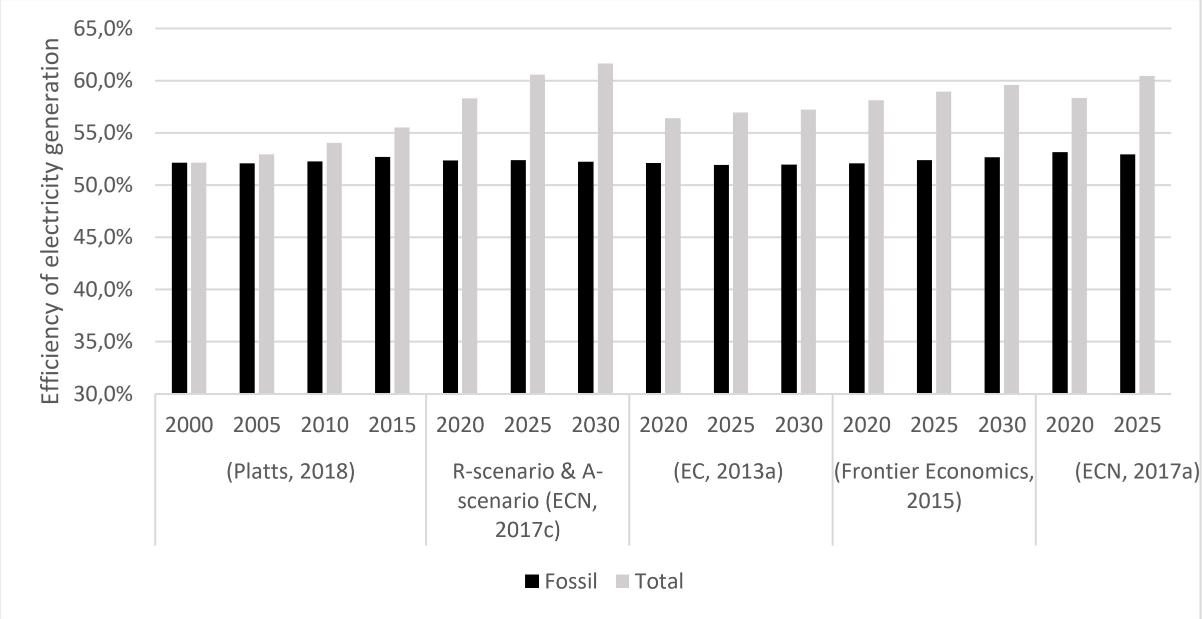


Figure 24: Past and future efficiency of electricity generation with equal loads for all capacity

When only the fossil fuel efficiency is considered (Figure 25), an overall increase can be observed between 2000 and 2015. This is followed by a decrease in efficiency in every scenario, except the scenario by Frontier economics. The relative decrease in expected gas fired capacity in comparison to coal and oil fired capacity could be the determining factor for the decrease in efficiency. As the gas fired capacity is more efficient than coal fired capacity.

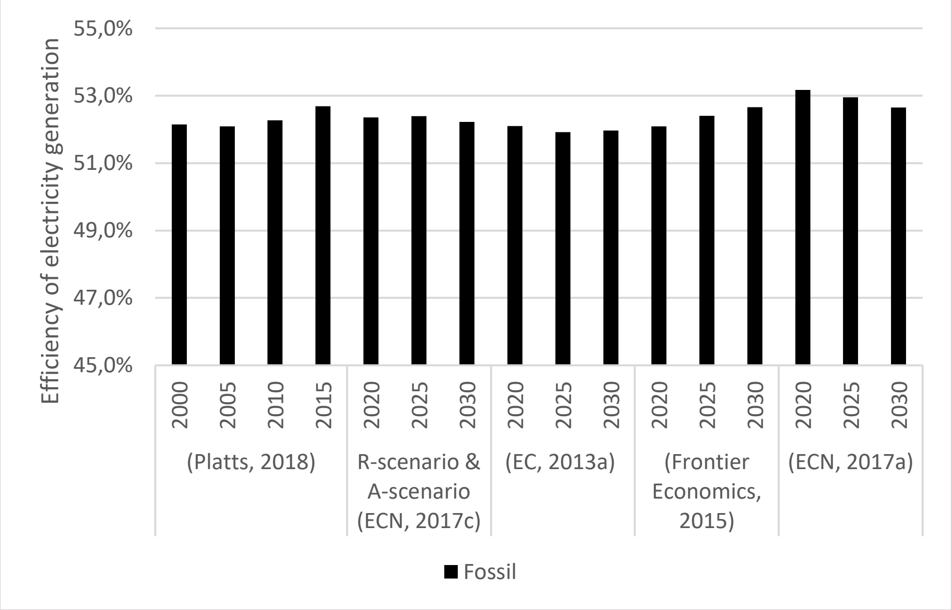


Figure 25: Past and future efficiency of electricity generation with equal loads for all capacity, fossil fuels only

8.3 Section conclusion

From the results it can be concluded that the overall future efficiency increases when looking at the future scenarios. However, when only fossil fuel efficiency is taken into account, the efficiency decreases in the majority of scenarios (3) and increases in two scenarios. The decrease in fossil fuel efficiency is a direct result of a change in the amount of gas fired electricity generation and the ration between gas and coal fired electricity generation. In 2018, the share of gas fired electricity generation in the fossil part of the mix was 65%. This changed to a range between 37 and 66%. As an effect of this change, the fossil mix efficiencies reached a range of 44.9-51.4 percent point. In comparison to the value of 2018, this is a change of -3.4 percent point (for 37% of gas fired electricity generation in the fossil mix) to +0.2 percent point (for 66% of gas fired electricity generation in the fossil mix). When reviewing the complete electricity mix, it becomes clear that this is dominated by the further increase of renewables in the mix, as the efficiencies for the total mix increases with a range of 3-9 percent point for future scenarios. In the best practice scenarios with the highest efficiency, efficiency increases with 8-17 percent point (in 2030) in comparison with future scenarios. Showing that the maximum efficiency gain is not reached by switching from coal fired electricity generation to gas fired electricity generation, but by switching from fossil sources to renewables, which arguably have an efficiency of 100%.

9. Future CO_2 intensity of electricity generation

9.1 Methodology

The sixth sub question aims to answer what the effects of a change in the share of natural gas in the Dutch power mix are on the CO_2 intensity of the power mix. Again, CHP might pose a problem for the calculation of the power mix, and should be accounted for. A similar method is used as in sub question five, with a correction for heat production, therefore using the electric efficiency as calculated pet fuel in sub question 5. The formula becomes as follows (Graus & Worrell, 2009; Hemmer & Klaassen, 2012):

$$CI = \sum \eta_i C_i Pa_i / \sum Pa_i \tag{9}$$

Where CI = CO_2 intensity [g CO_2/kWh]
η_i = the efficiency of generation with a fuel
C_i=CO_2 emission factor per fuel
Pa_i= adjusted power generation per fuel (corrected for heat production from CHP as in formula 8)

The emission factors used were found via 'Rijkdienst voor ondernemend Nederland' (RvO, 2018). Used values can be found in Table 12. The value for natural gas was used, as there was no approximation available for the use gas types other than natural gas. This assumption was deemed reasonable, as usage of other types of gas has been marginal in the historic electricity generation, and is not reported on in future scenario descriptions.

Table 11: Emission factors for several energy carriers (RvO, 2018)

Fuel	**Emission factor [kg CO2/GJ$_{\text{primary energy}}$]**	**Emission factor [tonne CO2/GWh$_{\text{primary energy}}$]**
Coke coal	94.0	338
Crude oil	73.3	264
Natural gas	56.5	203
Biomass	109.6	395

For this sub question, the equal load factor scenario was not reported on, as it was already used in the previous chapter, and reporting for the carbon intensity would lead to a repetition of results as found in Chapter 8.

9.2 Results

9.2.1 Future scenario emittance

When reviewing future scenarios, a decreasing trend can be observed for three out of five scenarios concerning total electricity mix, but an increasing trend for the majority of fossil mixes. Figure 26 provides insight in both trends for all scenarios. What springs to the eye is the fact that the total mix is more carbon intensive than the fossil fuel mix in three scenarios, these scenarios provide a high ratio of biomass to the total fuel mix (0.46 in scenario ECN, 2017a), or a combination of a high ratio of fossil fuels in the mix and a moderate ratio between biomass and the total mix; EC, 2013a (0.6 and 0.24) and Frontier economics (0.5 and 0.26). As visible in Figure 26 three out of five scenarios expect an increase in the carbon intensity in the near future for the fossil capacity.

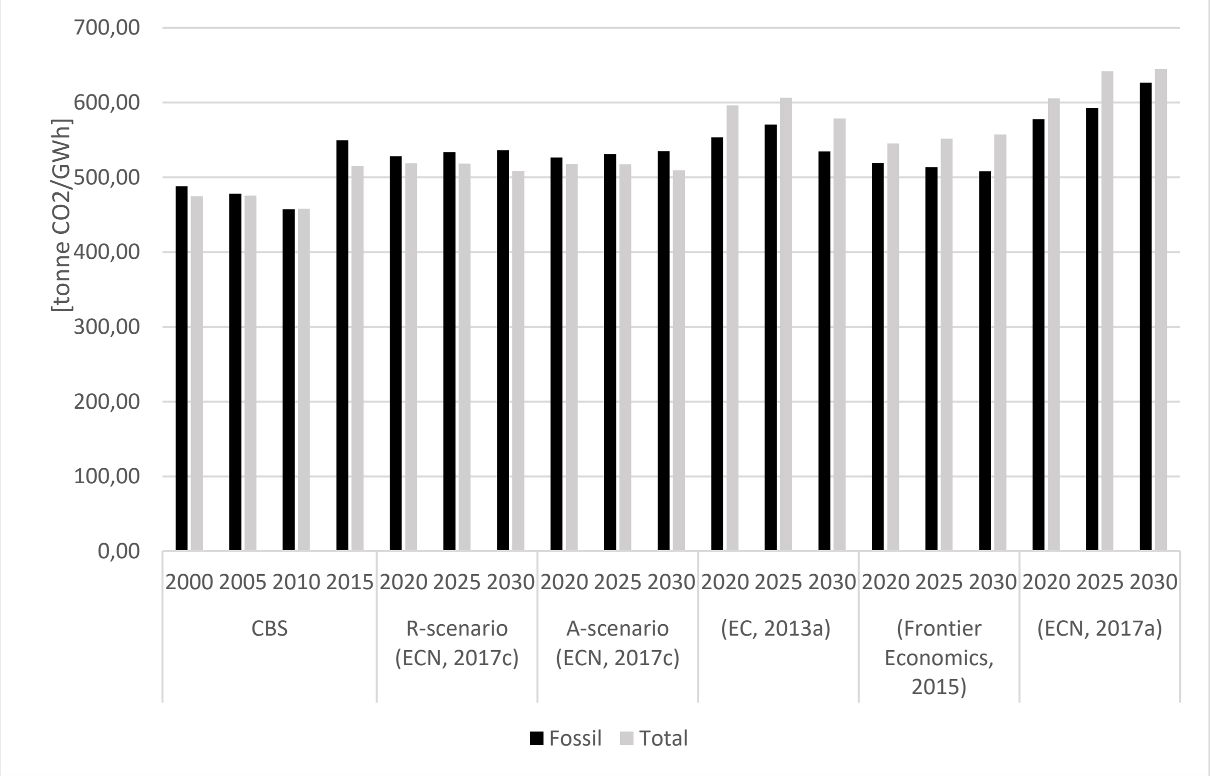


Figure 26: CO$_2$ intensity of past and future electricity generation

9.2.2 Best practice

Figure 27 shows the results for the carbon intensity, based on the best practice scenario as calculated for the efficiency. These values are in several cases worse than the values for the carbon intensity of the future electricity generation. Therefore Figure 28 was developed, showing the best practice aiming at the carbon intensity. These two figures directly provide an insight in the duality of proposed generation methods. As the most efficient is not per se the one with the lowest carbon intensity, and vice versa. For example, the efficiency of nuclear power generation is 37%, and therefore not included in the best practice scenario for efficiency, on the other hand, it has zero end-of-pipe emissions and therefore should be included in the best practice scenario for carbon intensity.

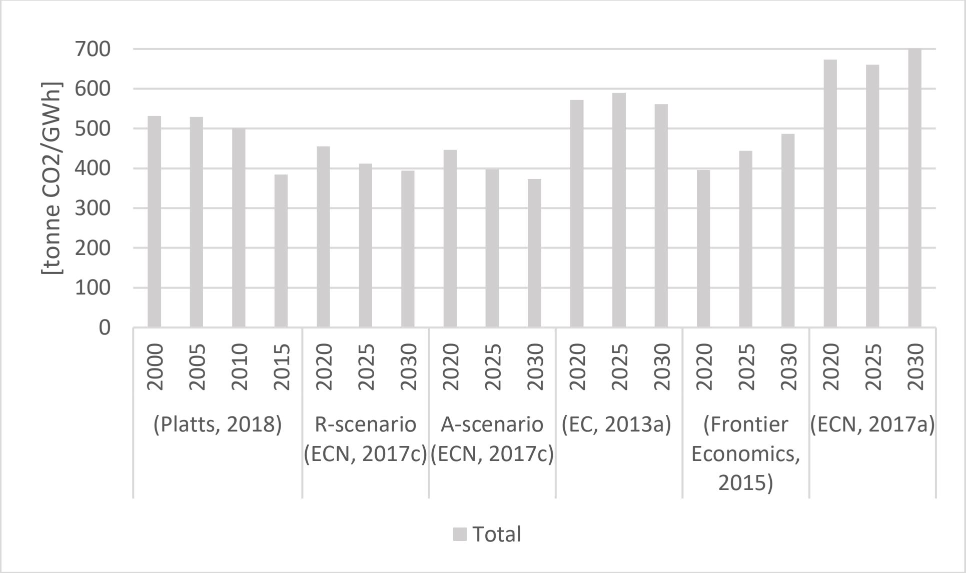
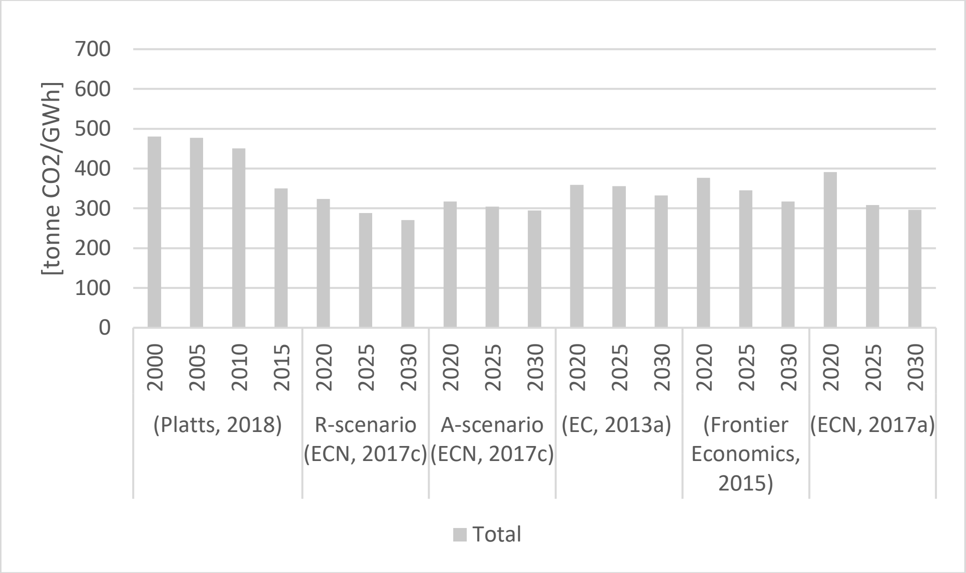


Figure 27: CO$_2$ intensity of past and future electricity generation, best practice for efficiency



9.3 Section conclusion

When focussing on the fossil part of electricity generation, two scenarios show an increase in CO_2 intensity. These are the same scenarios as the two which had an decreasing efficiency in sub question 5. These two results are caused by the shift in the fraction of generation by coal fired capacity or gas fired capacity. The ratio of gas fired generation to coal fired generation changes from 62:31 to a range of 37:63 to 66:34 in 2030 in future scenarios. The change in ratio induces changes in carbon intensity for the fossil fuel mix, where the carbon intensity in 2017 was 512 tonne CO_2/GWh it changes to a range of 657 tonne CO_2/GWh (low natural gas, high coal) to 561 tonne CO_2/GWh (high natural gas, low coal) in future scenarios. Future scenarios are thus always expected to have a higher carbon intensity for the fossil mix when comparing to the year of 2017, as the ratio between gas fired electricity generation and coal fired electricity generation increases in all future scenarios compared to 2017. Furthermore, it was found that the future ratio between fossil fired capacity decreased in the coming future is a good prospect, until a certain point, where biomass co-firing becomes too large. Some advocate that biomass has a carbon intensity of 0 g CO_2/kWh as it is part of the short carbon cycle, but this research incorporates emissions by biomass, leading to higher carbon intensities in scenarios where the value for biomass is high, as efficiency is not high; 37% in comparison to coal (43 and gas 56%), and the carbon intensity of the fuel is also the highest (107 kg/GJ).

10. Future flexibility of electricity generation

10.1 Methodology

10.1.1 Indicators

To address the flexibility of the electricity mix in the future, the current composition of gas and coal types of powerplants is projected onto the future scenarios to make an estimate on the future composition. For the major categories of powerplants (simple cycle, cogeneration, combined cycle) flexibility properties are researched on the basis of former research and presented in a table.

The next step is to assess the flexibility on the basis of the theory as described in Chapter 2. However, the metrics proposed by Denholm & Hand (2011) only cover the flexibility of a single power plant. Therefore the metrics were adjusted to fit with the larger size and different properties of a national grid. The researched flexibility factors are:

- Flexible provision capacity π [$MW_{flexible}/MW_{total}$] → Which part of the power provision could be considered as flexible capacity. Capacity is deemed to be flexible when it covers the properties as mentioned by Aalto & Korkmaz Temel (2014); controllable output and easily shut down. This research includes, nuclear, coal fired, gas fired (only combined cycle turbines), and oil fired capacity in the flexible provision capacity, as these meet the criteria as noted by Aalto & Korkmaz Temel (2014). The amount of flexibility per individual powerplant or type of fuel here is not considered, flexibility is only considered as a polar question.
- Power ramp (up) capacity ρ_{up} [MW/min] → The power ramp capacities will be calculated for every single installation on the basis of its fuel type and the type of its turbine. The total power ramp capacity will then be calculated as the maximum increase of MW per minute which the electricity grid could generate.
- Power ramp (down) capacity ρ_{down} [MW/min] → Will be calculated with a similar method as the power ramp up capacity.
- Reliable electricity provision capacity ε [$MWh_{reliable}/MWh_{total}$]. → The energy provision capacity will resemble to some extent to the flexible provision capacity, however it provides insight in to what extent the electricity generated was generated by reliable sources. In this category, the nuclear, coal fired, gas fired (all capacity), oil fired, and hydropower sources are considered.
- High flexible provision capacity Π [$MW_{high\ flexible}/MW_{flexible}$] → as the aforementioned parameters, except the power ramp capacity, are influenced strongly by the amount of renewables in the electricity mix, another parameter which provides more insight in the unique capacities of gas fired capacity in comparison to coal fired capacity. Capacity is deemed as highly flexible when the ramp rate is higher than 10%, and the output is controllable.

10.1.2 Indicator data

The used types of powerplants for the different flexibility parameters can be found in Table 13. Firstly, the ramp rate is merged into one category, as most researches work with one ramp rate, which is equal for both ramping up as ramping down (Brouwer, Van Den Broek, Seebregts, & Faaij, 2015; Gonzalez-Salazar, Kirsten, & Prchlik, 2018; Ulbig & Andersson, 2015). As visible, not all categories cover the same types of powerplants. Only high critical steam turbines are considered for coal-fired technology, as all installed capacity in the Netherlands is currently of this type (Platts, 2018). For gas-fired capacity, gas turbines and combined cycles are taken into consideration for the flexible capacity and the ramping capacity. The internal combustion turbines, are not taken into account as these are commonly part of a system in greenhouses, and therefore cannot be accounted on for ramping or flexibility. However, it is reliable capacity for the electricity generation and therefore is considered for the last parameter. A third gas based technology, steam turbines, were also present in the Netherlands, however, as no data on ramp rates was available for this technology, and total capacity was very small (<0.8 GW) this category was merged with the gas turbine category.

Table 12: Reviewed electricity generating technologies for flexibility

π	Coal – High critical steam turbine. Gas turbines. Combined cycle. Nuclear powerplant
ρ	Coal – High critical steam turbine. Gas turbines. Combined cycle. Nuclear powerplant
ε	Coal – High critical steam turbine. Gas turbines. Internal combustion engines. Combined cycle. Biomass. Nuclear powerplants
Π	Gas turbines

Used ramp rates in this research can be found in Table 14. As visible the High critical steam turbine, gas turbine, and CCGT ramp rate is presented as a range. This research uses the average value, based on the expected heterogeneity of the built capacity.

Table 13: Ramp rates for electricity generating technologies

Fuel	**Plant type**	**Ramp rate**
Coal	High critical steam turbine	1.5-3.0%/min (de Vries, 2009)
Gas	Gas turbine	10-20%/min (de Vries, 2009)
Gas	CCGT	3-5%/min (de Vries, 2009; Lund, Lindgren, Mikkola, & Salpakari, 2015)
Nuclear	-	5%/min (Brouwer et al., 2015)

10.1.3 Future flexibility changes

To create the results, all researched values were converted into percentages, in order to create values which could be presented in one figure per scenario. The research only looked at future scenario values, and not at equal load or best practice scenarios as in sub question 5 and 6, as these would not yield any relevant information for the research.

The values of π, ε and, Π are already percentual values, however, ρ had to be adjusted. This has been achieved by dividing the value of ρ [GW/minute] with the total amount of GW in the system. However, as this value was relatively small in comparison to π, ε, and Π, ρ was multiplied with a factor 10 to create insightful values. It should be noted that these values of ρ separately do not harness any value. For this research it is important to look at the percentual change of ρ over time, and between different scenarios.

10.2 Results

Figure 28 displays the historic and future scenario values for flexibility on the measured parameters. While small, it becomes visible that the historic trend shows an increase in flexibility on three of the measured parameters (π increase from 60 to 76%, ε 76-85%, ρ 61-65%. Π decreases from 30 to 28%). When future trends are reviewed, it becomes clear that flexibility will decline in all future scenarios, this is a result of the replacement of fossil fuels by renewables, and the addition of renewables to fulfil the increasing electricity demand. Lowest values are found in the ECN, 2017a scenario. Flexible capacity and reliable capacity decline to 6% and 28%, starting around 60% in 2018. Furthermore the decline is different in each scenario, whereas the decline in flexibility is small in the EC, 2013a scenario and large in the ECN, 2017a scenario. This again is in line with the increase in renewables in the electricity mix, and not dominated by a change in the fraction between coal fired and gas fired capacity. A table with the exact values is published in Appendix B.

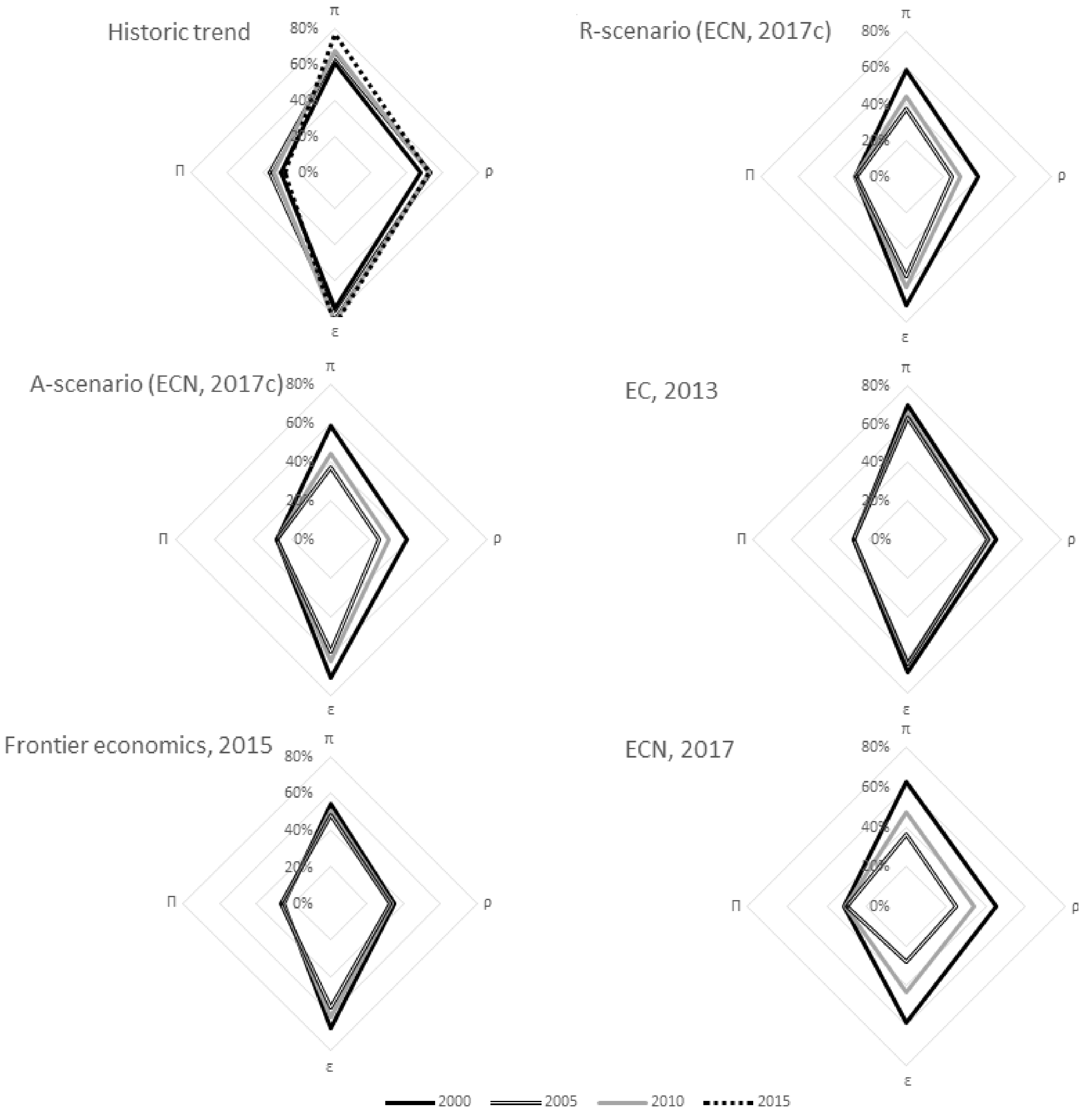


Figure 28: Flexibility: historic and future trends

10.3 Section conclusion

The flexibility of the future scenarios decreases in comparison to the current scenarios. The value of π decreases with 13-40 percent point, ρ 11-28 percent point, ε 20-57 percent point, and Π shows a small increase of 0-2 percent point. The first three categories can be explained by the decrease in relative amount of both capacity and generation by fossil fuels in comparison to renewable fuels, as described in Chapter 4**.** In three out of five scenarios, this effect is even further enhanced by a decrease in the fraction of gas fired electricity generation to coal fired electricity generation. The increase in the value of Π is explained by the relative capacity increase of gas fired turbines, which are the only power plants which are deemed highly flexible, in comparison to the total amount of fossil fuels. This is mainly due to the fact that ratios between types of installations within the gas fired capacity are kept constant for the future scenarios, therefore an increase in the ratio gas fired capacity to coal fired capacity will result into an increase of Π. The effects of these changes could not be interpreted for future scenarios, as no values could be found on minimum requirements for the research parameters for a national mix in order to stay well operating.

11. Combined effects of future electricity generation

The last sub question researches the combined effects of the change in future electricity generation, as calculated separately in sub question 5-7.

11.1 Methodology

11.1.1 Input data

For this sub question, the output data from sub questions 5 to 7 are used as input for a multicriteria analysis. Output data on efficiency, CO_2 intensity (both fossil as total), and from all scenarios are imported into a multicriteria analysis tool; ‘DEFINITE’. Aim of this multicriteria analysis is to create one overall score which represents the total stress future changes could pose for every scenario. As the aforementioned output data is influenced strongly by the presence of renewables in the electricity mix, two separate multicriteria analyses were performed. One on the complete fuel mix, and one focussing mainly on the fossil part of the electricity mix. The parameters for the fossil part are: fossil efficiency, fossil CO_2 intensity and high flexibility capacity. Standardization of input values will be provided in Appendix C to create full clarity on the decisions made for the multicriteria analysis.

11.1.2 Standardization of effects

Before measurement of impacts is possible, the impacts have to be standardized. This means that all impacts are transformed to a value between 0 and 1, where 1 is the best possible score, and 0 the worst. Figures for the chosen standardization methods can be found in Appendix C.

Where possible, the standardization method of ‘goal’ was used. This method divides the found values by a pre-set maximum value to provide a score between 0 and 1. The chosen maximum value was the value of the electricity mix in 2018. For this method, any decrease for one of these effects is seen as negative. This takes off from the precautionary principle, thereby stating that any lower value as the current value is deemed negative.

In the case the current value was not the maximum or minimum value, the goal standardization method could not be used. For these cases, standardization method ‘maximum’ was used. For this method, the effect scores are divided by the maximum value of an effect found in the provided data.

11.1.3 Weighting of effects

In order to assign weights to classify the importance of the input values, several ‘perspectives’ are created which pose a comprehensive set of weights. These perspectives should represent contrasting values which might arise in the direct future. The proposed perspectives and the weights can be found in Table 15.

Table 14: Proposed weighting for multicriteria analysis for complete scenarios

perspective effect	Equal importance	Low emission	High efficiency	Flexibility first
Total efficiency	25%	20%	50%	10%
Carbon intensity	25%	50%	20%	10%
π	13%	5%	5%	20%
ρ	25%	20%	20%	40%
ε	13%	5%	5%	20%

As values for reliable and flexible capacity overlap as they rely mainly on the fossil capacity, weights for these two values will be halved, in order to take away any effects of double counting.
For the second MCA, another set of perspectives was created, which should align with the other perspectives.

Table 15: Proposed weighting for multicriteria analysis focussed on fossil differences

perspective effect	Equal importance	Low emission	High efficiency	Flexibility first
Fossil efficiency	33%	17%	66%	17%
Fossil carbon intensity	33%	66%	17%	17%
Π	33%	17%	17%	66%

11.2 Results

The results of the multicriteria analysis for the different perspectives can be found in Figure 29. As visible, the EC scenario performs the best for all four perspectives. When low emissions and high efficiency are considered, margins to other scenarios are relatively small, when the equal importance perspective or the flexibility perspective are considered, margins are larger. When reviewing the built capacity of the EC scenario, it shows the highest ratio of fossil capacity to total capacity (0.63 followed by 0.44 by Frontier economics) and the second highest ratio of gas fired capacity to coal fired capacity (1.5, to 1.9 for Frontier economics). This has led to a high flexibility for this scenario, which gives it an advantage over the other scenarios. In the same time, the high natural gas to coal fired electricity generation tackles a part of the carbon intensity which is generated by the high amount of fossil fuels in the mix. The fraction of renewables to fossil fuels is the highest for the ECN, 2017 scenario. Thereby contributing to the highest score for efficiency. But as the amount of biomass in the mix is very high, it leads to adverse effects to the carbon intensity of the complete mix for the ECN 2017 scenario.

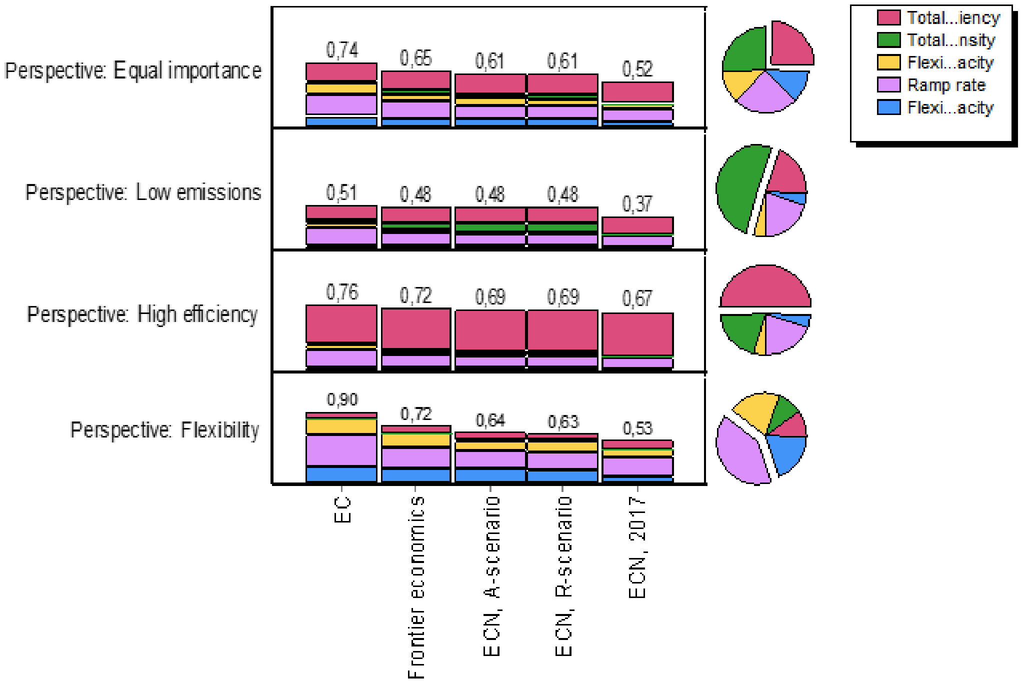


Figure 29: Ranking of multicriteria results for future electricity generation in the Netherlands for different perspectives

When reviewing the fossil parameters, it becomes clear that the ECN, 2017 scenario scores the worst of the researched scenarios. The ECN scenario scores only the best for the flexibility, but the differences between the scenarios for this parameter are much smaller than for the other parameters. Furthermore the ECN 2017 scenario scores considerably worse for the fossil carbon intensity. This is because the added renewable electricity generation replaces gas fired electricity generation, thereby increasing the ratio of electricity generated by coal in the fossil mix. As the high flexible capacity effect is based on capacity rather than actual output, the results differ from the other two categories. Here the ECN, 2017 scenario has a better score for flexibility while housing a lower production ratio of natural gas to coal fired production (0.6). The capacity ratio between highly flexible capacity and the total fossil capacity is the highest of all (0.3).

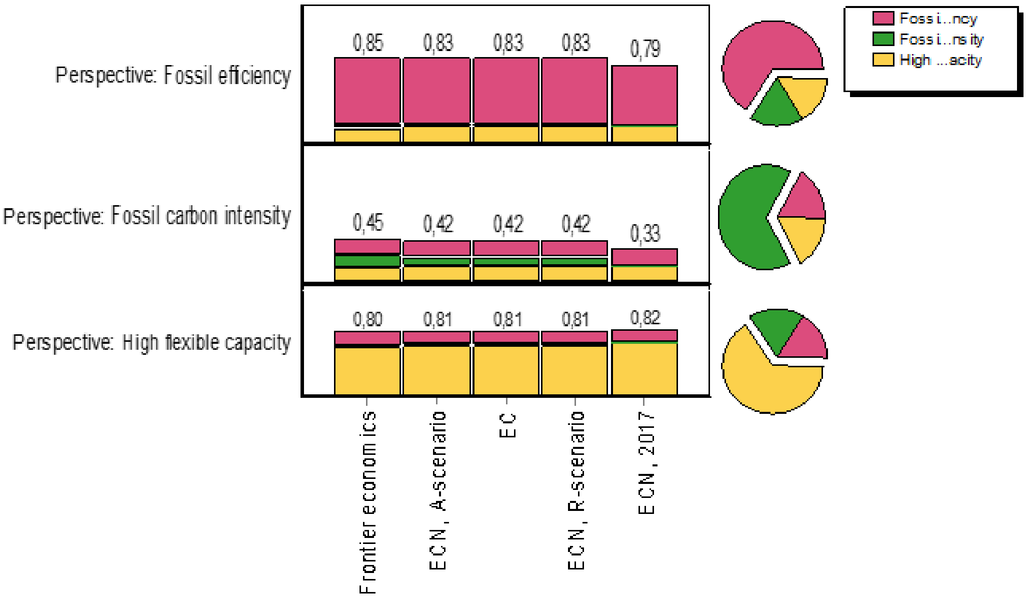


Figure 30: : Ranking of multicriteria results for future fossil electricity generation in the Netherlands for different perspectives

Another way to visualise the scores is represented in Figure 31. In this figure the points represent the rank of every scenario for every perspective, where rank 1 is the highest. Again it becomes clear that the earlier discussed EC scenario ranks first for all four perspectives. Furthermore it becomes visible that the ECN, 2017 scenario, performs the worst of all scenarios on the basis of the researched parameters.

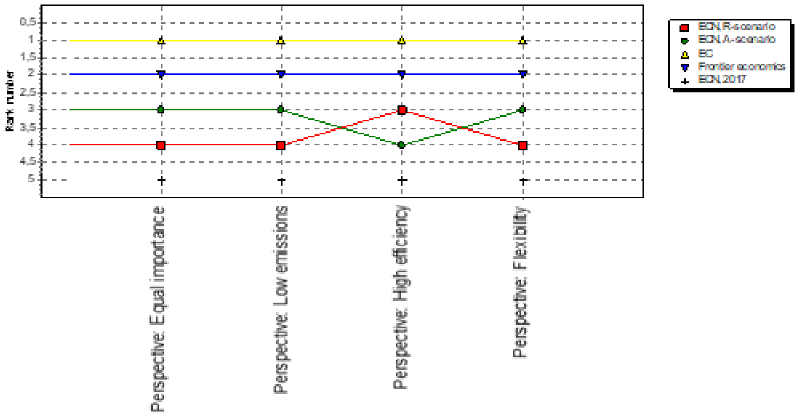


Figure 31: Ranking of multicriteria results for future electricity generation in the Netherlands for different perspectives

A similar figure was created for the fossil parameters. As visible, there are more interchanges of ranks between the different scenarios for the different perspectives. When reviewing Figure 32 it becomes clear that the differences between the scenarios for every perspective are relatively small, and thus will not be very robust.

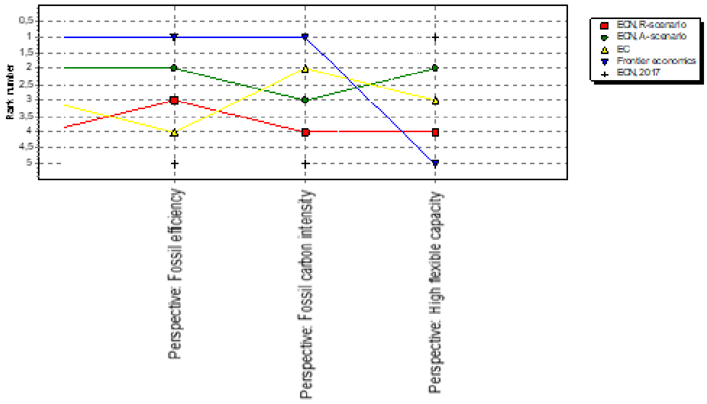


Figure 32: Ranking of multicriteria results for future fossil electricity generation in the Netherlands for different perspectives

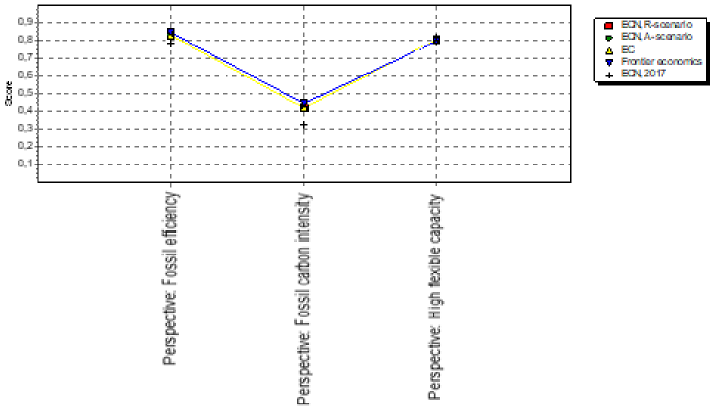


Figure 33: Scores of multicriteria results for future fossil electricity generation in the Netherlands for different perspectives

11.3 Section conclusion

This section used a multicriteria analysis to search for an answer to the sub question “What are the combined effects of the effects found in sub question 5-7?”. The ‘Definite’ tool was used to review the total effects in future scenarios with different perspectives on what is important. These different perspectives were used as optimization of one effect can lead to adverse effects for another parameter (See section 9.2.2). The research found that the EC scenario performs the best in the majority of times when the complete mix is reviewed, and for the majority of perspectives. It is found that the ratio of gas fired capacity to coal fired capacity, the ratio of fossil fired capacity to renewable capacity, and the share of biomass in the complete mix are important. Where the first should be as high as possible, and the latter should be lower. Not as low as possible as this in turn provides adverse effects on the flexibility of the scenarios. To create further insight in the effects on future of fossil electricity generation, another multicriteria analysis was performed. These resulted in the highest efficiencies for the scenarios which had the highest ratio between natural gas and coal fired capacity. However differences are marginal as the differences in efficiency reach only 3.6 percent point in future electricity scenarios When the fossil carbon intensity is reviewed, the same figure takes shape, with aggravated results, as the carbon intensity of natural gas is around 40 kg/GJ lower than for coal. As the high flexibility parameter is based on capacity and not on actual output, the results differ from the other two categories. Here a high ratio between gas turbines and other fossil capacity is important, which is the highest in the ECN, 2017 scenario with a score of 0.3.

12. Discussion of the research and uncertainties

This section will discuss the main uncertainties and the effects these could have on the research, followed by recommendations for future research.

12.1 Capacity and capacity developments uncertainties

The two main uncertainties for the current capacity are the mothballed capacity and the fuel input types into the powerplants. For the mothballed capacity, the research assumes that all mothballed capacity is noted, however it could be that more capacity will be mothballed in the near future, or reactivated again. Plans for mothballing and reactivation are crucial parts of information for companies, and therefore not shared beforehand. Current mothballed capacity is 9.8% of the total capacity (19% of the total gas fired capacity) in the Netherlands. Future reactivation or inclusion of this capacity in the research would lead to a lowering in load factors for the gas fired electricity generation sector. Furthermore the fuel input doesn't become completely certain from the Platts database, it states an alternative fuel sometimes, mainly biomass. This becomes bigger in time, according to interviews with RWE (Rigter, 2019). As electricity becomes more and more generated with biomass in old coal fired powerplants, this will lead to a blurring of the load factors for coal fired capacity and biomass fired capacity. An unfair lowering in load factor for coal fired capacity might be expected, and an unfair increase in load factor for capacity fired by biomass. However, this would not affect the results. Even if all electricity generated by biomass (4678 GWh in 2018) was generated in coal-fired powerplants, this would lead to a load factor decrease of 11%, which would still result in a higher load factor for coal than for natural gas-fired powerplants (a difference of 14 percent point). Inclusion of the mothballed capacity for the natural gas, would lead to a further lowering of the load factor by 10 percent point, to 39%.

12.2 Prices for cost calculations uncertainties

For the cost calculations, main uncertainties are the investment prices and the future fuel and CO_2 emission prices. For future scenarios, investment and O&M prices are not expected to drop dramatically as the technology for electricity generation by coal and natural gas is quite mature (IEA, 2016b). However, fuel prices for both coal and natural gas are expected to drop in comparison to the current price, thereby influencing the required CO_2 price for a change in merit order (World bank, 2019). For different variable O&M costs and a ratio of future expected prices, a range of 125.57-234.80 €/tonne CO_2 emitted can be expected, which is up to 20 times as much as the average emission cost over the past 5 years.

12.3 Scenario uncertainties

When assessing the scenarios, future renewable capacity and generation is presented as one category in the researched scenarios. However, for the research a distinction between different types of renewables is required, as electricity generation by biomass is defined to produce end-of-pipe CO_2 emissions. Therefore the research froze the current distribution of renewables, and projected this on future scenarios, as extrapolation of current trends would result in a complete domination of the renewable sector by wind and solar power, which is unexpected, as renewables are not completely reliable, and the required land use for wind parks and solar PV panels would be huge for these scenarios. However, future distribution of renewables might change in the favour of wind power and solar power over biomass, thereby influencing the future values for total carbon intensity and total efficiency for scenarios which are heavily dependent on renewables. If the research advocated that the carbon intensity of biomass as a fuel is 0 gCO_2/MJ, as the emitted carbon is a part of the short carbon cycle, scenarios relying heavily on renewables, and thus biomass would have heavily improved values for the carbon intensity; e.g. the future total carbon intensity of the ECN, 2017 scenario would drop drastically from 645 to 158 tonne CO_2/GWh generated.

12.4 Multicriteria uncertainties

Uncertainties as described before will affect the multicriteria analyses for the future, especially the uncertainties as described in Chapter 12.1 and 12.3, such as the exclusion of mothballed capacity and the chosen value for CO_2 emissions by biomass will have influence on the outcomes of the multicriteria analyses for the future. Therefore sensitivity analyses were performed on the outcomes of the multicriteria analyses to view how much the outcomes could be effected. The results of these analyses can be found in Appendix D. As visible, the results of the multicriteria analysis for the complete electricity sectors are relatively robust for all parameters, the different perspectives do not change place very much for different weights, and lines tend to be separated by a margin. However, the results for the fossil electricity generation only are less robust. The lines interchange a more, and there is less separation between the lines. Important points of uncertainty for this multicriteria analysis are the fossil efficiency and the future capacity. The first point could increase with 1 or 2 percent point before 2030 (IEA, 2016b). While the second point could be influenced strongly by the reactivation of mothballed gas fired capacity, which is also highly uncertain. These two points make that the multicriteria analysis on fossil powered electricity generation for the future should be perceived with the data used in mind. However, conclusions drawn concerning the principal differences between gas and coal fired capacity and their influence on the efficiency, flexibility, and carbon intensity of electricity generation are unaffected by these uncertainties.

12.5 Future research

This research added to the literature by reviewing the effects of a change from gas fired capacity to coal fired capacity and electricity generation. Where other research focusses on the overall electricity mix and addition of new technologies, this research tried to distillate the effects caused by the change within the fossil-fired capacity and generation. Further research could build on this research to review other parameters which mark the difference between coal- and gas-fired capacity, e.g. changes in lifetime of the built capacity due to cycling and the economic costs caused by shortening of lifetime for different future scenarios, or could produces models for the future with a focus on this fraction of the capacity (Kumar et al., 2012; Troy, Denny, & O’Malley, 2010). This would lead to an enhanced understanding of the possible need for gas-fired capacity in the future in order to keep a reliable electricity grid, which can meet future flexibility demand with the lowest carbon intensity as possible.

13. Conclusion

The research looked for an answer to the research question: What are the driving factors behind a change in the share of natural gas use in the fuel mix for electricity generation in the Netherlands, and what effects might be expected until 2030?

It was found that the driving forces behind the changes in the electricity mix are both policies, in the form of policies, as economics, mainly in the form of the short run marginal costs. Here, the policies are one of the drivers behind the decrease in fossil electricity generation, and the increase in renewables for electricity generation. The short run marginal costs are one of the main drivers for the ratio between gas and coal fired electricity generation. A mechanism to influence the short run marginal costs, and thus the ratio are the CO_2 emission prices. To create a situation where gas fired electricity generation has a lower SRMC, a price in the range of 125-142 €/tonne CO_2 is required (depending on flexible operation and maintenance costs). Taking into account possible further fuel price changes, this ratio expands to 126-235 €/tonne CO_2. It should be stated that it is highly unlikely that CO_2 emission prices will reach this value, as it is a 1005-1961 % increase to the current value. Therefore coal fired electricity generation will likely remain a more economic option than electricity generation fuelled by gas.

The composition of the future electricity generation mix in the Netherlands is influenced both by the increase in renewables as changes in the ratio between coal and gas fired capacity and generation. This will lead to an expected range of 47.9-51.4% of fossil based capacity in the future, compared to 53.4% at present. While the fossil to total ratio decreases, the ratio within the fossil capacity changes too, from a current value of 2.3 for the gas fired to coal fired capacity to a future range of 2.7-3.3. In the same period however, load factors for gas fired capacity drop more than for coal fired capacity, leading to future generation ratios between gas and coal fired electricity generation of 0.6 to 1.9, compared to the current value of 1.9. This change in ratio lead to a future fossil efficiency between 47.9-51.4%, compared to a the current value of 51.2%. This same ratio has effects on the expected future fossil carbon intensity, which is expected to range from 508-627 tonne CO_2/GWh compared to the current value of 512 tonne CO_2/GWh generated (and total future electricity mix values of 509-645 CO_2/GWh). Regarding the flexibility the following has been found: a decrease of 13-40 for the flexible provision capacity, a decrease of 11-28 percent point for the power ramp capacity, and a decrease of 20-57 percent point for the reliable electricity provision capacity. The only parameter which shows an increase is the value of the high flexible provision capacity, with an increase of 0-2 percent point. Values could not be interpreted as no minimum required value could be found for the researched parameters in order to have a well-functioning national electricity grid. Starting from the precautionary principle, it could however, be argued that the current electricity system works correct under current flexibility values, and any deterrence of these values could be viewed as adverse effects.

When the results of this research are taken into account, recommendations for future policies could be proposed. As found in the research, the ratio between gas-fired, and coal-fired capacity should be as high as possible. To push this, two main influencing mechanisms are available, a higher CO_2 price to improve gas fired capacity's position in the liberalized market, or laws to ensure the position of gas-fired capacity. The Dutch government has already started the procedure to ban coal as a fuel for electricity generation, but could take this further to other industries by increasing the CO_2 emission price. Furthermore the ratio between fossil-fired capacity and renewables should be kept an eye on. As the reliability of the future grid could be jeopardized by this increase. However, addition of future technologies in the form of electricity storage could overcome this problem and lower the need for future reliable capacity.

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Appendix A: Correlation, correlation tests and histograms

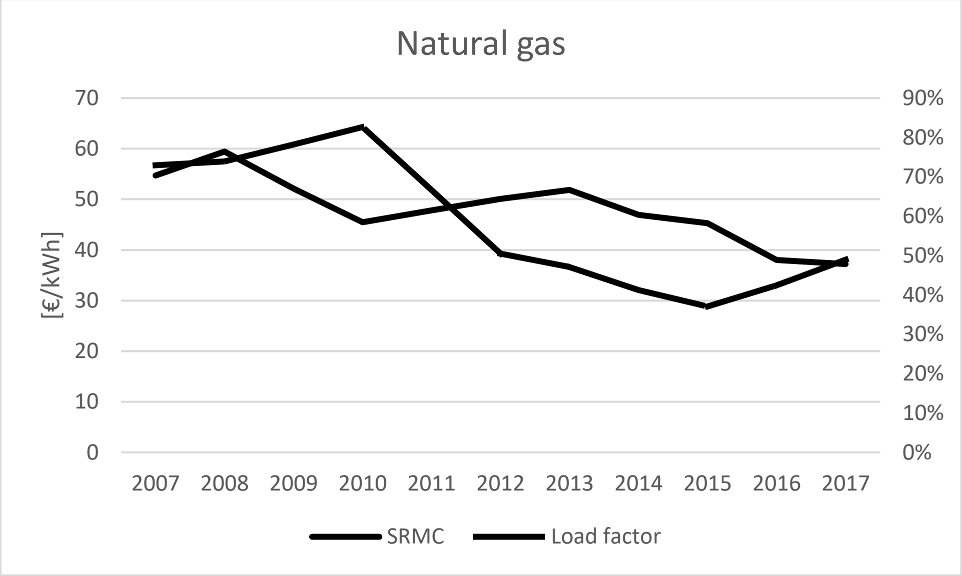


Figure 34: SRMC and load factor for natural gas in the Netherlands

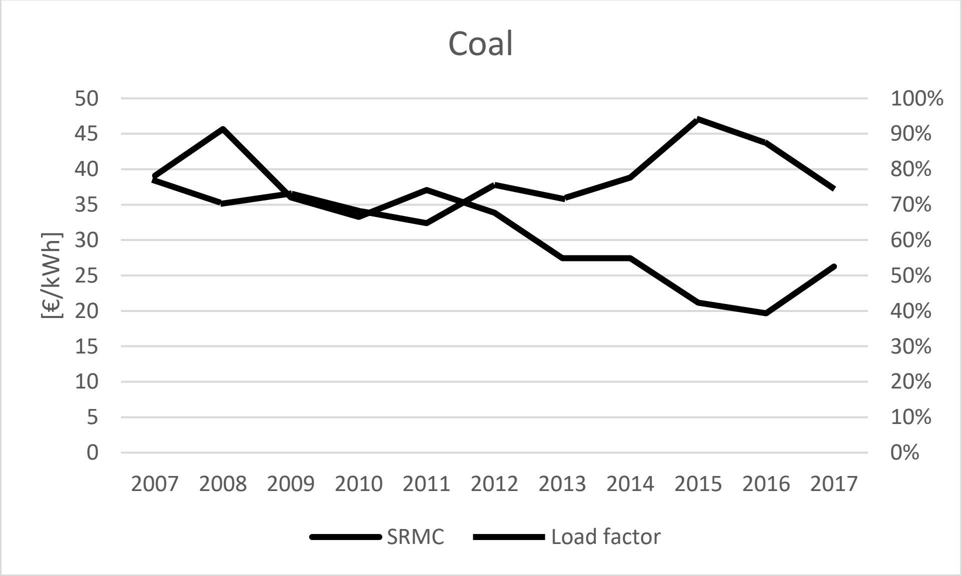


Figure 35: SRMC and load factor for coal in the Netherlands

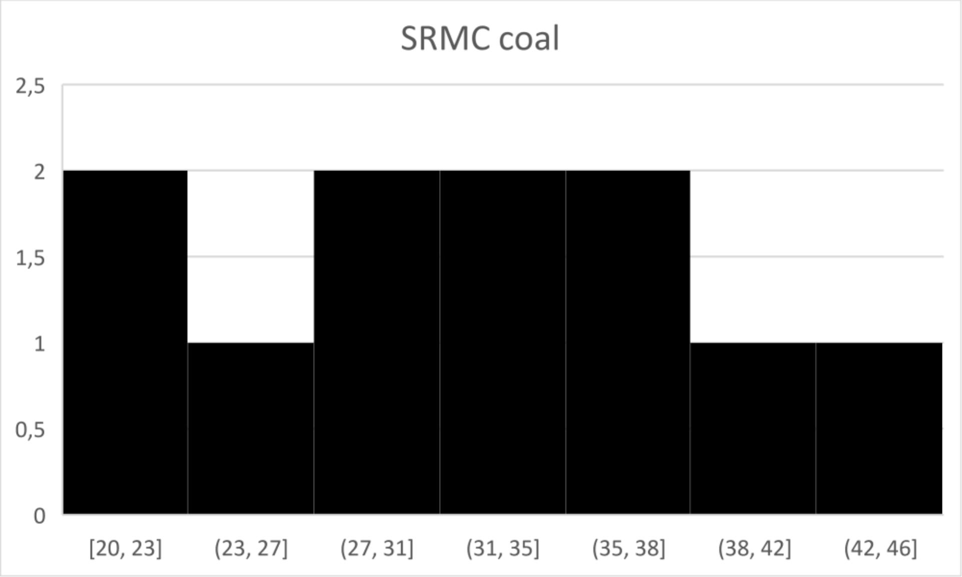


Figure 36: Histogram of SRMC for coal fired capacity in the Netherlands

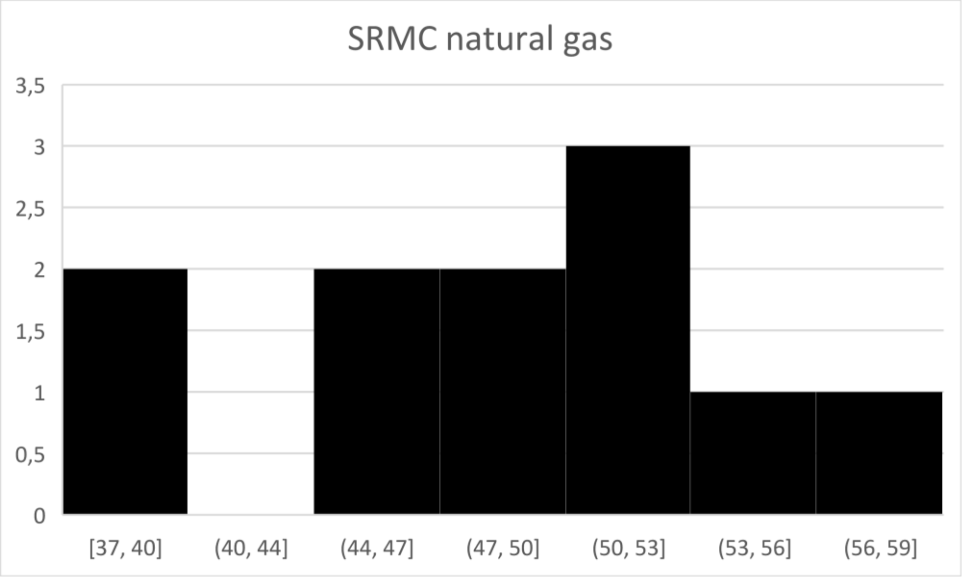


Figure 37: Histogram of SRMC for natural gas fired capacity in the Netherlands

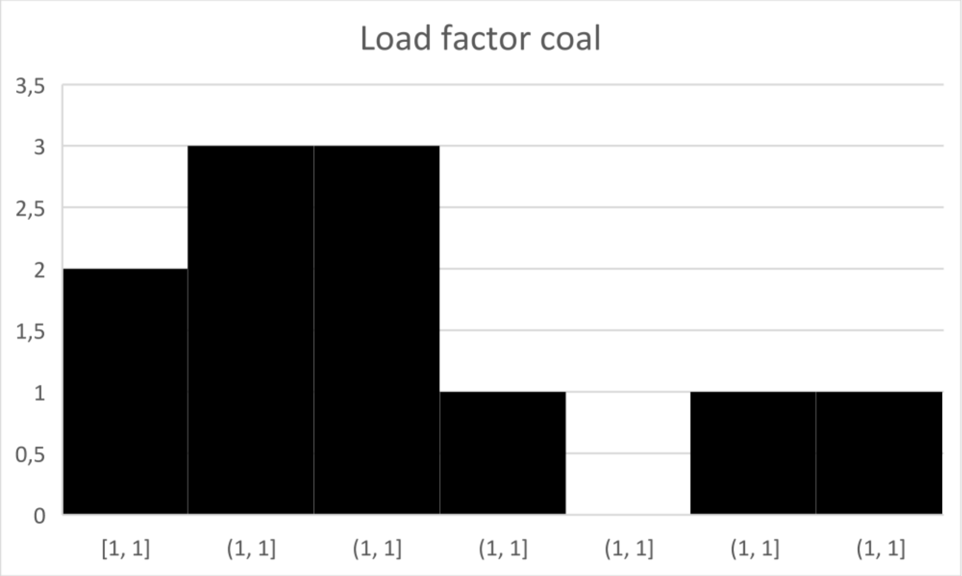


Figure 38: Histogram of load factors for coal fired capacity in the Netherlands

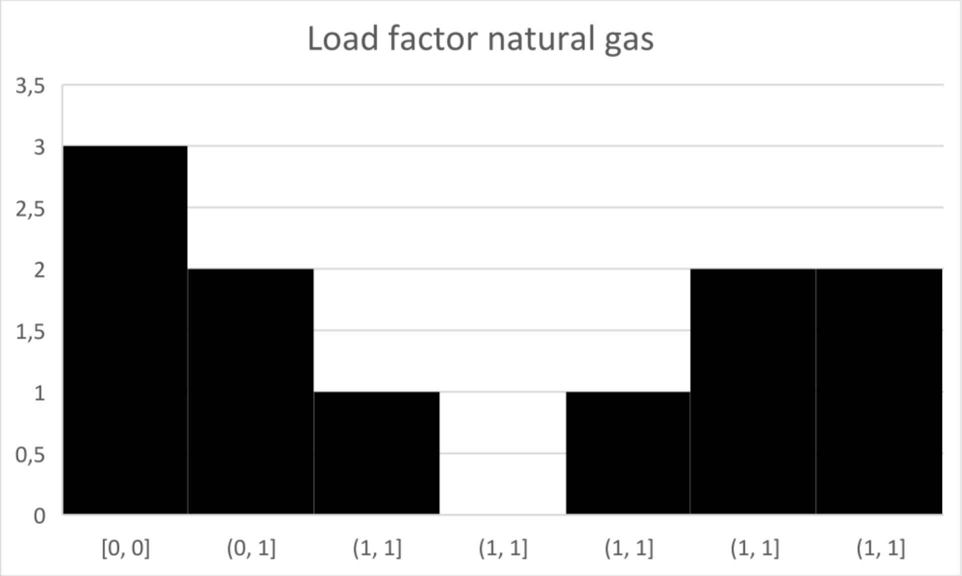
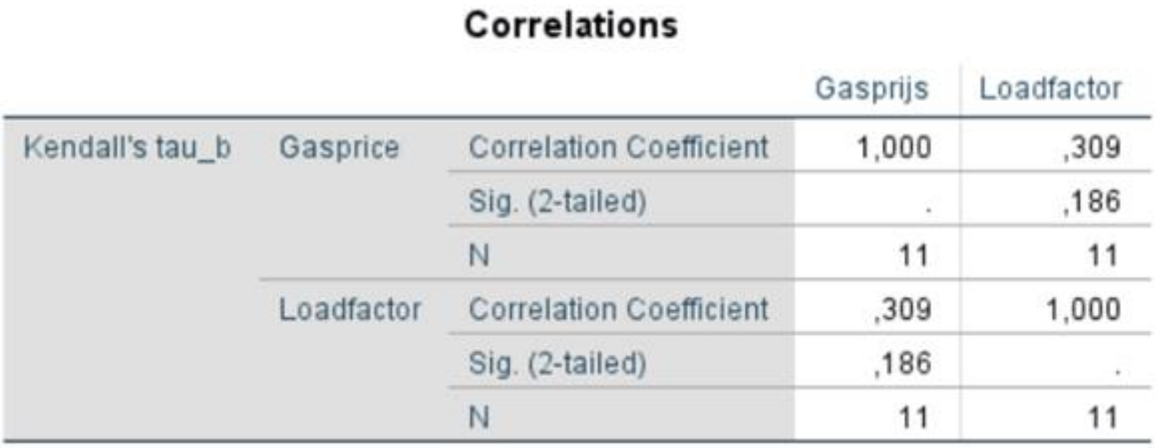


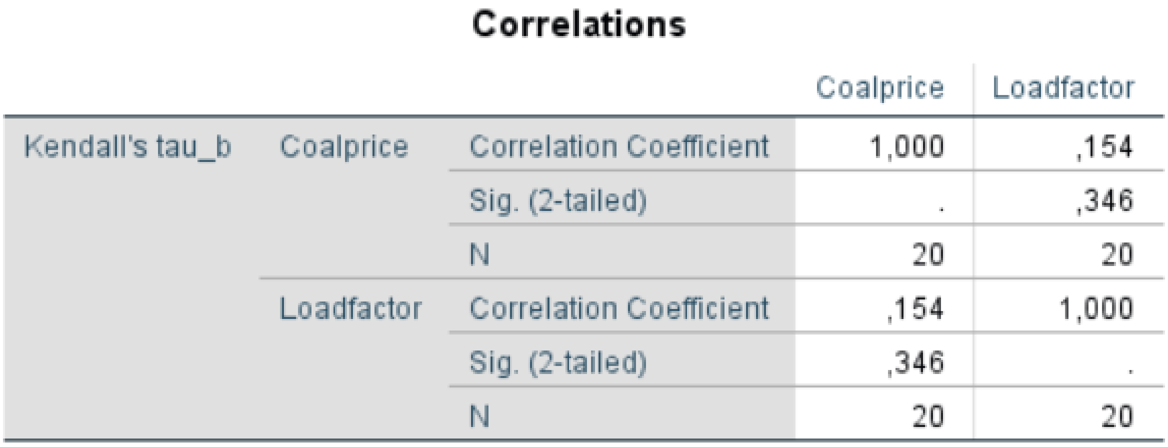
Figure 39: Histogram of load factors for natural gas fired capacity in the Netherlands



Correlations

			Gasprijs	Loadfactor
Kendall's tau_b	Gasprice	Correlation Coefficient	1,000	,309
		Sig. (2-tailed)	.	,186
		N	11	11
	Loadfactor	Correlation Coefficient	,309	1,000
		Sig. (2-tailed)	,186	.
		N	11	11

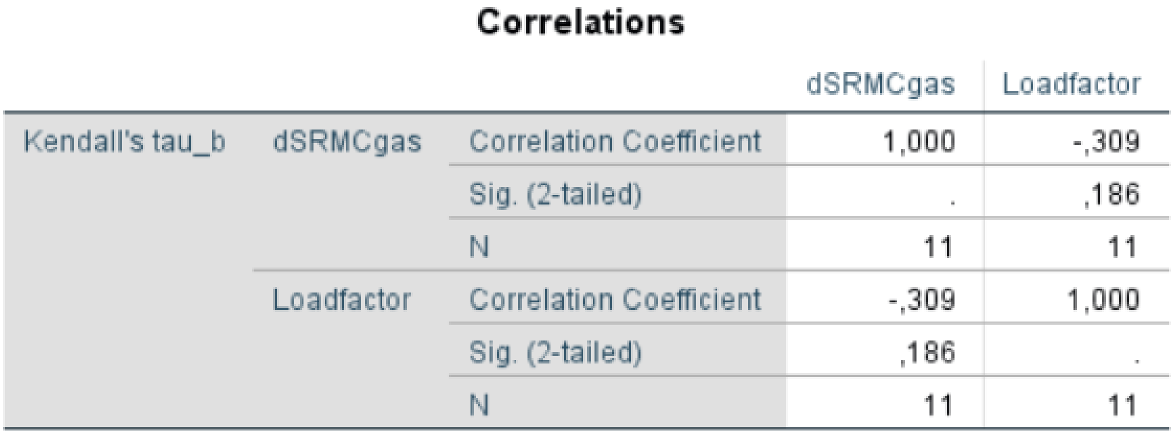
Figure 40: Kendall's tau for gas price and load factor of gas fired capacity



Correlations

			Coalprice	Loadfactor
Kendall's tau_b	Coalprice	Correlation Coefficient	1,000	,154
		Sig. (2-tailed)	.	,346
		N	20	20
	Loadfactor	Correlation Coefficient	,154	1,000
		Sig. (2-tailed)	,346	.
		N	20	20

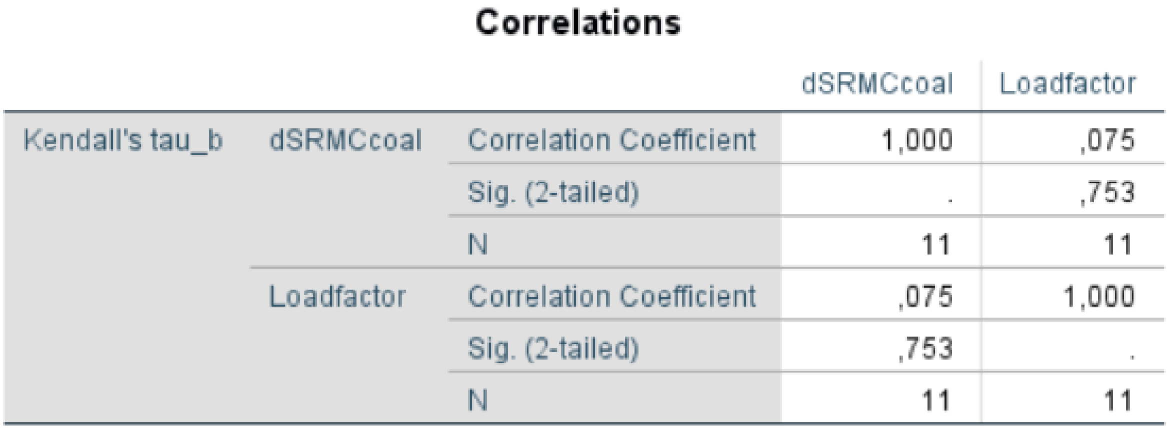
Figure 41: Kendall's tau for coal price and load factor of coal fired capacity



Correlations

			dSRMCgas	Loadfactor
Kendall's tau_b	dSRMCgas	Correlation Coefficient	1,000	-,309
		Sig. (2-tailed)	.	,186
		N	11	11
	Loadfactor	Correlation Coefficient	-,309	1,000
		Sig. (2-tailed)	,186	.
		N	11	11

Figure 42: Kendall's tau for a difference in SRMC and load factor of natural gas fired capacity



Correlations

			dSRMCcoal	Loadfactor
Kendall's tau_b	dSRMCcoal	Correlation Coefficient	1,000	,075
		Sig. (2-tailed)	.	,753
		N	11	11
	Loadfactor	Correlation Coefficient	,075	1,000
		Sig. (2-tailed)	,753	.
		N	11	11

Figure 43: Kendall's tau for a difference in SRMC and load factor of coal fired capacity

Appendix B: Future flexibility values

Table 16: Exact values of future flexibility changes

Year	**2020**	**2025**	**2030**
R-scenario (ECN, 2017c)			
π	58%	44%	37%
ρ	39%	30%	25%
ε	71%	61%	55%
Π	28%	28%	28%
A-scenario (ECN, 2017c)			
π	58%	44%	37%
ρ	39%	30%	25%
ε	71%	63%	57%
Π	28%	28%	28%
EC, 2013			
π	69%	65%	63%
ρ	46%	43%	42%
ε	69%	64%	64%
Π	28%	28%	28%
Frontier Economics, 2015			
π	54%	51%	48%
ρ	35%	34%	32%
ε	68%	62%	57%
Π	25%	26%	27%
ECN, 2017			
π	63%	48%	36%
ρ	45%	34%	25%
ε	59%	44%	28%
Π	31%	31%	30%

Appendix C: Standardization and uncertainty of MCA

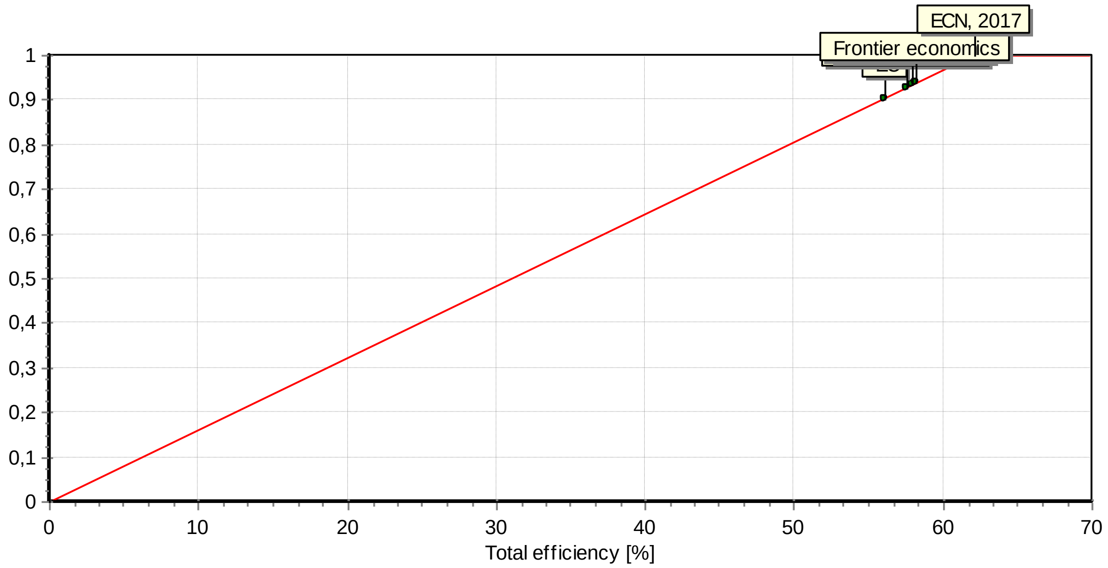


Figure 44: Standardization method of total efficiency

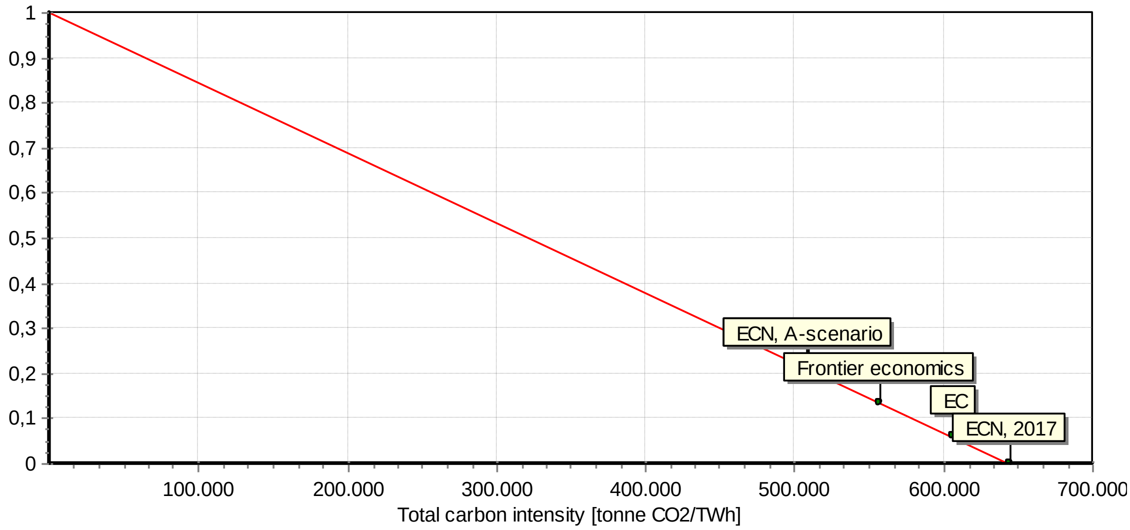


Figure 45: Standardization method of carbon intensity

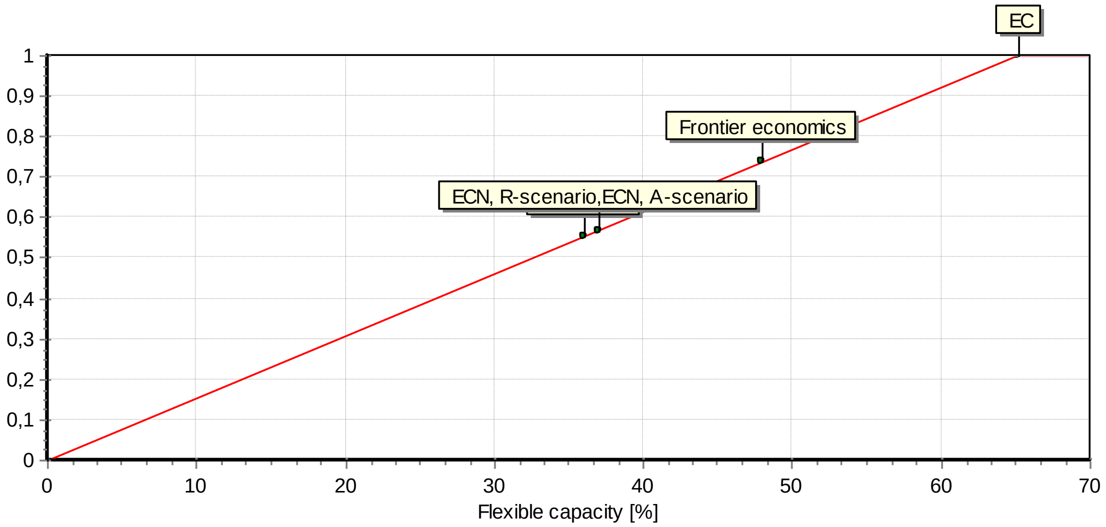


Figure 46: Standardization method of flexible capacity

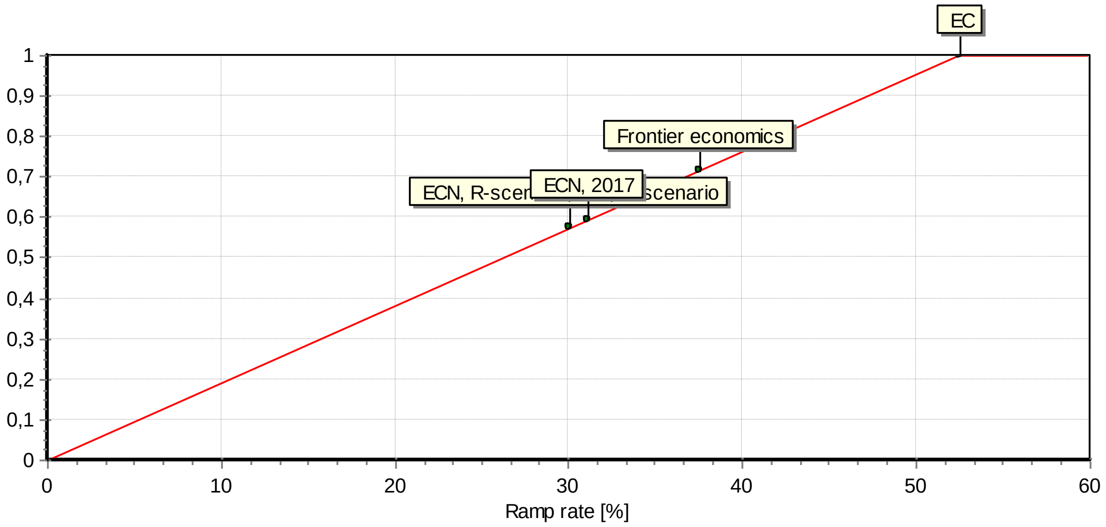


Figure 47: Standardization method of ramp rate

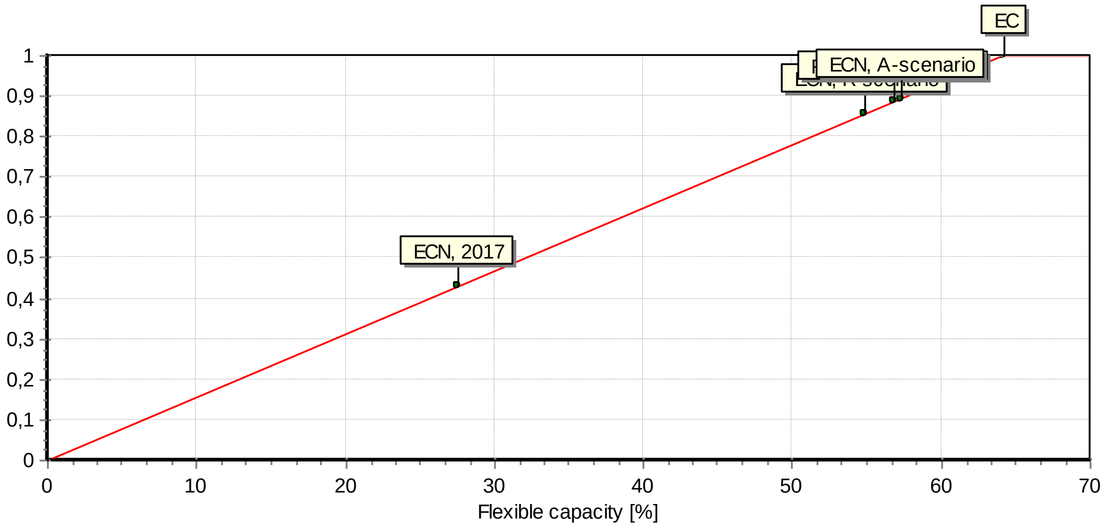


Figure 48: Standardization method of reliable capacity

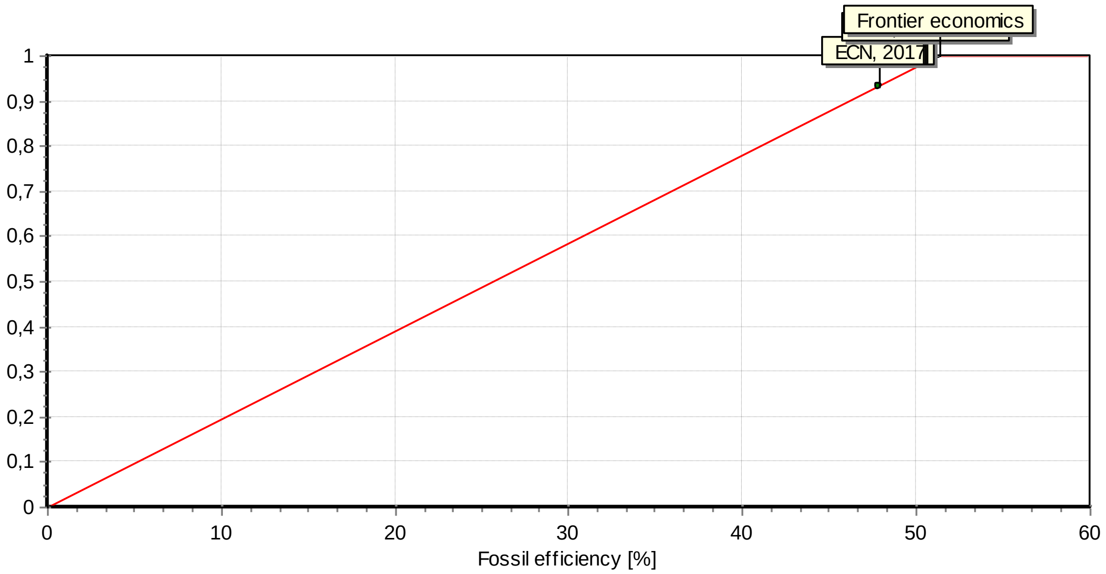


Figure 49:: Standardization method of fossil efficiency

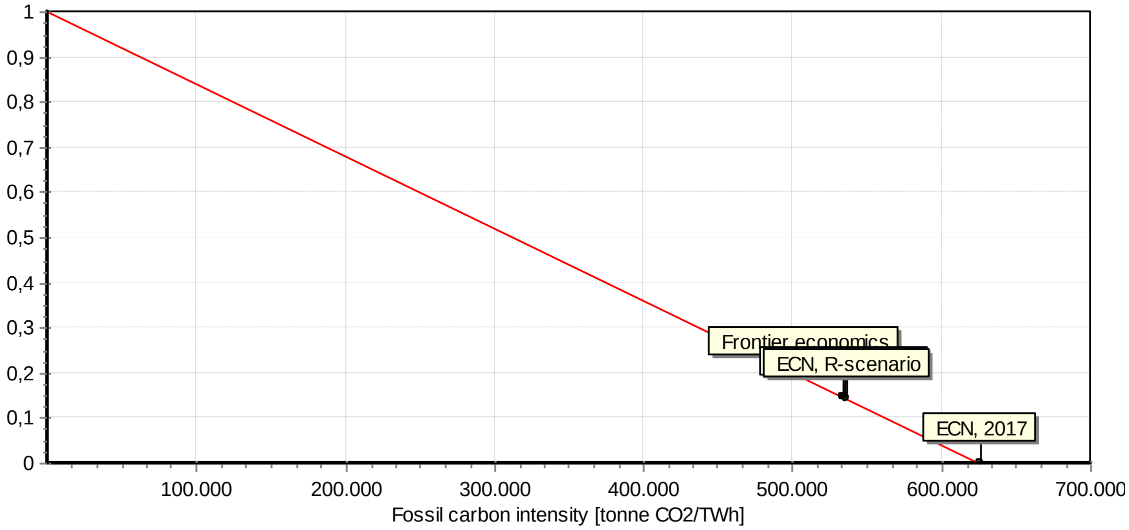


Figure 50: Standardization method of fossil carbon intensity

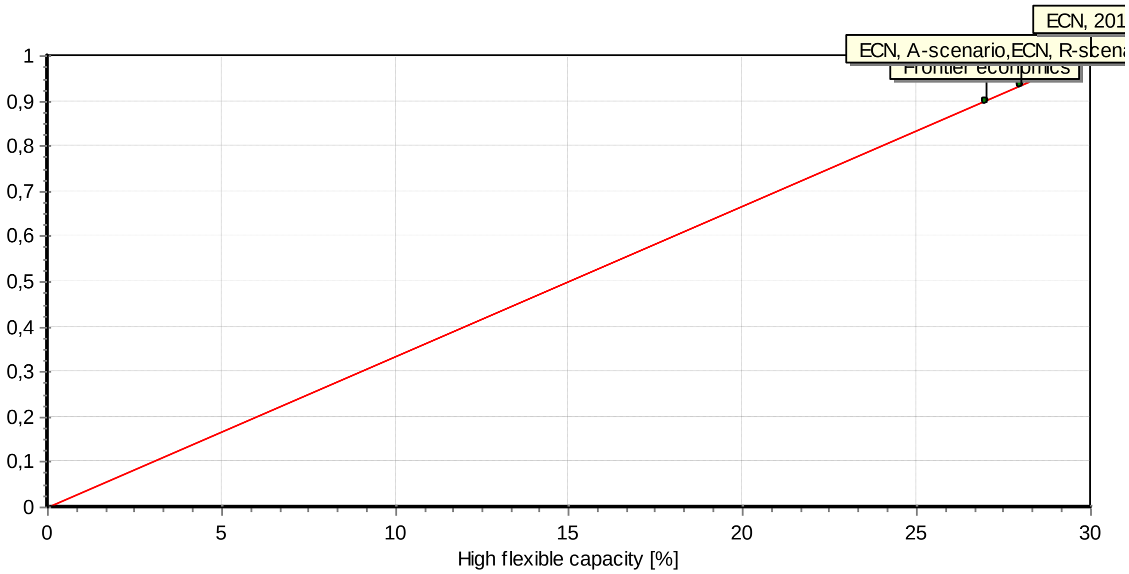


Figure 51: Standardization method of high flexible capacity

Appendix D: Sensitivity of MCA

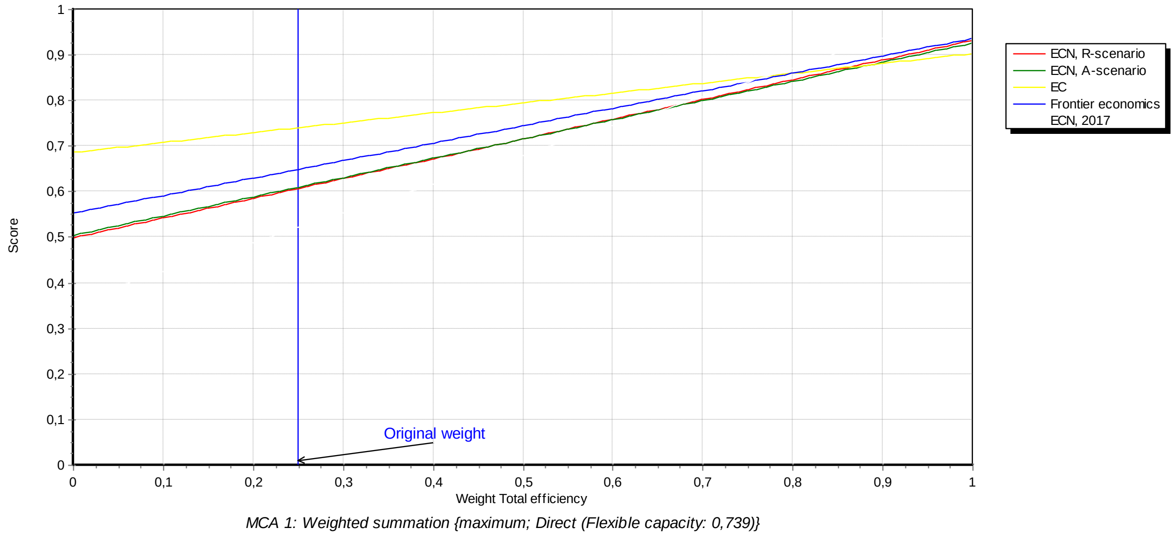


Figure 52: Sensitivity of multicriteria analysis results for efficiency

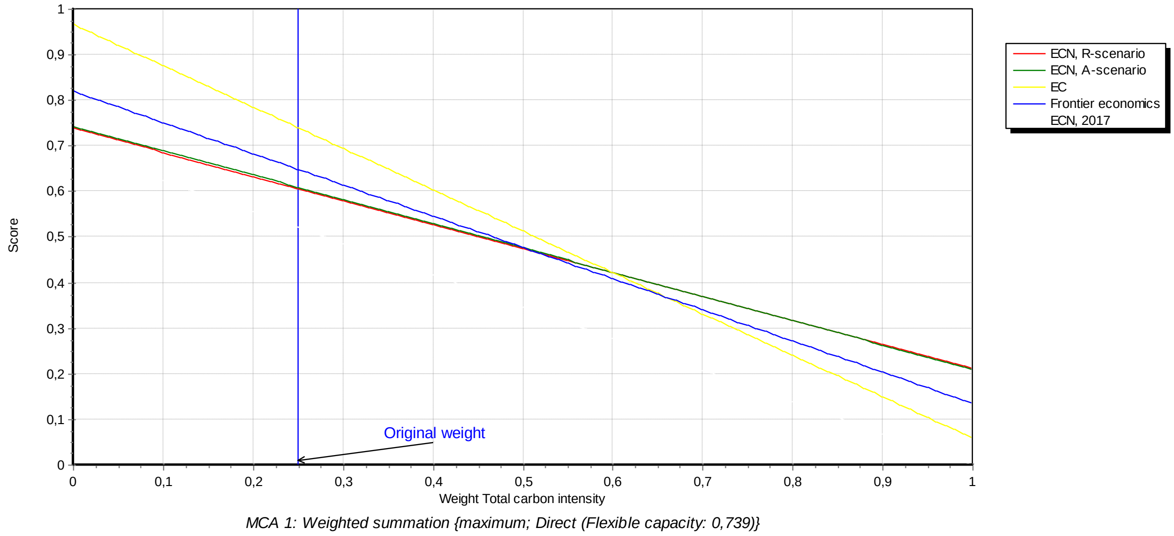


Figure 53: Sensitivity of multicriteria analysis results for carbon intensity

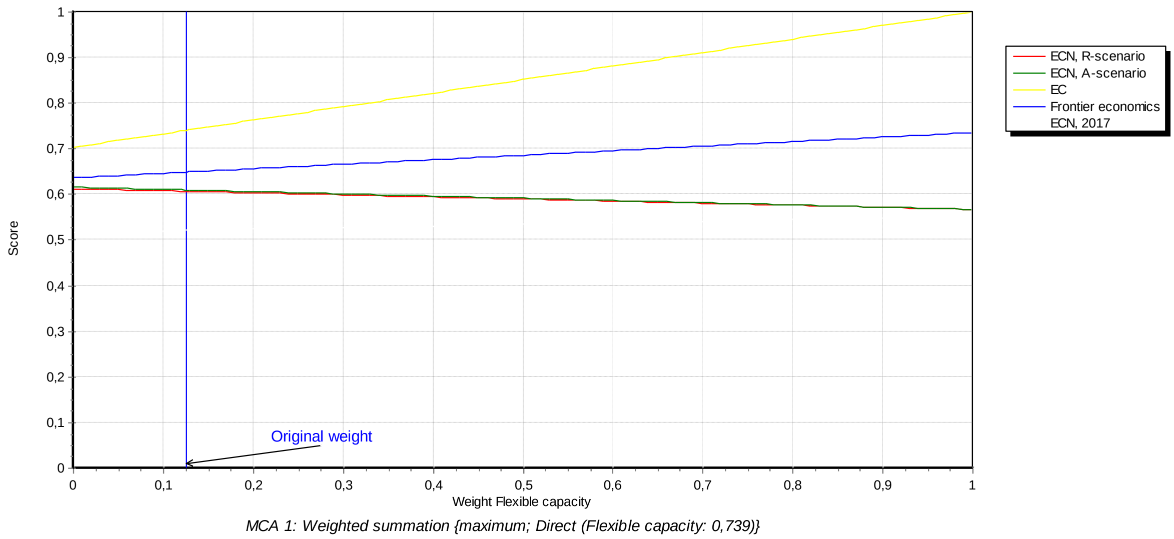


Figure 54: Sensitivity of multicriteria analysis results for flexible capacity

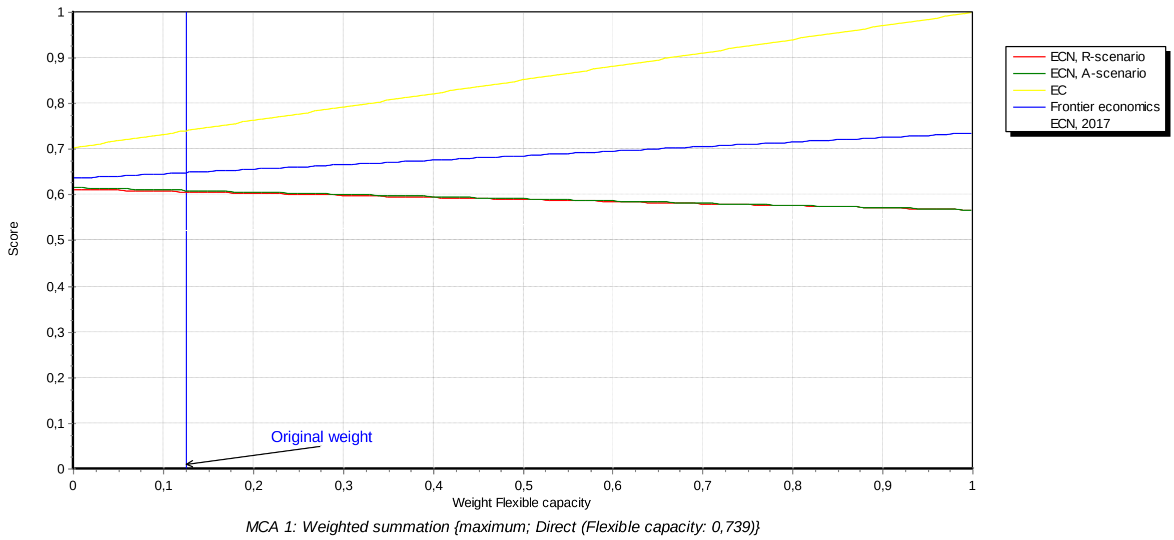


Figure 55: Sensitivity of multicriteria analysis results for ramp rate

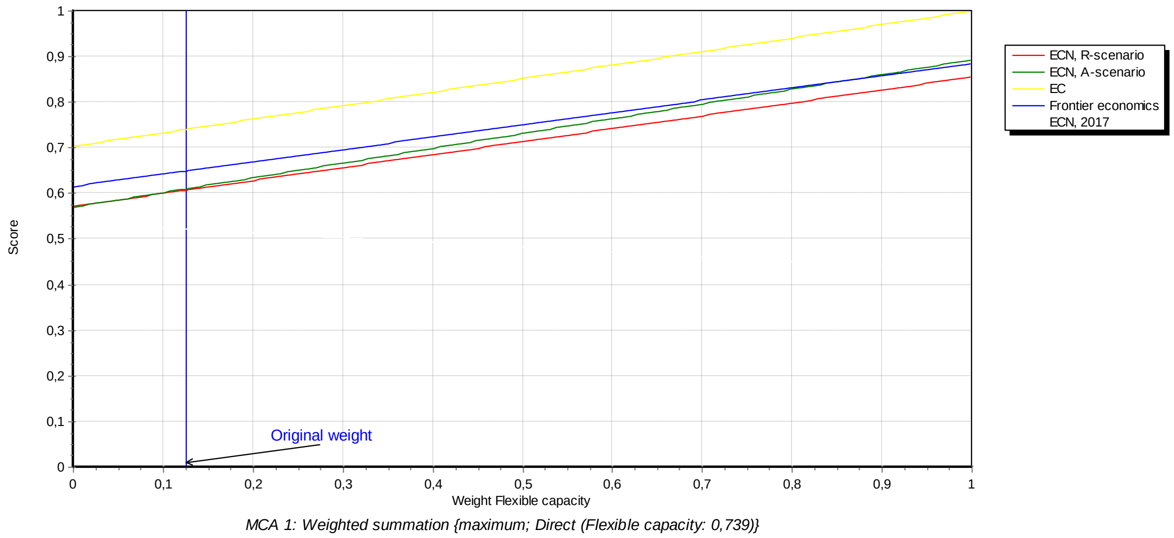


Figure 56: Sensitivity of multicriteria analysis results for reliable capacity

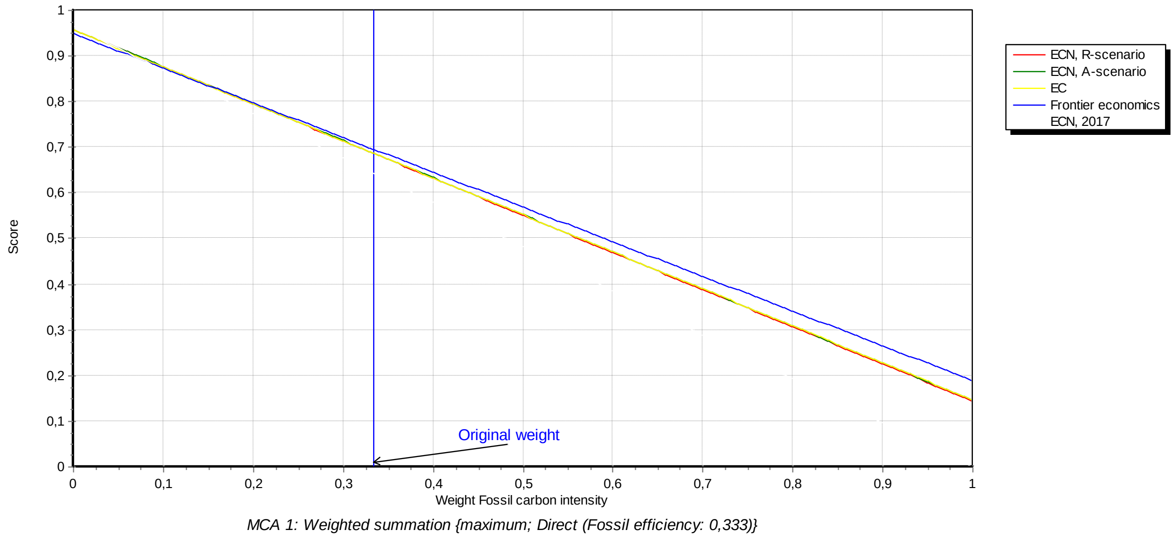


Figure 57: Sensitivity of multicriteria analysis results for fossil fuel electricity generation; fossil carbon intensity

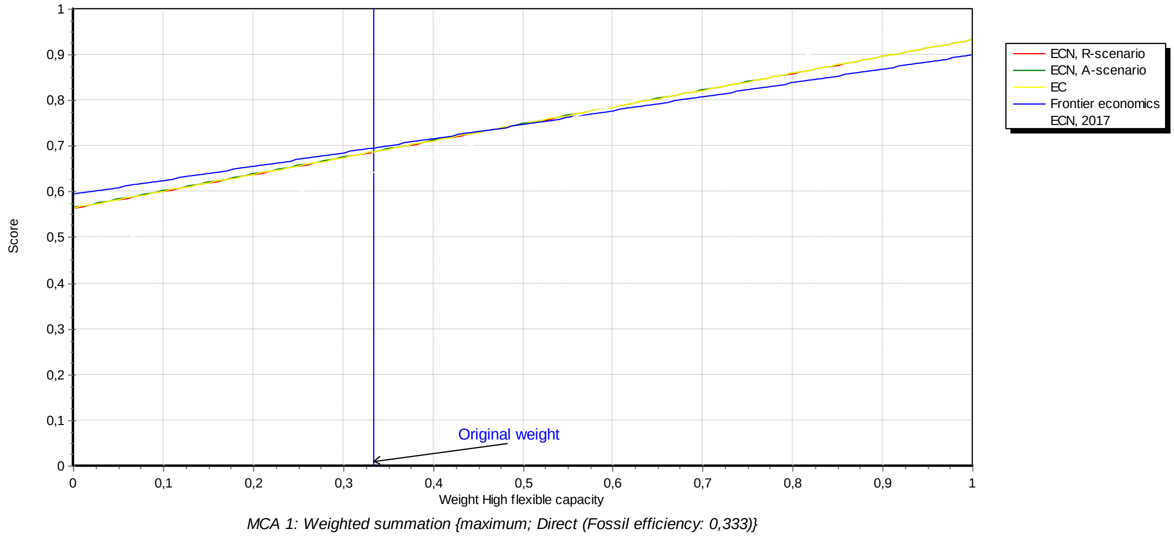
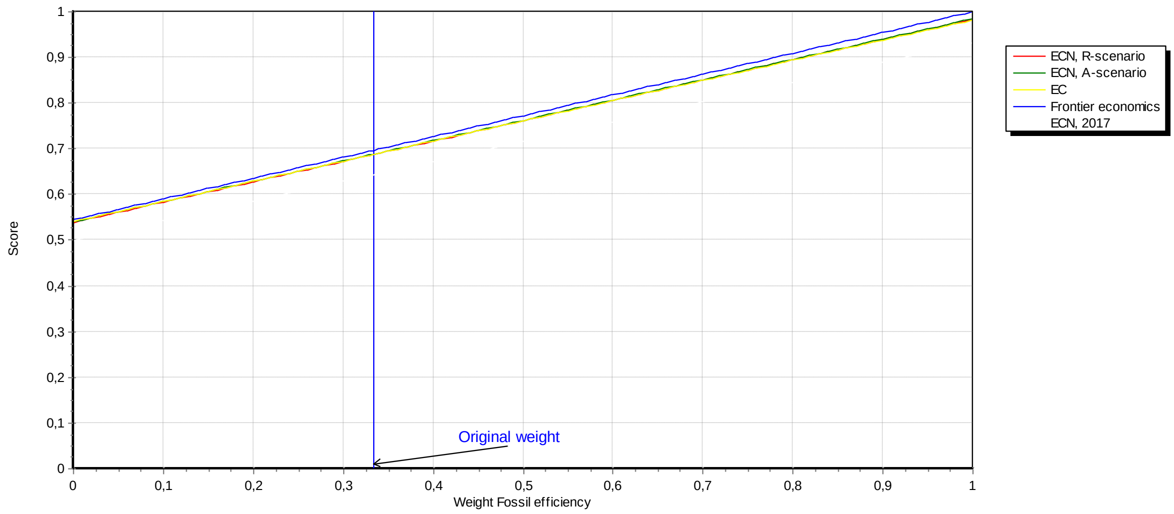


Figure 58: Sensitivity of multicriteria analysis results for fossil fuel electricity generation; high flexible capacity



MCA 1: Weighted summation {maximum; Direct (Fossil efficiency: 0,333)}

Figure 59: Sensitivity of multicriteria analysis results for fossil fuel electricity generation; fossil efficiency

Furthermore probability figures were created with a 5 percent point variation in both weights and scores.

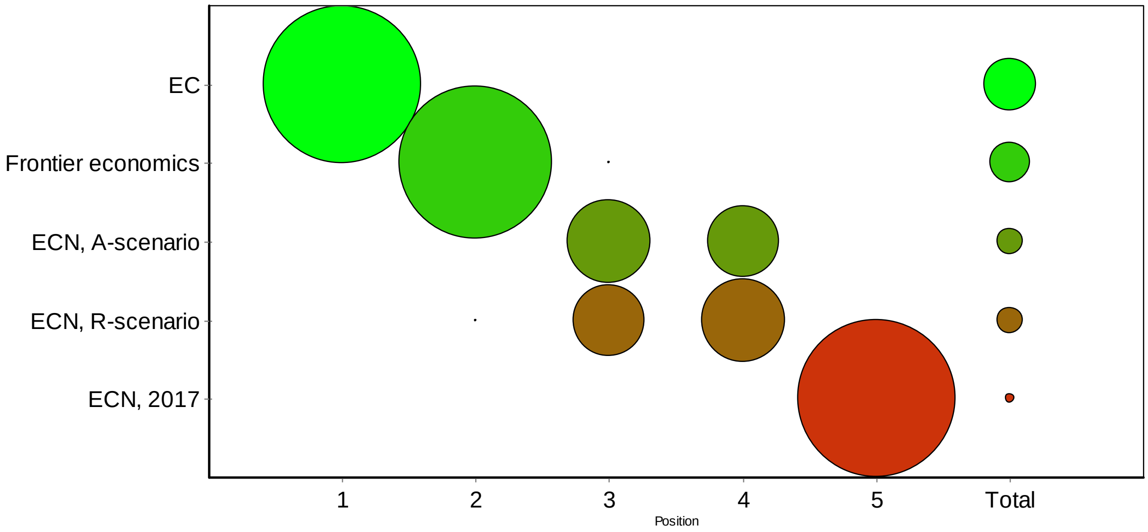


Figure 60: Probability figure for future electricity generation; 5 percent point variation for weights and scores

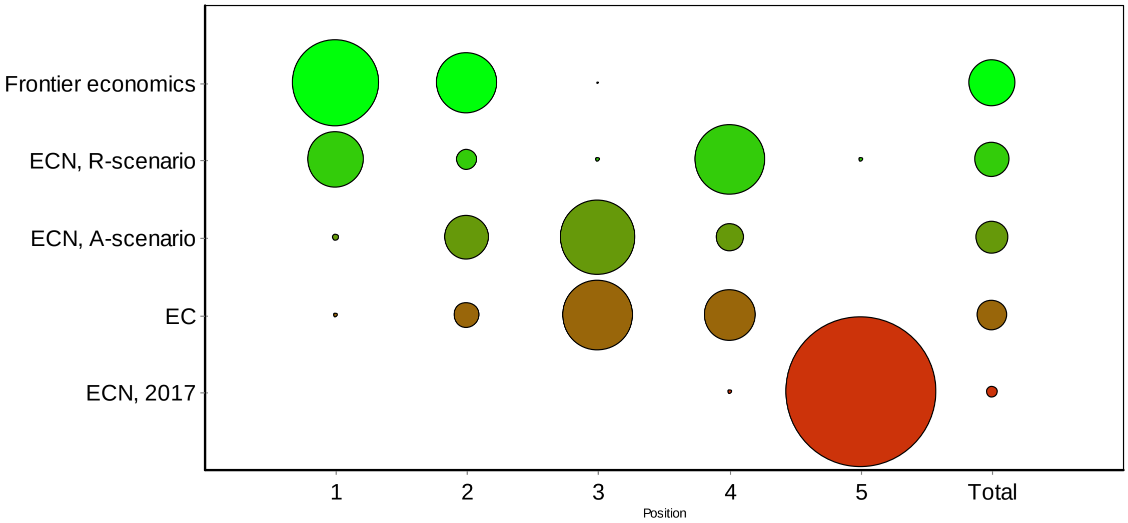


Figure 61: Probability figure for future fossil electricity generation; 5 percent point variation for weights and scores