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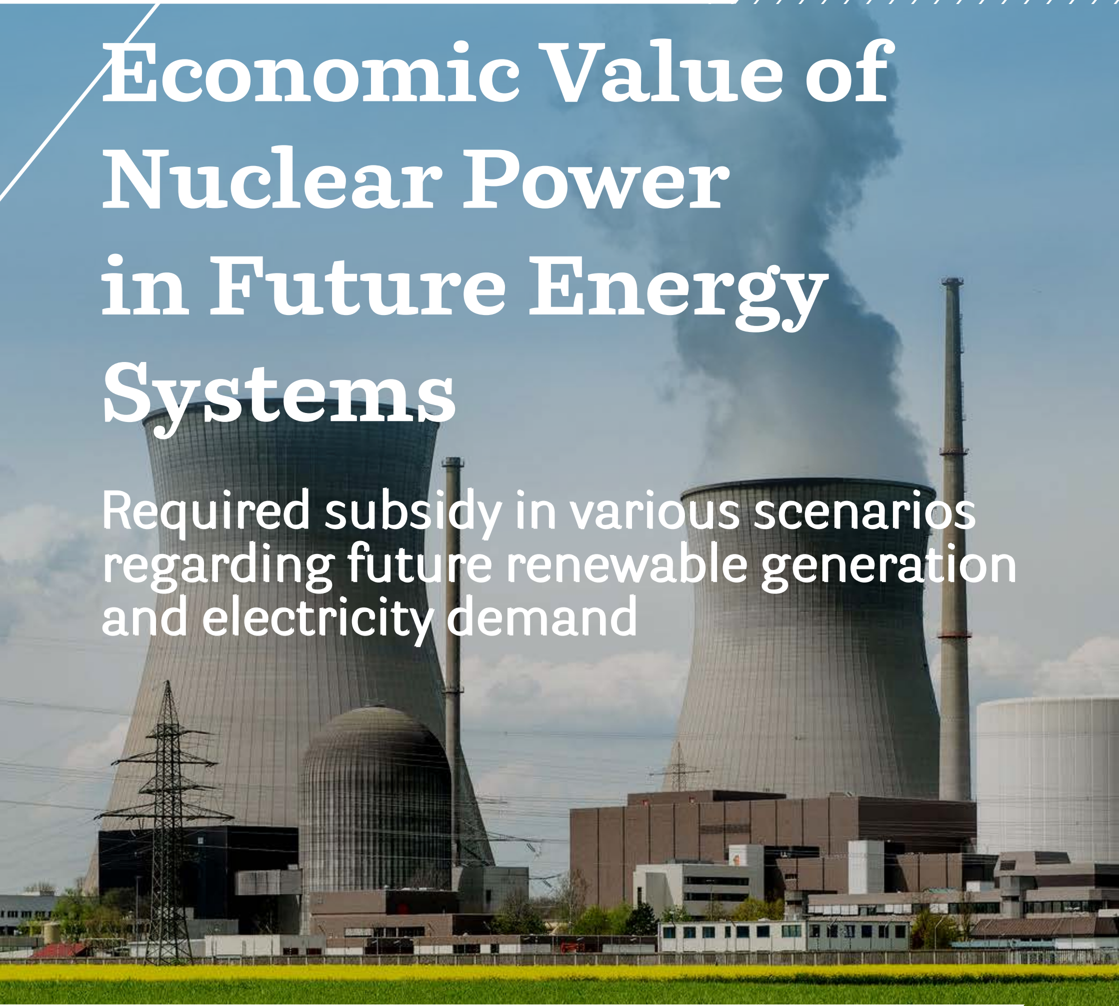
Economic Value of Nuclear Power in Future Energy Systems

Required subsidy in various scenarios regarding future renewable generation and electricity demand



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Summary

1. In order to reduce the absolute levels of carbon emissions, the nature of energy systems has to change dramatically. This is the reason governments are promoting the development and use of renewable energy sources like solar PV, wind turbines, hydropower and biomass. Despite these policies, the growth in renewable energy will likely not be sufficient to reduce carbon emissions to the extent required to meet climate targets, also because the demand for electricity is going to increase because of electrification and production of hydrogen. Therefore, the attention is increasingly also going to another non-carbon energy source, which is nuclear power. The Dutch government, for instance, recently declared that it will enable the construction of two new nuclear power plants in the Netherlands.

2. Nuclear power is, however, highly debated, because of its perceived safety, security and environmental risks. Next to that, it is debatable to what extent nuclear power fits within electricity markets which are characterised by high shares of intermittent generation. Because of the presence of these sources, more flexible sources are required which can help the electricity system to remain in balance all the time, but nuclear power is generally seen as a so-called base-load provider with high fixed costs. Therefore, it may economically not be efficient to have such a type of power plant in future electricity markets which are dominated by high shares of renewable generation. In order to shed more light on this topic, we explore the economics of an investment in a nuclear power plant of 1000 MW in the Dutch electricity market when there is already a large installed capacity of renewables.

3. By exploring the economic value of an investment in a nuclear power plant under various scenarios regarding the future electricity market, we hope to contribute to the societal debate on the potential role of nuclear energy in low-carbon electricity systems. We also hope to provide more understanding of the economic mechanisms behind the business case of investments in power plants. Although this understanding is one of the crucial elements in the societal debate, it is of course not sufficient, as it only gives information on the economics of investing in a nuclear power plant in relation to various circumstances in an electricity market. For the final societal decision whether or not to allow for such an investment, also discussion is needed of (equally) relevant aspects, such as safety, security and environmental issues, and the societal acceptance.

4. The economic value of a nuclear power plant basically depends on four factors: a) the plant characteristics, including its construction costs and construction duration, lifetime, operational and maintenance costs, fuel costs, ramping constraints, costs of handling and storing waste, and decommissioning costs, b) the degree of utilisation (which is called the capacity factor), c) the capture price (which is the average electricity price the plant actually receives), and d) the contribution

to reducing carbon emissions. While the first factor can be seen as exogenous, the others are very much related to the characteristics and functioning of the electricity market. In our analysis, we ignore the costs of any required network extension, realizing that these costs may be quite different for various generation technologies.

5. In this paper, we have analysed how both the utilisation of a new nuclear power plant and its capture price are related to the amount of renewable generation and the magnitude of the electricity demand (i.e. the degree of electrification in for instance industry and transport). In addition, we have analysed the impact on the reduction of carbon emissions by the electricity system. In order to assess these effects, we compare the results with similar increases in offshore wind, onshore wind and solar capacity, taking into account the differences in the respective capacity factors. Hence, we assess the profitability of an investment in a nuclear power plant in comparison to the profitability of investments of similar sizes (in terms of production) in renewable technologies.

6. Referring to a number of external sources, we assume that a nuclear power plant can be build for 4.2 million euro/MW in 7 years of time (after the licensing procedures have been finished), while the plant can be in operation for 60 years of time. After that period, the power plant has to be decommissioned at 15 percent of the initial investment costs. We also have learned from a number of external sources that a (modern) nuclear plant can, to some extent, operate in a flexible way. For the renewable sources, we also use the latest external information on their characteristics. As for solar PV, the costs very much depend on the type of installation (utility scale is much less expensive than small rooftop installations), we have used numbers which are in the middle of ranges published by, for instance, Frauenhofer ISE (2021). Since the costs of technologies may go down in the future, as they have done so in the past for in particular solar PV and wind, we also explore the sensitivity of our results for various assumptions on the plant characteristics.

7. For our analysis, we use a partial hourly equilibrium model of an electricity market, with profit maximizing producers and utility maximizing consumers who both respond to market prices. This model is calibrated on the Dutch market situation in 2019 (in terms of prices and market size). We analyze the profitability of an investment in a 1000 MW nuclear power plant as well as investments in similar amounts of solar PV, onshore wind and offshore wine (controlling for differences in capacity factors). We took the year 2019 as reference as the energy prices in that year were quite representative for the prices in previous years, and probably also for the (longer term) future. It is not likely that the current (extremely) high prices will hold in the longer term as they are related to the current (and expected) scarcity circumstances. Nevertheless, we conduct a sensitivity analysis with much higher prices of gas and carbon.

8. The model analysis is done for a number of scenarios regarding the amount of already installed renewables (related to government objectives) and the increase in electricity demand (related to assumed increases in electrification and hydrogen production). As the installed capacities in these technologies are related to government objectives (and resulting support mechanisms), they can be treated exogenously. The installed capacity of gas-fired capacity, however, results from commercial investments, and, therefore, it has been treated endogenously in the model in order to mimic the long-term dynamics of electricity markets.

9. From the model analysis, it becomes evident that the LCOE (Levelized Costs of Energy) of technologies are not constant, but that they very much depend on the market situation. In a scenario with a high amount of renewables and only a modest increase of demand, the utilisation of all technologies is reduced. This results from the fact that even low-marginal cost producers stop producing when the electricity prices become too low. Even in the presence of support schemes for renewables, a smart scheme design requires that support is not given to production when the market price is below the marginal costs. As a consequence, the LCOE of these technologies become much higher when there is a high amount of renewables. Note that we have ignored any potential grid constraints on production as we assume that the currently increasing grid bottlenecks will be solved through extensions of grid capacity. Otherwise, the production by in particular renewables will be even lower because of congestions in periods of favourable weather conditions.

10. For a nuclear power plant, we find that the capacity factor is strongly reduced, from about 90 to about 60 percent, when the electricity market is characterised by a high share of renewable generation. This effect is partially mitigated when the demand for electricity has increased strongly. In relative terms, renewable technologies experience a similar decrease in capacity factors.

11. The capture price of the nuclear power plant, however, appears to be less sensitive to the amount of renewables in the system than the capture prices for wind and solar. In a scenario with a high installed capacity of wind and solar generation, the capture price of a new nuclear power plant reduces from the current 40 to about 35 euro/MWh. The capture prices for wind and solar (including the prices for green certificates), however, decrease from about 50 to 10 euro/MWh when there exists already a high share of renewables in the market. The reason that the nuclear power plant experiences a much smaller reduction in its capture price is that it is able to benefit from high (scarcity) prices when solar PV and/or wind turbines are not able to produce because of weather circumstances. From this, we learn, that for the economic assessment of various generation technologies, one should also look at the prices which can be realized as they depend strongly on market circumstances.

12. Using external information on the construction, operating and decommissioning

costs, duration and the lifetime, as well as the model results regarding utilisation rate and capture prices in various scenarios, we calculate the present value of an investment in a nuclear power plant. We compare this present value with the ones for similar investments in solar PV, onshore wind and offshore wind. It appears that, for all scenarios, all these technologies need external subsidies in order to fully recoup their fixed costs. Note that currently, offshore wind production does not receive any subsidy, but this is because of the fact that a significant part of the costs of offshore wind is financed in a different way (i.e. through public expenditures).

13. From these results follows that without any governmental support, commercial investors will likely not invest in a nuclear power plant as in all scenarios such an investment is loss making. Based on a number of scenarios regarding the (Dutch) electricity market, we also find that a nuclear power plant needs more subsidy (in euro/MWh) than an onshore wind turbine, but less than an solar PV installation and an offshore wind park. In a scenario with a high share of renewables, however, also onshore wind turbines require more subsidies than a nuclear power plant, which is related to the strong decline in the capture price of renewable power plants. Hence, when there is a large installed capacity of renewables, investing in a nuclear power plant is more efficient than further extending the renewable capacity.

14. As the promotion of renewable generation and possibly also nuclear power is related to climate policy objectives, we express the required subsidies per technology in terms of the realized reductions in carbon emissions (the so-called abatement expenditures measured in euro per ton of carbon emission reduction). This emission reduction results from the replacement of gas-fired power plants by one of the other techniques (nuclear, solar PV, onshore wind or offshore wind). It appears that in a scenario with a high amount of (already) installed renewables, the abatement expenditures (in euro/ton carbon) for nuclear are significantly lower than for wind and solar generation. This is related to the relative strong decline in the capture price for the renewable technologies. This implies that it is more efficient to install a nuclear power plant than renewable technologies to reduce carbon emissions.

15. Although providing subsidies for a loss-making technology forms a cost to society, there are some groups which benefit, such as electricity consumers who benefit from lower electricity prices. When we sum up all the economic effects in society, we obtain the overall welfare effects. By expressing these welfare effects in terms of the realized reduction in carbon emissions, the social abatement costs result (measured in overall welfare effect in euro per ton of carbon emission reduction). The conclusion from the social abatement costs is similar as the previous conclusion: the costs per ton of carbon emission reduction for nuclear are lowest in a scenario with high amounts of renewable capacity. Hence, building a nuclear power plant is a relatively efficient way of reducing carbon emissions.

16. Nuclear power plants benefit more from higher gas or carbon prices than renewables. Because of their high availability factor, nuclear power plants are able to produce electricity when gas-fired power plants set the electricity price, and hence, they experience higher electricity prices when the costs of gas-fired power plants increase. This holds in particular for scenarios with already high amounts of renewables. If in such a scenario, the carbon price is 10 times as high as in 2019 (so, about 250 euro/ton), the required subsidy for nuclear power reduces to about 25 euro/MWh, while renewables only see a small decline in their required subsidies.

17. To make the hourly average electricity price (i.e. the price paid by consumers) less sensitive to (extreme) gas prices, renewable technologies appear to be equally helpful as nuclear power plants. Investing in both nuclear and renewables as wind and solar makes the average electricity price less strongly related to the gas price.

18. Finally, the results are, of course, sensitive to the assumptions made. When the construction and decommissioning costs of nuclear are twice as high as assumed, the required subsidy for nuclear power exceeds the subsidy needed for solar PV. Less dramatic increases in the assumed construction costs, however, do not change the above conclusions. We also find that the construction costs of solar PV should reduce by more than 50 percent in order to arrive at a similar required subsidy level as a nuclear power plant. Changing the assumption regarding the lifetime of the nuclear power plants does not really affect the outcomes. The results appear also to be robust for various values of the discount rate. Moreover, the results do not change significantly when we assume a higher amount of flexibility within the electricity market, which may happen in the future because of investments in storage, and further international integration of markets.

1 Introduction

1.1 Background and objective

In order to reach international climate-policy objectives, carbon emissions have to be strongly reduced in a short period of time (IEA, 2021). Most of the carbon emissions result from the use of fossil energy, which implies that there are basically two options to reduce the emissions of carbon: reducing the use of energy as well as replacing fossil energy by non-carbon energy carriers. The use of energy depends on both the volume of economic activity, i.e. economic growth, and the energy intensity of economies. As societies continuously aim for further economic development, reduction in energy use is generally pursued by improving the energy efficiency. In the past, the energy efficiency annually increased by approximately 1 to 2 per cent. This relative reduction in energy use is, however, more or less neutralized by the absolute increase in economic activity, and in the future they may be not really different. Hence, as energy use likely remains strongly related to economic growth and as long economies are growing, improvements in energy efficiency may be needed just to compensate for the increasing use of energy.

This implies that in order to reduce the absolute levels of carbon emissions, the nature of energy systems has to change dramatically. This is the reason governments are promoting the development and use of renewable energy sources like solar PV, wind turbines, hydropower and biomass. The speed of the growth in these non-carbon energy sources is, however, constrained by a number of factors, such as spatial factors (e.g. available locations), social factors (e.g. social acceptance of wind parks nearby residential buildings) and financial factors (in particular the levelized costs of energy compared to market prices). Despite governments are implementing policies to overcome these constraints, it is likely that the actual growth in renewable energy will not be sufficient to reduce carbon emissions to the extent required to meet climate targets (IEA, 2021). Therefore, the attention is increasingly also going to another non-carbon energy source, which is nuclear power (see e.g. MIT, 2018). The Dutch government, for instance, recently declared that it will enable the construction of two new nuclear power plants in the Netherlands.

Although nuclear power is just as renewable sources, like solar PV and wind turbines, a non-carbon energy source, it is highly debated. This debate is mostly directed at the safety, security and environmental risks of nuclear energy. Next to that, it is debatable to what extent nuclear power fits within electricity markets which are characterised by high shares of intermittent generation. After all, because of the presence of these sources, more flexible sources are required which can help the electricity system to remain in balance all the time. As nuclear power is generally seen as a so-called base-load provider with high fixed costs which should be utilised as much as possible, it may economically not be efficient to have such a type of power plant in future electricity markets which are dominated by high shares of renewable generation. Such an inefficiency, if it exists, however, should be weighed against the benefits of having less carbon emissions if the nuclear power plant replaces, for instance, a coal or gas-fired power plant. Moreover, the economic value of nuclear power in systems with high shares of renewables should also be assessed against the background of a growing demand for electricity resulting from electrification in particularly industry and transport, including the production of hydrogen through electrolysis.

1.2 Research scope

In this paper, we assess the trade-off between the costs of adding a nuclear-power plant to an electricity system with already high shares of renewable generation and various levels of electricity demand versus the benefits of having lower carbon emissions. We explore this trade-off by determining the societal costs of operating a nuclear power plant per unit of reduction in carbon emissions in various scenarios. These scenarios vary in terms of the future shares of renewables as well as the future level of electricity demand. The future development in renewable generation can be inferred from government objectives regarding the deployment of in particular wind and solar electricity, while the future levels of electricity demand can be estimated on the basis of policy ambitions for electrification, for instance in relation to the production of hydrogen through electrolysis.

The analysis is done by developing and applying a partial-equilibrium model of an electricity market. In this model, the supply side of the market consists of firms operating a number of generation techniques (i.e. gas, nuclear, offshore wind, onshore wind, and solar). The demand side is modelled as a function of the market price plus an hourly varying intercept, while the level of this intercept is determined by external scenario assumptions (in particular regarding the growth of electrification and hydrogen production). International traders are added to mimic the interaction with neighbouring markets. Moreover, next to the market for the commodity electricity, the model also includes a market for green certificates in order to include the preferences of some consumers for renewable electricity. The model simulates market equilibria for each hour in one (future) year, this means that it optimizes the behaviour of firms and consumers given the installed capacities. However, we also treat the available capacity of gas-fired power plants endogenously, which means that the installed capacity of these plants is set at such a level that their operational profits per MW installed (resulting from the captured electricity price and utilisation) remain constant. So, if operational profits increase due to higher prices, we assume that more gas-fired capacity will be installed, and the other way around. Hence, we assume that the installed capacity of gas-fired power plants will be adapted to market circumstances, while the installed capacities of solar PV, wind, solar PV nuclear are exogenously determined. [1]

The model is calibrated for the Dutch market, which means that in the baseline the model outcomes (in particular electricity prices, consumption and production levels) reflect the actual situation in this market in a particular year. As 2019 is the last year

[1] This is also how the current electricity market actually functions: renewables are subsidised in order to realize governmental objectives in terms of installed capacities, and the same may hold for nuclear in the future. See for further details on this approach Section 3.5.

before the corona crises with more (historically) normal values, that year has been chosen as baseline. In addition, we also took the official Dutch policy objectives regarding deployment of renewables in 2030 and 2050 as input for determining the future electricity system characteristics. In addition, we made assumptions regarding the future development of electricity demand, based on story lines regarding the electrification and role of electrolysis to produce hydrogen.

For the costs of the various technologies, we use the latest information available. We do realize that the costs of in particular solar, but also wind have reduced significantly in the recent past, and that this may continue in the future, while we also realize that the actual costs of a few recent nuclear power projects were significantly higher than expected initially. Therefore, we also have conducted a sensitivity analysis regarding the assumed values for the investment costs in solar PV and nuclear power plants. As several other assumptions may also affect the outcomes of our analysis, we extended this sensitivity analysis to a number of other factors.

By simulating the hourly market situations during one full year under various scenarios regarding electricity demand and installed renewable capacity, we determine, for each hour, the electricity price which can be captured by the different technologies and how much they will produce. Using these results, we determine the annual operational profits, and by comparing these with the annualized fixed costs, we determine the profitability of investments in the various technologies. Here, we will see that for the economic assessment, one should not only look at the costs, as often happens, but also at the revenue side (i.e. the capture price and utilisation) which vary much depends on the market circumstances. Based on the profitability, we calculate the subsidies which are needed to make the investments break even. Moreover, by expressing these subsidies in terms of carbon emission reduction, we find the abatement expenditures (in euro subsidy per ton of carbon reduction). We will also do this for the total welfare effects, which results in the social abatement costs (in euro welfare per ton of carbon reduction). By doing this not only for an investment in a nuclear power plant (of 1000 MW), but also for (additional) investments in similar amounts of renewables (controlling for differences in capacity factors), we are able to determine to what extent nuclear power is relatively more or less efficient to realize climate-policy objectives.

By exploring the economic business of an investment in a nuclear power plant, we hope to contribute to the societal debate on the potential role of nuclear energy in low-carbon electricity systems. We also hope to provide more understanding of the economic mechanisms behind the business case of investments in power plants. Although this understanding is one of the crucial elements in the societal debate, it is not sufficient, as it is only directed at the economics of a nuclear power plant in an electricity market. This implies that we do not go into other (equally) relevant aspects of the societal discussion of nuclear power, such as safety, security and environmental issues, and the societal acceptance. In addition, we do not go into all kind of factors which may hinder an efficient construction of nuclear power plants (see e.g. MIT, 2018), such as a lack of coordination or lack of qualified experts, and we ignore all costs which may be required for licensing procedures and discussions in society. We do, however, the same for the other (renewable) technologies (offshore wind, onshore wind and solar), which gives them an equal treatment in our analysis, albeit an analysis which is only focused on the position of these various technologies in an electricity market which various amounts of renewables and various levels of electricity demand.

1.3 Outline of this paper

We start by describing the economic principals behind the functioning of current (zonal) electricity markets as well as the current and expected future role of nuclear in energy systems. Then we describe the method of our research, which consists of the development, calibration and application of a partial equilibrium model of the (Dutch) electricity market. Afterwards, we present the results of our analysis, by going into the impact of adding a nuclear power plant of 1000 MW to the Dutch electricity market. This impact is described for the electricity price, aggregated load level and production mix, carbon emissions, overall welfare, required subsidy to make the investment in the nuclear power plant break even, and the abatement costs per unit of reduction in carbon emissions. Next, we compare these results with the results of adding similar amounts of more generation by solar PV and wind turbines. Finally, we conduct a sensitivity analysis by exploring the impact of the assumptions regarding crucial parameters, such costs of capital and expected lifetime of plants, on the model results. In the final section, we present the resulting conclusions of the analysis.

2 Nuclear Power in Electricity Markets

2.1 Introduction

Before being able to determine the potential role of nuclear power, one has first to analyse the economics of electricity systems. This analysis is given in the next subsection. Then we briefly describe the role of nuclear power in various electricity markets up to now. Next, we go into the potential role of nuclear power in a number of scenario studies regarding the future of low-carbon electricity systems.

2.2 Economics of electricity markets

In most developed countries, electricity systems have been liberalized. This means that a central coordination of investments and dispatch has been replaced by a market mechanism with decentralized decision making regarding investments in power plants and commercial trade. However, the functioning of the electricity grid is still centrally coordinated. In nodal electricity markets, like in the USA, the system operator remains responsible for real-time dispatch. In zonal electricity markets, like those in Europe, producers are having program responsibility giving them incentives to align commercial contracts in forward markets with real-time dispatch (see Mulder, 2020). For the remaining, we focus on zonal electricity markets.

In zonal markets, the electricity price is based on peak-load pricing. In times of sufficient generation, electricity prices (so-called off-peak prices) are related to short-term marginal costs. In times of scarcity, electricity prices (peak prices) are related to the willingness-to-pay of power consumers. In principle, the deviation between these peak prices and the short-term marginal costs results in the operational profit which can be used to compensate for the fixed costs of investments. Hence, the occurrence and level of peak prices give incentives to producers to expand generation capacity. As a result, in a case where the demand for electricity is always below the level of installed capacity, the electricity prices will never give any compensation for investment costs, which makes that no investor will build a new power plant. In times of scarcity, however, the prices can be high for a significant number of hours, and if investors expect that this will remain the case for a many years in the future, they are having an incentive to build a new power plant (see e.g. Mulder, 2020).

In this way, zonal electricity market give incentives for investments in electricity plants. As power plants have different technical characteristics and different levels of fixed and variable costs, the incentives for the various types of plants also differ. For instance, investors have incentives to build a plant with low fixed costs and high variable costs when the number of hours of scarcity only happens a limited number of hours in a year when that particular type of plant may be the so-called price-setting (marginal) plant. Such plants are called peak plants and provide flexibility to the market. Such power plants only run a limited number of hours during a year, when demand is high, but the revenues realized in such hours are sufficient to recoup the fixed costs. The opposite type of power plant are the so-called base-load plants which run almost all the time. These plants typically have high fixed costs and low variable costs. As a result, they will be dispatched many hours which enables them to make an operational profit during most of the hours in a year. These profits are determined by the spread between the market price of electricity and the marginal costs of these plants. Nuclear power plants belong to this category.

Technically speaking, nuclear-power plants are quite different from solar PV installations and wind turbines. However, from an economic perspective they have something in common what makes them different from fossil-fuel plants. A key economic characteristic of fossil-fuel plants (e.g. coal or gas-fired power plants) is that they have to make costs for every unit of electricity they generate. After all, they have to burn coal or gas in order to make steam which is used to set a turbine in motion which creates the electrical energy. Hence, every unit of electricity causes specific (marginal) costs which depend on the market price of the fuels used and the conversion efficiency of the power plant. In contrast, nuclear power, solar PV and wind turbines have much less additional costs when they generate electricity. Once the installations have been build, there are no or hardly additional costs for every unit of electricity production. This means that the fixed costs of these types of power plants, which also include the fixed maintenance costs and decommissioning costs, constitute the major part of their total costs. This has a number of consequences.

First of all, the financial risk for investments in nuclear, wind and solar plants is significantly higher than for fossil-fuel or biomass plants. When a coal-fired plant has to stop its production, for whatever reason, is does not have the short-run marginal costs (i.e. costs of using coal) anymore. However, when a nuclear power plant is not able to continue its operation, it does hardly save on costs, while it does not see any revenues anymore. In other words, for a nuclear power plant solar PV and wind turbines, most of the costs are sunk, which means that the costs have already been made and cannot be reduced.

Another financial consequence is related to the price formation in electricity markets. When there is abundant capacity (i.e. market demand is below the level of installed generation capacity), electricity prices are based on the marginal costs of the marginal power plant, as we have seen above. When this marginal power plant is a gas-fired power plant, the electricity price is related to the price of natural gas (and carbon). When this marginal plant is a nuclear power plant, solar PV installation or wind turbine, then the electricity price is almost zero as these plants hardly have marginal costs. As a result, gas-fired power plants can be said to be financially hedged through the relationship between electricity and gas prices, while this is not the case for the other types of plant. Just because their costs are mainly sunk, they run the risk that they will not get any revenue for their production.

In order to create sufficient financial revenues as compensation for the sunk costs of these plants, therefore one of the two following conditions need to be satisfied. Either, fossil-fuel or biomass plants (which also have short-run costs for operation) are price-setting plants, which makes that the electricity price is related to their marginal costs and which results in so-called infra marginal profits for the plants with high fixed and low variable costs. Or, the total electricity demand exceeds the level of installed capacity, which results in peak prices all the time.

The likelihood that one of these conditions is satisfied is, however, challenged by the increase in renewable energy generation. The promotion of solar PV installations and wind turbines by governments makes that the so-called merit order (i.e. the supply curve in the electricity market) moves to the right. This means that there are less hours of scarcity (and peak prices), while gas-fired power plants may be less often the price-setting plant. As a consequence, this merit order effect of renewable energy makes electricity prices go down.

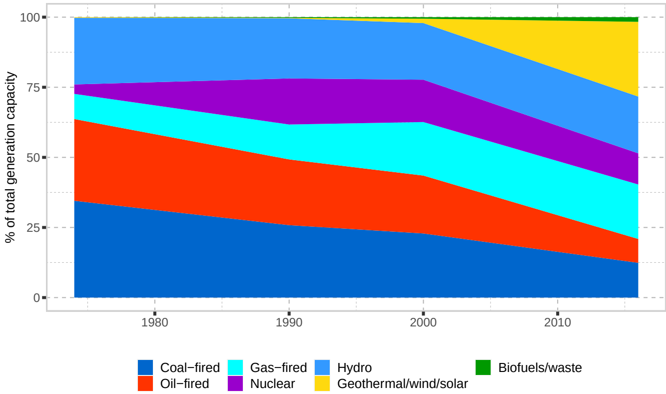
For nuclear-power plants this means, just as for other infra marginal power plants, that their marginal revenues (i.e. the prices they receive) go down, resulting in less profits. In addition to the price reduction, there is also the risk for the nuclear power plants, that their utilisation will go down. This will happen when the supply of electricity by renewable sources is sufficient to meet total demand. In such a situation, the nuclear power plants are not (or less) needed anymore. If this only occurs for a few hours or so, then it may be efficient for the electricity company to continue producing with the nuclear power plant because of the costs of ramping up and down of these plants (the so-called dynamic dispatch costs). As a result, the electricity price will become negative. If the situation of oversupply by renewable sources takes longer, then it may become efficient for the company to reduce the volume of production. In that case, the company will not make any revenue anymore. Hence, when the capacity of renewable electricity increases strongly while the demand for electricity does not, the business case for power plants with high fixed cost, such as nuclear power plants, is seriously challenged.

In this paper, we explore the sensitivity of the business case of nuclear power in a liberalized electricity market with various amounts of renewable generation and various demand levels. In order to assess this sensitivity, we conduct a similar analysis for the business cases of solar PV and wind turbines. Before going to our analysis, we first briefly describe the actual and historical role of nuclear power and the forecasts for this role according to a number of scenarios.

2.3 Role of nuclear power in historical perspective

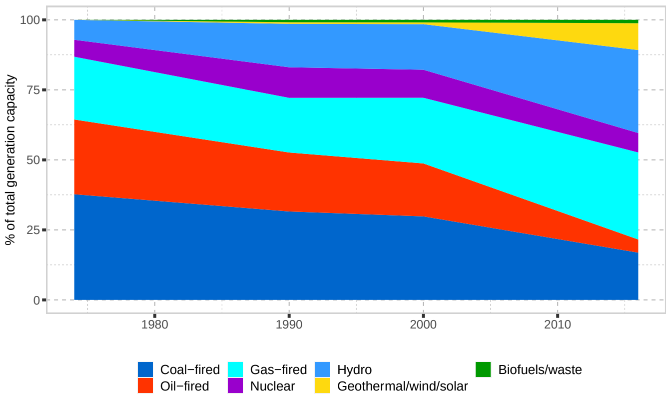
Since the oil market crisis in the 1970s, many countries started to build nuclear power plants. As a result, the share of this generation technology in electricity systems grew strongly. In 1990, the share of nuclear generation capacity in total generation capacity in OECD Europe was 16 percent, while it was only a few percent in 1974 (see Figure 2.1). Since then, however, the share of nuclear reduced gradually until about 10 percent currently. Also, in OECD America the amount of nuclear power capacity remained more or less stable on the level of about 115 GW, which implies that its share in total generation capacity in this region declined as well (see Figure 2.2).

Figure 2.1 Composition of electricity capacity in OECD Europe (percentage), 1974-2016



source: IEA (2019)

Figure 2.2 Composition of electricity capacity in OECD America (percentage), 1974-2016



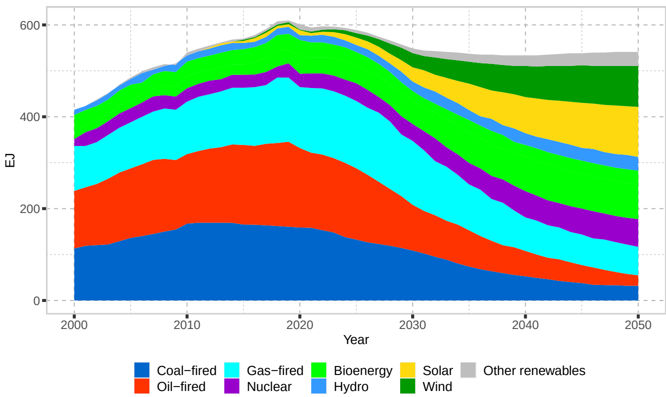
source: IEA (2019)

In the same period, the amount of installed gas-fired generation capacity increased strongly from 200 to 500 GW in OECD America. Also in OECD Europe, the amount of gas-fired capacity more than doubled. This implies that in many countries, since 1990, electricity generation became more dependent on natural gas and less on nuclear energy. Next to the increase in gas-fired generation, a significant increase occurred in the capacity of renewables. Note however, that because of the much lower capacity factors of renewables, a similar increase in installed capacity of solar PV or wind turbines results in a much lower increase in production by these technologies. Having said that, it is clear that not many investments have been made in nuclear power over the past decades. The current global installed capacity of nuclear power is about 400 GW, which level has been quite stable over the past decades.

2.4 Role of nuclear in scenarios for decarbonised power systems

Although the relative role of nuclear in electricity systems has declined in many countries over the past decades, in the future this may change. The reason for this is that the carbon emissions resulting from using energy should decline quickly and sharply in a short period of time in order to prevent much further climate change (IEA, 2021). This reduction is pursued through the promotion of renewables and energy efficiency, but it appears that both pathways are not sufficient to reach climate policies. Taking into account what could be achieved in terms of renewables and energy efficiency, the IEA expects that the global nuclear power capacity should increase to more than 600 GW in 2030 in order to reach climate objectives. In 2050, the global installed capacity should be about 800 GW in order to reach net zero carbon emissions. The global supply of nuclear energy global should double between 2020 and 2050 (IEA, 2021) (see Figure 2.3).

Figure 2.3 IEA NZE total energy supply



source: IEA (2021)

On top of this, nuclear power may be needed to reduce the gas dependence of electricity systems. As we are currently seeing in international energy markets, the extremely high gas prices have dramatically increased the electricity prices in many countries. The strong relationship between electricity prices and gas prices results from the fact that gas-fired power plants are often the so-called price-setting power plants. By raising the installed capacity of nuclear power plants, next to the increase of renewable capacity, the number of hours in a year that gas-fired power plants are price setting will reduce. This will not only result in a lower gas dependence of the electricity generation, but will also make electricity prices less strongly related to gas prices.

It is also expected that nuclear power plants will be able to provide more flexibility to electricity systems. While in the past they were basically known as base-load providers, nuclear power plants are technically able to operate flexibly and to respond to market circumstances. Operators of existing nuclear power plants in various countries are increasingly having experience to operate in a flexible way, while new power plants which are now under construction are designed for a flexible operation (Jenkins et al., 2018).[2]. Nuclear power plants operating in a flexible way can realize one or two power changes per period of 24 h, in which the power can be reduced from 100 to 20 percent of its technical capacity within 30 minutes, and vice versa (see Morilhat et al., 2019).

Because of these two factors (i.e. climate-policy objectives and less gas dependence) governments are increasingly considering nuclear power. In this paper, we focus on the climate policy objective and analyse the costs per unit of carbon emission reduction of adding a nuclear power plant to an electricity system which is characterised by various shares of renewable generation and various levels of increase in electricity demand.

[2]"Modern nuclear plants with light water reactors are designed to have strong manoeuvring capabilities. Nuclear power plants in France and in Germany operate in load-following mode, i.e. they participate in the primary and secondary frequency control, and some units follow a variable load program with one or two large power changes per day. (...). Most of the modern designs implement even higher manoeuvrability capabilities, with the possibility of planned and unplanned load-following in a wide power range and with ramps of 5 percent Pr per minute." OECD (2011)

3 Method of Research

3.1 Introduction

In order to assess the economic value of nuclear power, we proceed as follows. First, we construct a short-term partial equilibrium model that mimics the mechanics of a power market. We calibrate our model on the Dutch electricity market. Then, we assess the profitability of investments in generation capacity (nuclear, solar PV as well as wind) for different scenarios regarding the electricity market.

In this chapter, we elaborate on our method of research. First, we describe the framework that is used to model the power market. Then, we show the results of calibrating the model on the Dutch electricity market. Next, we describe our method to assess investments in generation capacity. Finally, we define our scenarios and policy-variants.

3.2 Framework of model of power market with nuclear energy

We model an energy system containing an electricity market and a green-certificate market. At both markets clearing prices and quantities are solved every hour for a period of one year. In the following, we briefly describe our modelling approach. First, we discuss the modelling of the electricity market, then we discuss the modelling of the green-certificate market. The mathematical formulation, use of data and relevant parameters, which are based on the work of Li and Mulder (2021), can be found in Appendix A.

For the supply side of the electricity market, we look at different producers. We include gas-fired power plants, nuclear-fired power plants, solar PV, onshore wind energy and offshore wind energy. We also include an international trader, which can trade electricity with a foreign electricity market. For a given hour, each producer optimizes its profit, subject to constraints based on its installed capacity and the availability of this capacity.

Both the installed capacities and the availability factors are treated as exogenous parameters. The installed capacities are based on actual data or government targets. The availability factors are settled as follows. We assume the availability factor of gas-fired capacity is one (which means that this capacity is permanently available), and the same goes for the trader's cross-border capacity. For nuclear-fired power plants, the availability factor for each hour is bounded by dynamic constraints, which are the production level in the previous hour and the maximum pace of ramping-up and ramping-down. Moreover, we schedule a refueling outage during which the availability factor of nuclear power is zero (i.e. a period in which this capacity is not available). For solar PV, onshore wind and offshore wind energy, their availability factors depend on external information on Dutch weather conditions (i.e. wind speed and sunshine). For simplicity, we assume their availability factors are the ratios between their actual electricity production and their installed capacities, adjusted by capacity factors.

For the demand of electricity, we assume a representative consumer, whose demand responds to price changes. We use historical data to construct a linear demand function in which an electricity tax is included. The slope of such demand function remains the same but the intercept changes over hours, reflecting the demand variation over time. Given the total supply and total demand, for each hour the electricity price is such that demand equals supply (which is the market equilibrium).

The model also includes a market for green certificates. A green certificate proves that energy has been produced from a renewable source. For renewable energy sources, each megawatt hour (MWh) of produced energy comes with a certificate. These certificates are tradable and can thus bring extra revenues for renewable producers. In our model, the supply of green certificates is equal to the total production of solar PV, onshore wind energy and offshore wind energy. Demand comes from consumers and depends on the consumption of electricity. Similar to the electricity price, the certificate price is such that total demand equals total supply.

3.3 Calibration of model on Dutch electricity market

We calibrate our model on the Dutch electricity market in 2019. This is the last pre-corona year which means that this year can be seen as fairly representative for 'normal' circumstances in energy markets.[3] Table 3.3 shows the assumptions on the installed capacities of the different electricity producers and the international trader. Other technology and cost parameters can be found in the Appendix B.

Table 3.1 Assumed values for installed capacities used to calibrate the model on Dutch power market in 2019

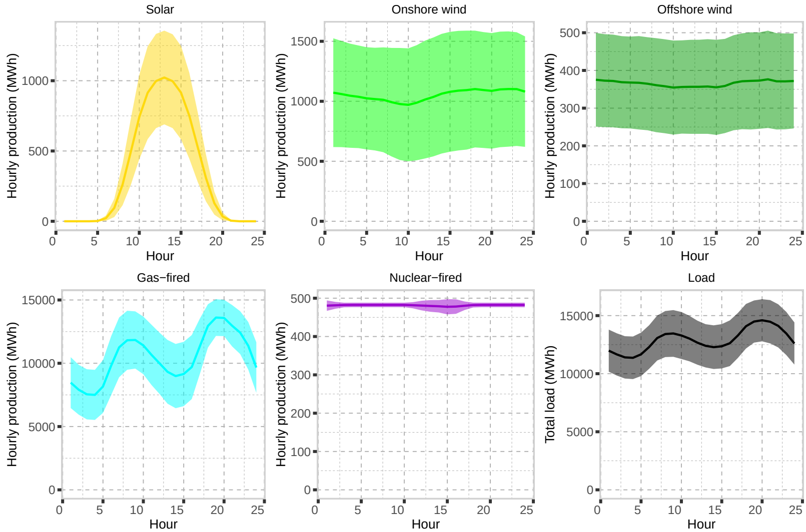
Capacity of	MW	Source
Solar PV	3937	ENTSOE (2021a)
Onshore wind	3669	ENTSOE (2021a)
Offshore wind	957	ENTSOE (2021a)
Nuclear	486	ENTSOE (2021a)
Gas-fired	15570	ENTSOE (2021a)
Cross-border transmission	3000	Li and Mulder (2021)

In Figures 3.1 and 3.2, we give an overview of our model output for the electricity market. We show the production of the different techniques (in color) and the load (in grey). We do this per hour (Figure 3.1) and per month (Figure 3.2). The lines indicate the aggregated average, while the colored areas give a measure of deviation from this average.

As expected, we observe that the average electricity production of solar energy follows a pattern during day and night. The average production levels of onshore and offshore wind energy do not show such a pattern, as the average electricity production is similar across hours. The average production of gas-fired power plants is load-following, in the sense that production is relatively high (low) when demand for electricity is relatively

[3] We realize, however, that in particular the installed capacity of renewable sources has increased since 2019. The precise baseline value of the installed capacities is however not so relevant for our analysis, as we are analysing future market conditions under various amounts of renewable generation and demand levels.

Figure 3.1 Hourly variability of production and load within a year (model results for calibrated Dutch market in 2019)



Note: For the nuclear-fired power plants only the hours in which the availability factor is equal to 1 are shown.

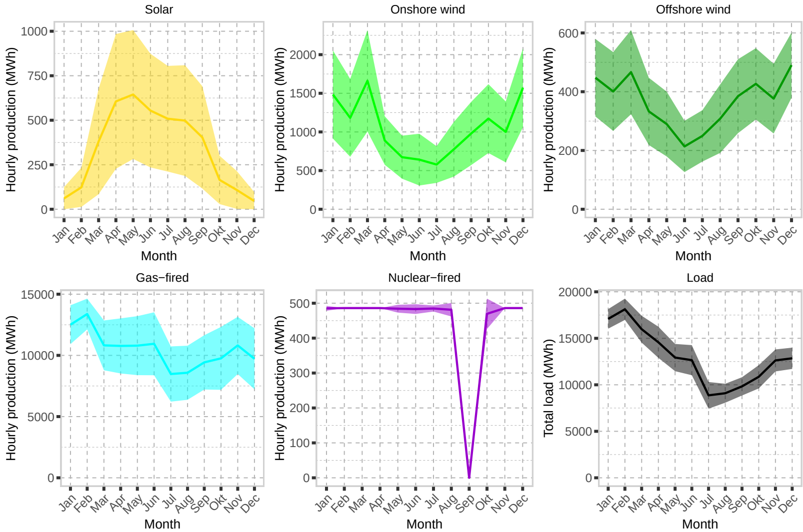
high (low). The average production of nuclear power plants is rather stable (and equals its maximum output).

When we look at the variation of the different techniques in Figure 3.1, we observe that the hourly variation of solar PV, onshore wind and offshore wind energy is higher than that of gas-fired and nuclear-fired power plants. This can be explained by the fact that the production of the renewable sources depends on weather conditions, which fluctuate over time. The production by the two other types of power plants does not depend on (unstable) weather conditions, such that their production varies less.

When we compare the variability in production of gas-fired power plants and nuclear-fired power plants, we see that the production of nuclear power plants fluctuates less. This can be explained by the limited speed of ramping-up and ramping-down of nuclear-fired power plants considered in our model (see Appendix B.2). Moreover, nuclear power plants precede gas-fired power plants in the merit order, while the total production of solar PV, onshore wind and offshore wind is most often not sufficient to satisfy all electricity demand. As a consequence, nuclear-fired power plants can operate mostly at their full capacity, while the production of gas-fired power plants varies with demand. In the future with increasing share of renewables this may chance, and to what extent that will affect the business case of nuclear power is what we are going to analyse in this paper.

From Figure 3.2, we observe that the production of renewable electricity sources

Figure 3.2 Monthly variability of production and load within a year (model results for calibrated Dutch market in 2019)



follows a seasonal pattern[4]. The production of solar energy is on average highest in April and May and lowest in winter, while the production of wind energy is lowest in summer and highest in winter months. The production of gas-fired power plants again follows demand, which is highest during winter and lowest during summer. The production of nuclear-fired power plants is again rather stable. In September there is no production, as our model contains a scheduled outage in that month.

In Figure 3.3, we compare the electricity price duration curve[5] resulting from our model with that of Dutch day-ahead electricity market in 2019 ENTSOE (2021c). We observe that our model represents the Dutch day-ahead electricity market fairly well.

We also compare the total load, average electricity price and total carbon emissions of our model with their actual values. These values are shown in Table 3.2.

Similar to Figure 3.3, Table 3.2 shows that the Dutch electricity market is fairly well represented by our model. Only the carbon emissions of our model are lower than the actual observed carbon emissions. This can be explained by the fact that we do not consider coal-fired power plants. As the carbon emissions per unit of electricity production of a carbon-fired power plant are relatively high, our model underestimates the total amount of carbon emissions.

[4]This is related to the fact that the calibration is based on external information on actual weather circumstances in the Netherlands.

[5]An electricity price duration curve shows the proportion of time for which the electricity price is higher than a certain number. To create an electricity price duration, we order hourly electricity prices from the highest to the lowest.

Figure 3.3 Electricity price duration curves in the model and the Dutch electricity market in 2019

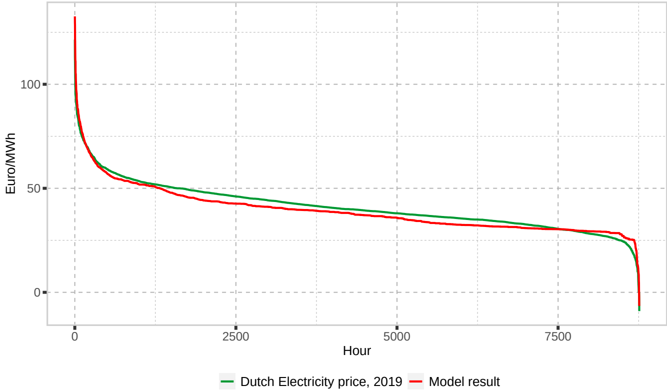


Table 3.2 Total load, average electricity price and total carbon emissions in the model and the Dutch electricity market in 2019

	Load (TWh)	Average electricity price (Euro/MWh)	Carbon emissions (million ton)
Dutch electricity market, 2019	113	41.20	42.1[1]
Model results	113	39.47	36.7[2]

Notes:
1 : PBL (2021)
2 : We do not consider coal-fired power plants in our model as the expectation is that they will not be in operation (as coal power producers) anymore within a few years time. As a consequence, the carbon emissions in our model are lower than the actual carbon emissions.

3.4 Method of assessing investments in generation capacity

The short-term partial equilibrium model described above is helpful to analyse the utilisation and revenues of various types of power plants, including nuclear plants. However, in order to properly assess the economic value of nuclear power, we also need to take into account long-term aspects of these plants. We do this by looking at the Net Present Value (NPV) of the investments in nuclear power plants[6]. Moreover, we also calculate the NPV of investments in solar PV, onshore wind energy and offshore wind energy to decide whether nuclear is a less or more expensive option to reduce carbon emissions.

In order to calculate the NPV of an investment, we need to know its cash outflows (costs) and cash inflows (benefits). For all considered power plants (nuclear, solar PV, onshore wind and offshore wind), the cash outflows we consider contain construction costs, fixed operations and maintenance costs and decommissioning costs. Moreover, we consider costs that only apply to nuclear power plants. These are variable operations and maintenance costs, fuel expenditures and the costs of waste processing and storage. Table

[6]The NPV is a common measure to assess investments. It combines the cash flows of an investment project over its entire lifetime. Future costs and benefits are expressed in value of money today using a discount rate.

3.3 lists the assumed values regarding these cash outflows.

Table 3.3 Assumed values regarding cash outflows of various electricity generation technologies

		Technology			
Cost	**Unit**	**Nuclear**	**Solar**	**Wind (on-shore)**	**Wind (off-shore)**
Construction cost	€/kW installed	4230	750*	1125*	2160*
Fixed O&M cost	€/kW installed	90	32.4	55.8	157.5
Variable O&M cost	€/MWh produced	1.35	-	-	-
Fuel cost	€/MWh produced	9.00	-	-	-
Cost of waste	€/MWh produced	2.07	-	-	-
Decommissioning cost	% of construction cost	15*	5*	5*	5*

Notes:
All values come from OECD-NEA (2019), page 94, except the values indicated with an *, which come from IEA-NEA (2020). We assume an exchange rate of 0.90 Euro/USD.
The assumed values for the renewable energy technologies are relatively low compared to what is stated by Frauenhofer ISE (2021). That report states that the fixed costs per MW installed capacity are between 530 and 1600 for solar PV, between 1400 and 2000 for onshore wind and between 3000 and 4000 for offshore wind. The costs of Solar PV very much depend on the type of installation: large utility scale PV installations are about 50 percent less expensive than small rooftop installations.

Both for the construction cost and the decommissioning cost, nuclear power plants are more expensive than the power plants that use a renewable energy source. When comparing solar PV, onshore wind energy and offshore wind energy, we see that solar PV has the lowest (construction) costs (as we assume that the solar PV will be relatively large installations, but not utility scale), followed by onshore wind energy. In Section 6 we conduct a sensitivity analysis with respect to the construction cost of nuclear power to show the sensitivity of our results with respect to this parameter. Moreover, in Appendix D, we test the sensitivity of the results for the construction costs of solar PV.

For the cash inflows of the considered power plants, we include the revenues from selling the products. All considered power plants generate revenues by selling electricity on the electricity market. The electricity producers who use a renewable source (solar PV, onshore wind and offshore wind) also make revenues by selling green certificates. The prices of both electricity and green certificates are endogenous in our model, which means that they follow from demand and supply for each single hour.

When all cash inflows and outflows throughout a year are determined, the Net Present Value (NPV) of the revenues and expenditures over the lifetime of the installed capacity can be calculated. The decision rule for a single project is to accept a project if the NPV is at least positive . A positive NPV implies that the (discounted) cash inflows exceed the (discounted) cash outflows. If the NPV is negative the opposite is the case, implying that investors are not willing to invest in such power plants. Only if subsidies are given, the NPV of such a project can become positive and thus attract investors. In the remainder of this report, we calculate the subsidy level that is required to make the NPV non-negative. That is, the required subsidy is the difference between the annual operational profits and the annualized costs, if the latter exceed the former. We express this required subsidy per unit of production, which allows us to compare the various technologies.

In order to be able to calculate the NPV, we have to make assumptions regarding the lifetime, the construction duration, and the discount rate (WACC). Table 3.4 lists our assumptions. In Section 6 we also consider the sensitivity of our results with respect to these parameters.

Table 3.4 Assumptions regarding lifetime, construction duration and discount factor (WACC) of various electricity generation technologies

		Technology		
Parameter	**Unit**	**Nuclear**	**Solar**	**Wind (on- and offshore)**
WACC	%	7	7	7
Lifetime	Years	60	25	25
Construction duration	Years	7	1	1

Note: All values come from OECD-NEA (2019). In Section Section 6 we analyse the sensitivity of our results for alternative values for these parameters.

3.5 Definition of scenarios

This report assesses the economic value of nuclear power in future energy systems where we will have way more renewable capacity and also a higher electricity demand. As both the size of demand and the supply side of the electricity market in the future are unknown, we consider different scenarios. These scenarios differ in the share of renewable energy and the demand for electricity. The set of assumptions that are used for the model calibration is our departure scenario. In the remaining, we refer to this scenario as the *Baseline*-scenario. In the following, we describe the other scenarios that are considered. An overview of the assumptions that characterize the scenarios is shown in Table 3.5. The installed capacities of the different techniques are shown in columns 2 to 6, the seventh column shows the total yearly demand and the percentage increase compared to the departure scenario in parentheses.

We consider two alternative amounts of renewables in the future, which we call *Medium Renewables* and *High Renewables*. The two levels are based on climate policy targets set by the Dutch government. The *Medium Renewables*-level uses the targets as given in the Dutch Climate Agreement. For the *High Renewables*-level, we consider prospects on the amount of renewables in 2050. We use the scenario study of Berenschot and Kalavasta (2020) for the installed capacities of solar energy and wind energy. We combine this with the Noordzee Energie Outlook (Cleijne et al., 2020) to distinguish between on- and offshore wind energy.

For the capacity of gas-fired power plants we reason as follows. As the marginal costs of solar- and wind energy are lower than that of a gas-fired power plant, the increase of solar PV and wind energy leads to a reduction in the utilisation of gas-fired power plants. This reduces the revenues of these plants. We assume that, as a consequence of the decrease in revenues, the total capacity of gas-fired capacity will be reduced. The decrease in capacity increases the scarcity in the market, such that the electricity price increases (during hours at which the electricity price is higher than the marginal cost of gas-fired power plants) and, and as a result, the revenue per MW installed capacity gets back to its original level. We implicitly assume that there are no stranded assets and the market will find a new long-term equilibrium.

Table 3.5 Installed capacities per technology (MW) and increase in demand (%) per scenario

Scenario	Technology					Yearly load TWh (increase in %)
	Solar	Onshore wind	Offshore wind	Gas	Nuclear	
Baseline[B]	3937	3669	957	15570	486	113 (0%)
Medium Renewables- Low Increase Demand[M1]	14300	3700	11500	14000	486	120 (5.6%)
Medium Renewables- Medium Increase Demand[M2]	14300	3700	11500	16000	486	140 (23.5%)
Medium Renewables High Increase Demand[M3]	14300	3700	11500	21000	486	180 (59.8%)
High Renewables- Low Increase Demand[H1]	38000	11000	38000	11500	486	132 (16.7%)
High Renewables- High Increase Demand[H2]	38000	11000	38000	17000	486	180 (59.8%)

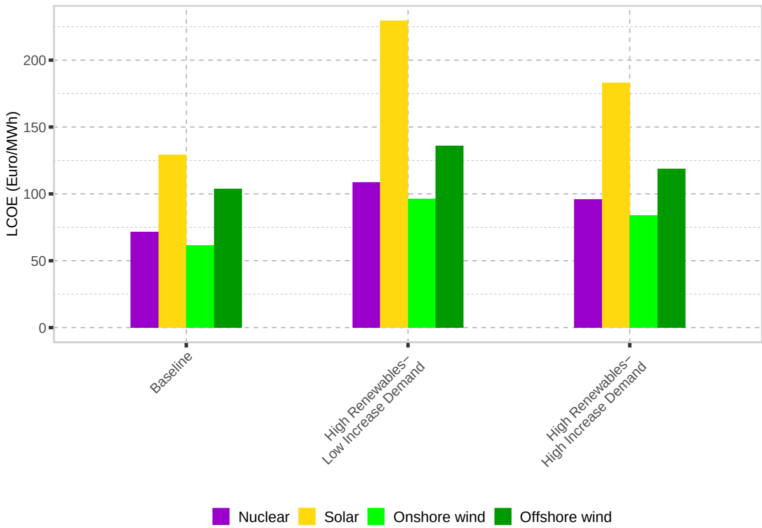
Notes:
B: Installed capacities and demand based on 2019 levels.
M1 : Installed capacities of renewables based on Climate Agreement, demand as in 2030 without extra electrification, see Moraga and Mulder (2018).
M2 : Installed capacities of renewables based on Climate Agreement, demand as in 2030 with extra electrification, see Moraga and Mulder (2018).
M3 : Installed capacities of renewables based on Climate Agreement, demand as in 2050 with extra electrification.
H1 : Installed capacities of renewables based on climate studies of Cleijne et al. (2020) and Berenschot and Kalavasta (2020), demand as in 2050 without extra electrification, see Moraga and Mulder (2018).
H2 : Installed capacities renewables based on climate studies of Cleijne et al. (2020) and Berenschot and Kalavasta (2020), demand as in 2050 with extra electrification, see Moraga and Mulder (2018).

Lastly, for the demand in future electricity systems we consider three cases. For the *Low Increase*-level of demand, we assume that the electricity consumption increases by 0.5% every year (Moraga and Mulder, 2018). Starting from 2019, this boils down to an increase of 5.6% and 16.7% in 2030 (*Medium Renewables- Low Increase Demand*) and 2050 (*High Renewables- Low Increase Demand*), respectively. The *Medium Increase*-level and *High Increase*-level are based on the scenario analysis of Moraga and Mulder (2018). Because of electrification in heating and transport, the demand for electricity further increases. Taking the demand of 2019 as a base, the increase is equal to 23.5% in 2030 (*Medium Renewables- Medium Increase Demand*) and equal to 59.8% in 2050 (*High Renewables- High Increase Demand*).

The above assumptions translate into a degree of utilisation of the various technologies per scenario. Based on these utilisation rates, we are able to calculate the so-called Levelized Costs of Energy (LCOE), which measures the present value of all costs during the lifetime of a plant divided by the present value of the production during that same period. Figure 3.4 shows the LCOE per technology in the baseline and for two scenarios. It appears that the resulting LCOE values for the *Baseline*-scenario are quite similar to what is published by others. Frauenhofer ISE (2021), for instance, reports values for the LCOE for onshore wind between about 40 and 80 euro/MWh (our baseline value is 60), for offshore wind between 70 and 120 euro/MWh (our baseline value is about 100) and for solar PV values between 35 and 110 euro/MWh (our baseline value is about 125). Only for solar PV our LCOE in the baseline is a bit higher, but this can be attributed to the lower capacity factor which we assume for the Netherlands (9 percent, while Frauenhofer ISE

(2021) takes about 11 percent for Germany). The assumed values for the investment costs per MW are fairly similar to what this author assumes. From Figure 3.4, we also learn that the LCOE very much depends on the expected future market circumstances. In a scenario with a high amount of renewables without a strong increase in electricity demand, the utilisation rate of all technologies go down, resulting in a higher LCOE. This holds also for wind and solar. Although their availability is determined by exogenous (weather) circumstances, the decisions regarding actual production is also related to market prices: if these prices are below their marginal costs, producers will not produce. In particular for renewables it holds that when the production circumstances are favourable (i.e. a lot of wind or sunshine), there may be so much production that prices become negative, which makes that some producers will stop producing until prices equal their marginal costs. In addition to this effect, in order to compare the business case of various technologies, one should not only look at the costs per unit of production, but also the prices which can be captured. Therefore, the technologies can only be fully assessed by analyzing them in the context of the (fluctuating) situations in the electricity market. That is why we have defined a number of policy scenarios which we analysed against the background of different scenarios.

Figure 3.4 Levelized Costs of Energy (LCOE) of the various technologies



3.6 Definition of policy variants

In order to properly assess the economic value of nuclear power, we compare the construction of a nuclear power plant with the construction of extra solar PV, onshore wind energy or offshore wind energy. We therefore consider different policy variants.

For each scenario, we consider a *Base*-policy variant. In this policy variant, no extra power plants are constructed (on top of the capacities mentioned in Table 3.5). Within each scenario, we consider a *More nuclear*-policy variant, in which we add a nuclear power plant with a capacity of 1000 MW. Similar to an increase in renewables, an extra nuclear-fired power plant reduces the revenues of gas-fired power plants by taking over part of the production and by lowering scarcity (and thus electricity prices). Again, in order to control for this and to take into account the long-term dynamics of electricity markets, we assume that the total capacity of gas-fired capacity will be reduced accordingly such that each unit of gas-fired capacity receives the same return as in our departure scenario.

Table 3.6 *Assumed increase* in installed capacities per policy variant, per scenario (MW)

	Policy Variant		
Scenario	**More solar**	**More onshore wind**	**More offshore wind**
Baseline	10110	3140	2330
Medium Renewables-Low Increase Demand	9890	3070	2340
Medium Renewables-Medium Increase Demand	10000	3100	2300
Medium Renewables-High Increase Demand	10110	3140	2330
High Renewables-Low Increase Demand	11400	3000	1900
High Renewables-High Increase Demand	9430	3140	1940

Note: The changes are based on the capacity factors of the different production techniques. Given the capacity factor of a nuclear power plant cf_N and the capacity of a renewable power plant cf_R this increase is calculated as 1000 MW $\times$ cf_N / cf_R.

In order to compare the investment in a nuclear power plant with investments in renewables, we also consider three policy variants where we increase the installed capacities of solar energy, onshore wind energy or offshore wind energy. Note that these increases are on top of the growth in renewables considered in the different scenarios. As the capacity factor of renewables is lower than the capacity of nuclear power, we consider an increase in renewable capacity that is higher than the 1000 MW we considered for nuclear power. For the *Baseline*, *Base*-policy variant, we find for example a capacity factor of 91% and 9% for nuclear power and solar power, respectively (which is in line with data from IEA (2019)). For this scenario, we therefor consider a policy variant with an increase of $1000 \times 0.91\%/9\% = 10{,}110$ MW of solar capacity. After adjusting the capacity of gas-fired capacities in the same way as mentioned above, we get a policy variant which we call the *More solar*-policy variant. Similarly, we define a *More onshore wind*-policy variant and a *More offshore wind*-policy variant for each of the considered scenarios. Table 3.6 shows the changes in installed capacity of the renewable electricity producers per policy variant and scenario.

4 Impact of a nuclear power plant

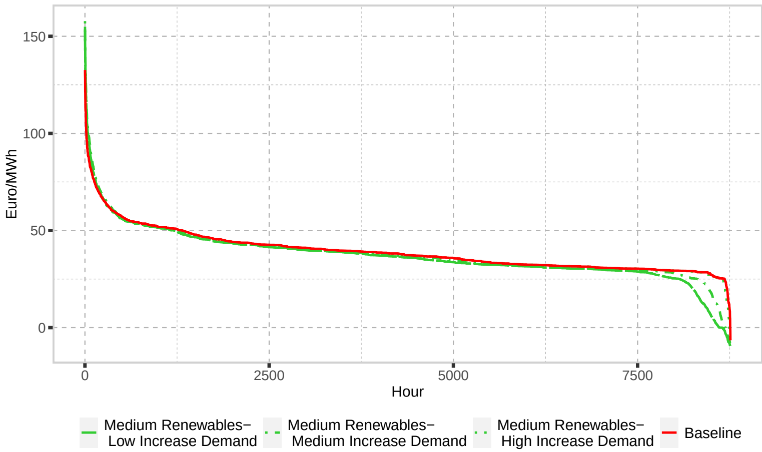
4.1 Introduction

In the following, we discuss the results of our analysis regarding the economics of nuclear power plants and the effect of nuclear power on the electricity system. First, we consider electricity prices in the *Base*-policy variant for all scenarios. Then, we subsequently discuss the effect of adding an extra power plant on electricity prices, electricity production, carbon emissions, welfare, required subsidy levels and abatement costs.

4.2 Electricity prices

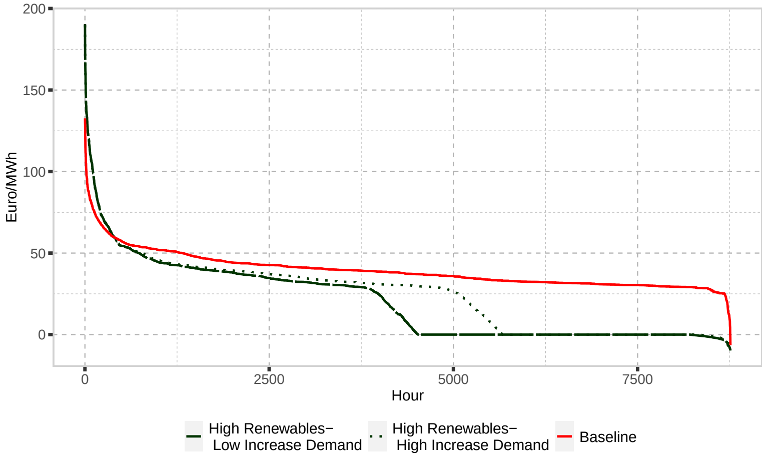
Figures 4.1 and 4.2 show the duration curves of the electricity price in different scenarios. Figure 4.1 compares the duration curves of the *Medium Renewables*-scenarios with different levels of electricity demand, and in Figure 4.2 the duration curves corresponding to scenarios with a *High Renewables*-level of installed capacities are shown.

Figure 4.1 Duration curves of electricity price in scenarios with *Medium Renewables* and various levels of electricity demand



In Figure 4.1, we observe that an increase in capacities of solar PV, onshore wind or offshore wind (and the decrease in capacity of gas-fired power plants) decreases electricity prices. Adding more of these renewable energy sources shifts the supply curve to the right, which further reduces the electricity price (at hours at which there is much solar energy and/or wind energy available). When we compare the duration curves within Figure 4.1, we see that the prices are reduced most in the *Low Increase Demand*-scenario and least in the *High Increase Demand*-scenario. Hence, it clearly follows from the model simulation that an increase in the demand for electricity shifts the demand curve to the right, such that the effect of the increase in renewable capacity on electricity price reduction is (partly) weakened.

Figure 4.2 Duration curves of electricity price in scenarios with *High Renewables* and various levels of electricity demand

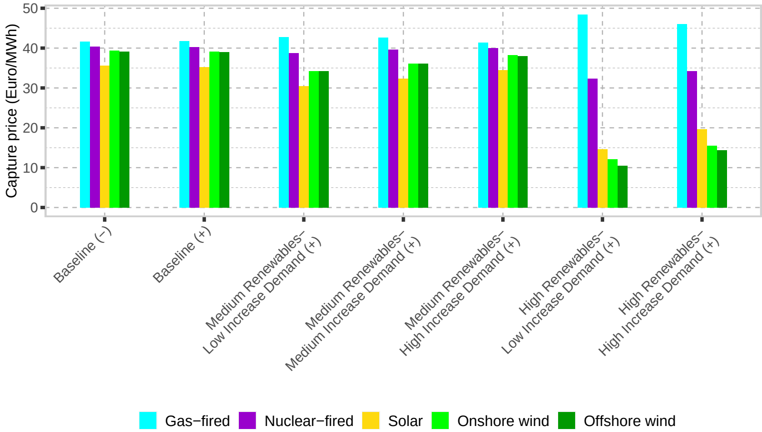


The results in Figure 4.2 are similar, but more extreme than in Figure 4.1. Due to the large increase of capacities of solar PV, onshore wind and offshore wind energy, electricity prices are now in general lower than in the departure scenario. Again, a relatively large increase in demand negates part of the price reduction.

Next, we consider the effect of the different scenarios on the different producers separately. The electricity price in our model is based on the principle of peak-load pricing. Renewable electricity producers have the lowest marginal costs of all producers, such that electricity prices will be lowest when these technologies are price-setting. Note that, due to the merit order, the hours with relatively low prices are thus the hours at which the production of renewable producers is relatively high. On the contrary, gas-fired power plants produce most when there is relatively little production from solar PV, onshore wind and offshore wind (and nuclear power plants). In these hours, prices are relatively high due to a) the higher marginal costs of gas-fired power plants and b) the relative scarcity in supply. As a consequence, electricity generated with solar PV, onshore wind and offshore wind is sold on average for a lower price per MWh than electricity produced by gas-fired power plants. The average price per MWh produced (the so-called capture price) of nuclear-fired power plants lies between the capture price of renewables and gas-fired power plants, following the merit order.

In Figure 4.3 we show how the capture price of the different technologies varies over the scenarios. For our departure scenario, we show the capture price both with (+) and without (-) an extra nuclear power plant. For the other scenarios, only the *More* *nuclear*-policy variant is considered.[7]

Figure 4.3 Capture price for different electricity producers for different scenarios/policy variants combinations



Note: *Base*-policy variant (-) and *More nuclear*-policy variant (+)

In the *Base*-policy variant of the *Baseline*-scenario, we observe that the capture price of solar PV, onshore wind and offshore wind is indeed lower than that of nuclear-fired power plants and gas-fired power plants. However, as the capacity of solar PV, onshore wind and offshore wind is relatively small in this scenario, the differences between the different producers are relatively small. At most hours, gas-fired power plants are price-setting, such that all producers (that produce during those hours) receive the relatively high electricity price. When we take a look at the *More nuclear*-policy variant for the same scenario, we see that the effect of adding a nuclear power plant is modest. As a nuclear-fired power plants replaces production of gas-fired power plants, which have higher marginal costs, the electricity price decreases. However, as the capacity of gas-fired power plants decreases because of the dynamics in the power market, this effect is largely nullified. For the other scenarios, the effect of adding a nuclear power plant is similar and, hence, negligible as well.

When we compare the different scenarios, we see that extra production by solar PV, onshore wind and offshore wind energy decreases the capture price of these power plants. In the *High Renewables- Low Increase Demand*-scenario this effect is most extreme. Compared to the departure scenario, the capture prices of solar, onshore wind and offshore wind energy reduce by more than 50%, 65% and 70%, respectively. In hours with favourable weather conditions, production of solar PV, onshore wind and offshore wind is so high that these plants become price-setting. As a consequence, the electricity

[7] Note that electricity producers that use solar PV, onshore wind and offshore wind also can sell green certificates. As a consequence, the capture price shown in Figure 4.3 is not the true price received by these power plants. In Section 5 we do consider both electricity- and green certificate prices.

price is rather low during these hours, which reduces the capture price of these power plants. We see that an increase in demand reduces the decrease in the electricity prices. Hence, increasing demand raises the captures prices for all technologies.

The capture price of gas-fired power plants increases when the number of renewables grows. Note that the capacity of the gas-fired power plants is such that the revenue per MW installed has a similar value as in the *Baseline*-scenario. When the number of renewables grows, part of the production of gas-fired power plants is taken over by these plants. As a consequence, in order to keep the revenue per MW installed at the same level, the capture price needs to increase. This is done by reducing the total capacity of gas-fired power plants, such that scarcity increases during hours at which there is little production from solar PV, onshore wind and offshore wind energy.

Similar to the capture price of the renewable electricity producers, the capture price of a nuclear power plant decreases when more solar PV, onshore wind and offshore wind is installed. During some hours, the nuclear fired power plant is the marginal producer, which leads to lower electricity prices. However, compared to solar PV, onshore wind and offshore wind energy, the decrease in the capture price is much smaller (20% in the most extreme scenario). This is caused by the fact that nuclear power plants can also produce during periods at which there is little solar- and wind energy available and the gas-fired power plants are price-setting (and prices are higher than they were). Hence, the capture prices of nuclear plants are less affected by a high share of renewables than the capture prices of renewables themselves.

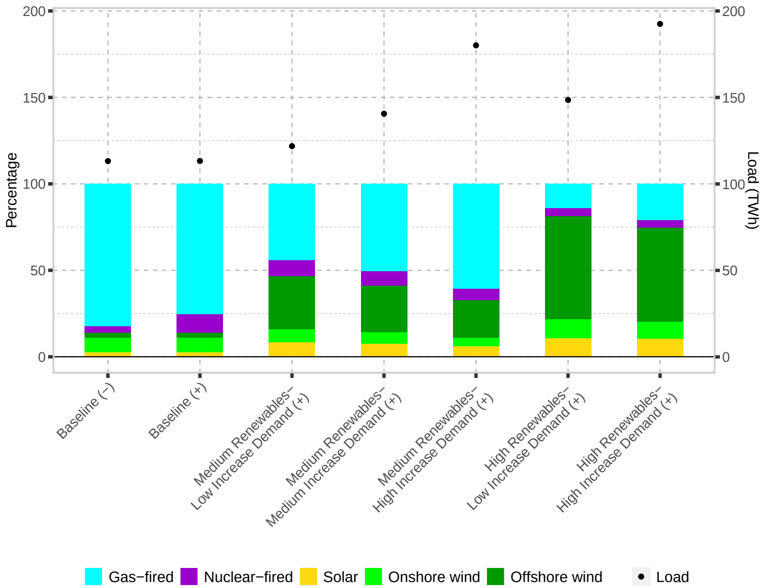
4.3 Electricity production

For the economic evaluation of investments, we not only need to look at the electricity prices, but also at the electricity production. The bars (left y-axis) in Figure 4.4 show the electricity generation mix in the different scenarios, separating the total electricity production by type of technology. Moreover, the dots (right y-axis) show the total yearly load per scenario-policy variant combination. For the *Baseline*-scenario, we show both the *Base*-policy variant (-) and the *More nuclear*-policy variant (+). For the other scenarios, we only consider the *More nuclear*-policy variant.

With the installed capacities as in 2019 (first bar), we see that the share of solar PV, onshore wind energy, offshore wind energy and nuclear power plant is relatively small. Most electricity is produced by gas-fired power plants. When a nuclear power plant is added in this scenario (second bar), the share of renewables remains similar. This is caused by the fact that these renewable plants have lowest marginal costs and remain infra-marginal suppliers. However, the marginal costs of gas-fired power plants are higher than those of nuclear power plants. The extra nuclear power plant therefore replaces part of the production by gas-fired power plants, such that the share of production of gas-fired power plants decreases when an extra nuclear power plant is added to the electricity system.

In the other scenarios, we see that the share of renewable energy producers becomes larger. Especially the share of offshore wind energy shows a large increase. The increase

Figure 4.4 Production mix and total yearly load (TWh) per scenario



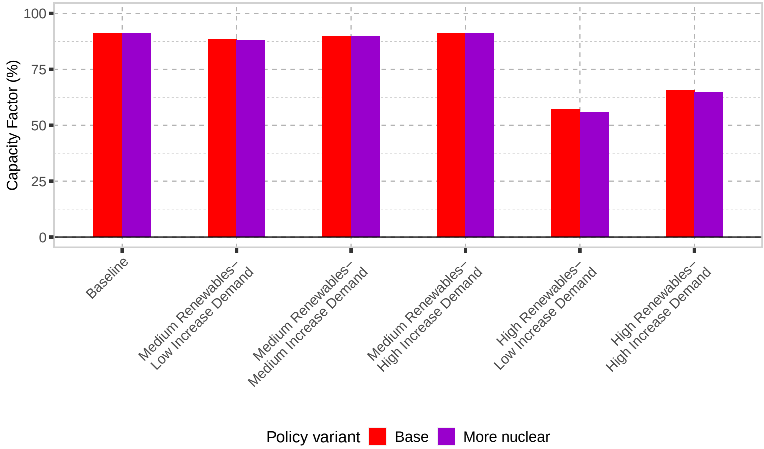
of the share of renewables reduces the share of gas-fired power plants. Compared to the *Baseline*-scenario with an extra nuclear power plant, the share of nuclear-fired power plants seems to decrease. This is caused by the fact that demand (and thus total load) is larger in the other scenarios. Moreover, the production of the nuclear-fired power plant decreases. Later in this section, we will come back to this.

When looking at the total load, we see that the load increases with the demand for electricity. Moreover, when we compare the total yearly load in the *High Renewables- High Increase Demand*-scenario and the *Medium Renewables- High Increase Demand*-scenario, we see that more electricity is produced (and consumed) when the capacity of solar PV, onshore wind and offshore wind energy increases. This is due to the fact that an increase in renewable production techniques leads to lower electricity prices and thus to a higher total load.

Next, we focus on the production by the nuclear power plants in the different scenarios. In Figure 4.5, we show how the capacity factor of a nuclear power plant changes between scenarios. The capacity factor is calculated as the ratio of actual (yearly) production and maximum (yearly) production and is expressed as a percentage. For all scenarios, we consider the *Base*-policy variant (red) and the *More nuclear*-policy variant (purple).

In the *Baseline*-scenario, the capacity factor of a nuclear power plant equals 91%. Note that this is an upper bound, as no electricity is produced in September due to a

Figure 4.5 Capacity factor of nuclear power plant, all scenarios



(assumed) planned outage. In this scenario, the capacity factor slightly decreases when an extra nuclear power plant is added. During hours when the nuclear power plant is the marginal producer, the increased available capacity of nuclear power does not result in an equal increase in nuclear production, which implies that the capacity factor of this technology declines.

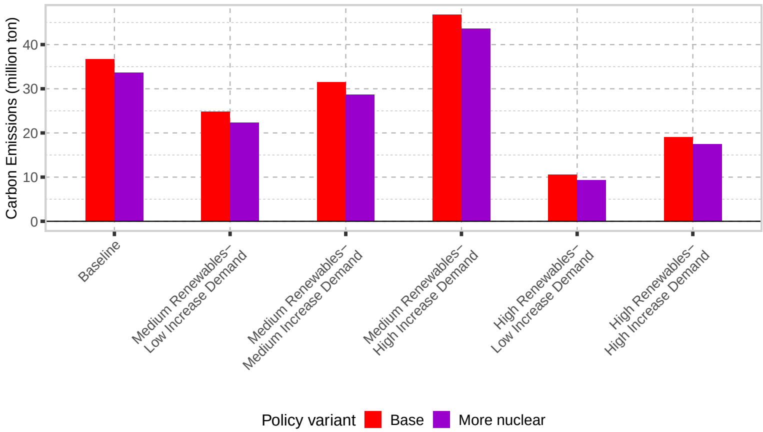
When the capacity of solar PV, onshore wind and offshore wind energy increases, there are more hours at which the production of these power plants is sufficient to satisfy demand. A nuclear power plant does not produce at its full capacity during these hours, such that its capacity factor decreases. When the amount of renewable capacity increases to the level of the *Medium Renewables*-scenarios, the capacity factor hardly decreases, or even stays at 91%, depending on the level of demand. In these scenarios, the production of solar PV, onshore wind and offshore wind energy is (at most hours) not sufficient to satisfy demand, such that nuclear power plants can still produce at their full capacity. Moreover, adding a nuclear power plant hardly changes the capacity factor in these scenarios.

However, when the amount of renewables increases further to the level of the *High Renewables*-scenarios, the capacity factor of the nuclear-fired power plant decreases substantially. In these (*High Renewables*-)scenarios, the capacity of solar PV and wind energy is sufficient to satisfy all demand in certain hours. At these hours, the nuclear power plant maximizes its revenues if it produces not at its full capacity. This results in an overall lower capacity factor. When the demand for electricity increases strongly, this effect is partly mitigated. In these scenarios with a relatively high share of solar PV, onshore wind and offshore wind, the negative effect of adding a nuclear power plant on the capacity factor is relatively large. However, compared to the differences between the scenarios, the effect remains small.

4.4 Carbon emissions

For the overall assessment of the economic value of adding a nuclear power plant, we also need to determine the effect on carbon emissions. These emissions are related to the production mix, total load and capacity factor of the different electricity technologies. Figure 4.6 shows the total yearly carbon emissions of the energy system in the considered scenarios, in the *Base*-policy variant (red) and the *More nuclear*-policy variant (purple).

Figure 4.6 Total carbon emissions per scenario, *base*-policy variant (red) and *More nuclear*-policy variant



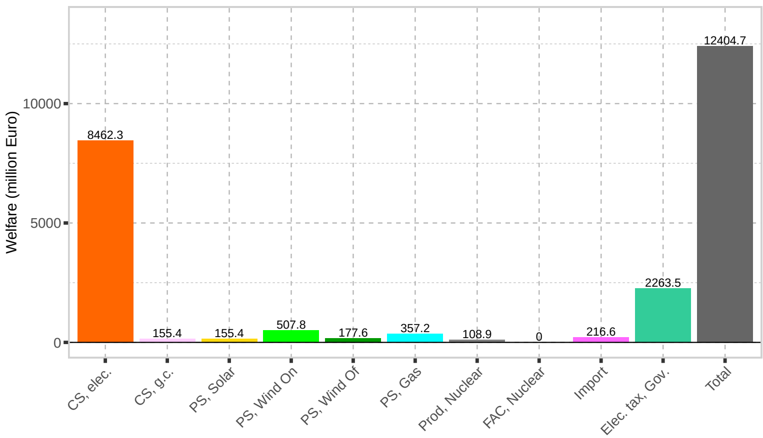
In Figure 4.6, we see how the total carbon emissions decrease when the size of installed capacity of solar PV, onshore wind energy and offshore wind energy grows. The renewable production techniques take over part of the production of gas-fired power plants, such that total carbon emissions decrease. On the other hand, we also see how the total carbon emissions increase when the demand for electricity is higher, as this implies that gas-fired power plants have to operate more often.

When we look at the policy variants within each scenario, we see that an extra nuclear power plant reduces carbon emissions in all considered scenarios. This is caused by a) the production by the extra nuclear power plant replacing production of gas-fired power plants and b) a reduction in the installed capacity of gas-fired power plants. We note that the reduction in the *Medium Renewables*-scenarios is larger than the reduction in the *High renewables*-scenarios. This is related to the decrease of the capacity factor of nuclear power plants we saw in Figure 4.5. When there is more solar PV, onshore wind and offshore wind energy installed, the capacity factor of nuclear power plants is relatively small. As a nuclear power plant replaces the production of gas-fired power plants, a lower production of nuclear-fired power plants implies a smaller reduction in the production of gas-fired power plants and thus a smaller reduction of carbon emissions.

4.5 Welfare

After looking at the supply side of the electricity market, we now consider the effect of a new nuclear power plant on the whole society by looking at welfare effects. In Figure 4.7, we show the welfare for different participants in the electricity market in the *Baseline*-scenario, without an extra nuclear power plant. We distinguish between electricity consumers, producers, an international trader and the government, while we also show the aggregated welfare effect. For the electricity consumers, we distinguish between a consumer surplus from consumption of electricity (*CS, elec.*) and a consumer surplus from consumption of green certificates (*CS, g.c.*). For each of the producers, the producer surplus (*PS*) is calculated as the difference between the yearly reveneus and total marginal costs due to producing and selling electricity. Note that the renewable electricity producers receive both the electricity price and the green-certificate price when they sell their electricity. The bar corresponding to *FAC, Nuclear* represents the Fixed Annual Costs that come with an extra nuclear-fired power plant (in the *Base*-policy variant it is thus equal to zero). The international trader (*Import*) generates welfare by trading electricity with foreign electricity markets. For each MWh consumed, electricity consumers have to pay an electricity tax to the government, (*Elec. tax, Gov.*). The last bar shows the total welfare, calculated as the sum of all other bars. We observe that the consumer surplus of consumers due to the consumption of electricity forms the largest part of the total welfare.

Figure 4.7 Annually aggregated welfare created in electricity market, over different groups in *Baseline*-scenario, *Base*-policy variant (million Euro)



Next, we investigate how the welfare in the *Base*-policy variant differs between the considered scenarios. In Table 4.1 we show again the annual aggregated welfare over the different groups. Note that all numbers are rounded.

Compared to the *Baseline*-scenario, total welfare increases in all other scenarios. To a great extent, the increase is caused by an increase in the consumer surplus from

Table 4.1 Annual operational welfare in electricity markets in groups per scenario, *base*-policy variant (million Euro)

	Scenario					
Renewables[1]	B	M	M	M	H	H
Demand[2]	-	L	M	H	L	H
Group						
CS, elec.	8462	9127	10373	13088	12446	15436
CS, g.c.	155	596	594	590	1233	1460
PS, Solar	155	410	448	498	312	505
PS, Wind On	508	382	416	457	257	382
PS, Wind Of	178	1611	1741	1897	1219	1919
PS, Gas	357	303	376	438	274	399
PS, Nuclear	109	101	105	107	49	62
FAC, Nuclear	0	0	0	0	0	0
International trader	217	198	206	228	569	460
Elec. tax, Gov.	2264	2429	2807	3601	2962	3841
Total	12405	15158	17066	20904	19321	24465

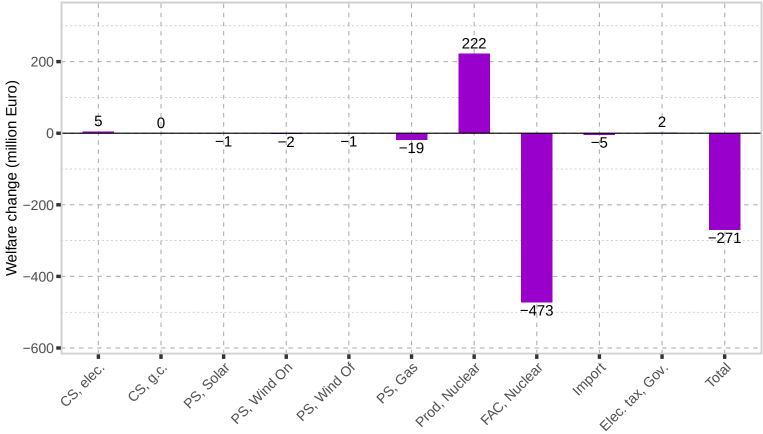
Notes:
1 : The level of renewables installed. 'B' = Baseline (2019 values), 'M'= Medium Renewables, 'H'= High Renewables.
2 : The increase of demand. '-' = No increase, 'L' = Low Increase, 'M' = Medium Decrease, 'H' = High Increase.

consumption of electricity. The increase in the consumer surplus is caused by a) an increase in total load (see Figure 4.4) and b) lower electricity prices (see Figures 4.1 and 4.2). Moreover, due to the increase in total electricity consumption, tax revenues of the government increase as well. The consumer surplus coming from consumption of green certificates also increases. For the producer surpluses of solar PV, onshore wind energy and offshore wind energy, we see a difference between the *Medium Renewables*- and *High Renewables*-scenarios. On the one hand, an increase in the installed capacities increases production, which has a positive effect on the producer surplus. On the other hand, the increase in installed capacities of solar PV, onshore wind and offshore wind energy lowers the capture price of these electricity producers, which affects the producer surplus negatively.

In the scenarios with *Medium Renewables*, the increase in installed capacities is larger than the reduction in (capture) prices, such that the overall effect on the producer surplus is positive. A further increase of installed capacities in the *High Renewables*-scenarios has a larger impact on capture prices, such that the relative increase is smaller. The producer surplus of gas-fired power plants stays approximately the same because their capacities are adjusted to keep the same return rate in different scenarios. For the nuclear-fired power plant, the producer surplus remains by and large the same in the *Medium Renewables*-scenarios. This is in line with previous results, which showed that the capacity factor and capture price of nuclear-fired power plants is not affected too much in these scenarios. In the *High Renewables*-scenario the producer surplus decreases, as both the capture price and the capacity factor become smaller. The international trader earns more profit in the *High Renewables*-scenarios as the price difference between the domestic market and the international market becomes larger.

Next, we investigate the effect of adding a nuclear power plant on the welfare distribution. Figure 4.8 shows such welfare effect in the *Baseline*-scenario. For most

Figure 4.8 Change in welfare in different groups due to adding a nuclear power plant, *Baseline*-scenario (million Euro)



groups the effect of the extra nuclear power plant is small. Due to slightly lower electricity prices, the consumer surplus of electricity shows a small increase, while the producer surplus of solar PV, onshore wind and offshore wind energy show a small decrease. Due to a reduction in gas-fired capacity, the producer surplus of gas-fired power plants decreases, though this effect is partly nullified by the higher capture prices. The producer surplus of nuclear power plants shows an increase due to the increase in production. This increase in producer surplus also contains the reduction in carbon emissions. The fixed annualized costs of the construction of a nuclear power plant are equal to 473 million Euro. As this cost is larger than the increase in the producer surplus of the nuclear-fired power plants and the other welfare effect are small, the total welfare effect of the construction of a nuclear power plant is negative.

We also show the effect of adding a nuclear power plant in the other scenarios in Table 4.2. For all scenarios, the effects of adding a nuclear power plant on the different groups are similar as we saw in the *Baseline*-scenario. The consumer surpluses show a (relatively) small increase, while the producer surpluses of solar PV, onshore wind, offshore wind and gas-fired power plants show a small decrease. These effects are largest in the *High Renewables*-scenarios. The producer surplus of nuclear-fired power plants increases, but the increase gets smaller as more solar PV, onshore wind and offshore wind power plants are installed. For all scenarios, the total welfare effects are negative. The welfare effect gets more negative as more solar PV, onshore wind and offshore wind power plants are installed and gets less negative when demand for electricity grows. This is in line with the results of the capacity factor and capture price of nuclear power plants discussed before.

Table 4.2 Change in operational welfare in electricity market due to extra nuclear power plant in groups per scenario, *base*-policy variant (million euro)

Renewables[1]	B	M	M	M	H	H
Demand[2]	-	L	M	H	L	H
Group						
CS, elec.	5	49	27	9	70	92
CS, g.c.	0	3	2	1	3	4
PS, Solar	-1	-9	-6	-4	-16	-20
PS, Wind On	-2	-8	-5	-2	-10	-15
PS, Wind Of	-1	-30	-18	-8	-57	-85
PS, Gas	-19	-17	-17	-13	-22	-20
PS, Nuclear	222	201	212	220	96	122
FAC, Nuclear	-473	-473	-473	-473	-473	-473
International trader	-5	-4	-5	-4	11	12
Elec. tax, Gov.	2	7	4	1	8	9
Total	-271	-280	-279	-274	-389	-374

Notes:
1 : The level of renewables installed. 'B' = Baseline (2019 values), 'M'= Medium Renewables, 'H'= High Renewables.
2 : The increase of demand. '-' = No increase, 'L' = Low Increase, 'M' = Medium Decrease, 'H' = High Increase.

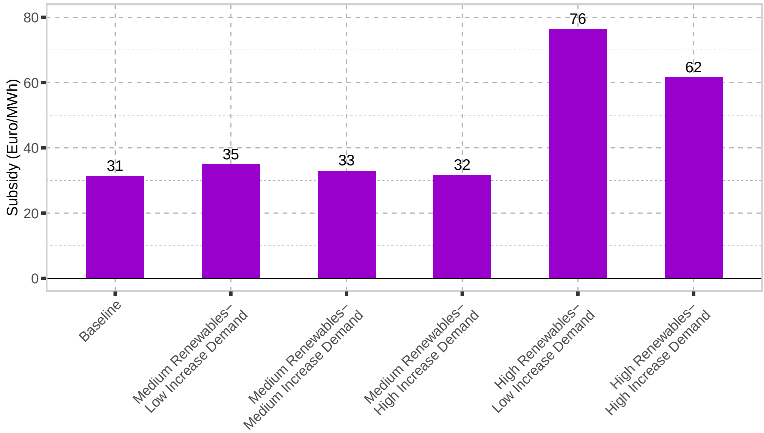
4.6 Required subsidy

Our key metric to assess the economics of adding a nuclear power plant to an electricity market with high shares of renewables and increasing demand is the subsidy required to make such an investment break even. In Figure 4.7 we considered the effect of adding a nuclear power plant on the welfare distribution in the departure scenario. We saw that the fixed annualized costs of a nuclear power plant are larger than the annual benefits, for all considered scenarios. Hence, we do not expect that commercial investors are willing to invest in a nuclear power plant. Only when subsidies are paid, the NPV of the investment in nuclear power can become non-negative and thus interesting for investors. In the following, we discuss the subsidy level that is required in order to make investing in a nuclear power plant break even. We express the subsidy level in euros per MWh produced.

In Figure 4.9, we show the required subsidy per MWh produced for all considered scenarios. The size of the required subsidy depends on the revenues of the nuclear power plant. The higher the revenues, the less subsidy is required. The revenues depend in turn on the capture price and the capacity factor of the nuclear power plant.

In our departure scenario, representing the Dutch electricity market in 2019, the required subsidy level equals 31 Euro/MWh. That is, in this scenario, in order for a nuclear power plant to break even, a subsidy of 31 Euro is required for every MWh of production. When the installed capacity of solar PV, onshore wind and offshore increases to the level of the *Medium Renewables*-scenarios, the required subsidy level approximately stays the same. This is in line with Figures 4.3 and 4.5, where we showed the capture price and capacity factor of a nuclear power plant in the different scenarios. Combined with the increase in demand, the modest increase in renewable installed capacity leads to a similar capture price and capacity factor as in the departure scenario. As the fixed annual costs do not depend on the revenues, the required level of subsidy is therefore also

Figure 4.9 Required subsidy level per MWh produced to make the NPV of an investment in a nuclear power plant nonnegative, per scenario (Euro/MWh)



similar between these scenarios. Within the *Medium Renewables*-scenarios, the required subsidy level is highest when the increase in demand is lowest.

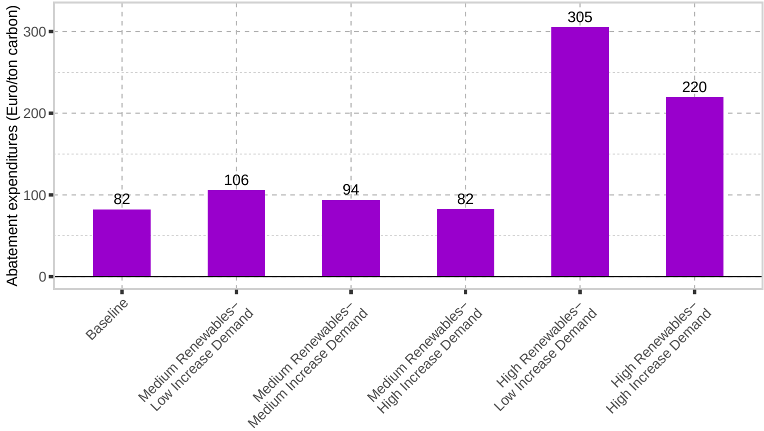
When, however, the increase in renewables is as large as in the *High Renewables*-scenarios, the subsidy per MWh produced is substantially higher. In the most extreme scenario, the required subsidy level equals 76 Euro/MWh, which is 145% higher than in the departure scenario. The increase is explained by a) the lower capture price and b) the decrease in the capacity factor of the nuclear power plant caused by the increase in installed capacities of solar PV, onshore wind and offshore wind. Both lead to a decrease in revenues, which has to be compensated by a larger amount of subsidy. Moreover, due to the lower capacity factor, the subsidy is divided over a smaller level of production, such that the subsidy per MWh produced further increases.

4.7 Abatement cost

The addition of a nuclear power plant to the electricity market leads to a reduction in the production by gas-fired power plants. As nuclear power plants do not emit carbon during the production of electricity, an extra nuclear power plants leads to lower carbon emissions. In the previous subsection we saw that subsidy is required in order to attract investors. Therefore, we can calculate and compare the so-called abatement cost of carbon, expressed in Euro/ton carbon. The abatement cost is calculated as the ratio of the total costs and the reduction in carbon emissions. First, we only consider the required subsidy level (abatement expenditures). Then, we also take into account other welfare effects (social abatement costs).

In Figure 4.10, we show the abatement expenditures of a nuclear power plant in the

Figure 4.10 Abatement expenditures of a nuclear power plant for the different scenarios (based on subsidy only)



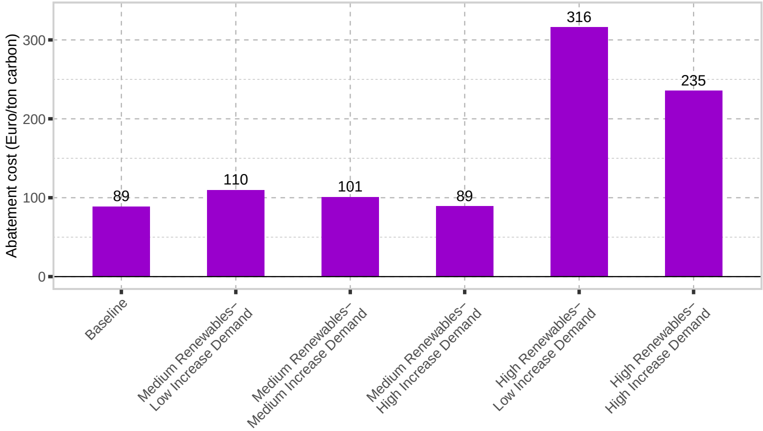
different scenarios, only by looking at the subsidy that is required to make the nuclear power plant break even. In the first bar of Figure 4.10, we find abatement expenditures of 82 Euro/ton carbon. That is, in the Dutch electricity system of 2019, the cost of reducing one ton of carbon emissions by constructing a nuclear power plant equals 82 Euro. Again, an increase of renewables as in the *Medium Renewables*-scenarios gives similar abatement expenditures. We note, however, that the (relative) differences are larger than in Figure 4.9, where we looked at the required subsidy level. This can be explained by looking at Figure 4.6, where we compare the (reduction of) carbon emissions in the different scenarios. Both in the *Low Increase Demand*- and *Medium Increase Demand*-scenario, the reduction in carbon emissions is smaller than in the departure scenario. Even though the required subsidy in these scenarios is similar, this difference in carbon reduction leads to higher abatement expenditures.

When we look at the *High Renewables*-scenarios, we see that the abatement expenditures of carbon are much higher than in the other scenarios. In the most extreme scenario, we find abatement expenditures equal to 305 Euro/ton carbon, an increase of 270% compared to the *Baseline*-scenario. The large increase in abatement expenditures is explained by a) the higher required subsidy level as shown in Figure 4.9 and b) the smaller reduction in carbon emissions displayed in Figure 4.6.

In Figure 4.11, we show the social abatement cost of a nuclear power plant in the different scenarios by looking at total welfare effects. That is, we also take into account the effect on consumer surplus, producer surplus of other producers, government electricity tax and the profit of the international trader when calculating the abatement costs.

The results are similar as in Figure 4.10, where we only considered the required subsidy level of the nuclear power plant. This is in line with Table 4.2, where we

Figure 4.11 Influence of nuclear energy on social abatement cost (based on total welfare)



saw that the surpluses of consumers, other electricity producers, international trader and government are hardly affected by the introduction of a new nuclear power plant. Overall, the social abatement costs in Figure 4.11 are slightly higher than the abatement expenditures in Figure 4.10. As the overall decrease in producers surpluses is larger than the increase in consumer surplus, abatement costs based on total welfare are higher than abatement costs that are based on required subsidy only. However, the difference is small.

5 Comparing more nuclear with more solar or more wind capacity

5.1 Introduction

In the previous section, we discussed the investment in a nuclear power plant and the economic effects of adding a nuclear power plant to the Dutch electricity system. In this section, we compare the investment in a nuclear power plant with the investment in solar PV, onshore wind and offshore wind in terms of required subsidies and abatement expenditures of carbon. Therefore, we repeat the analysis of the *More nuclear*-policy variant for the *More solar-*, *More onshore wind-* and *More offshore wind* policy variants. First, we look at the capture price and capacity factor of the different techniques in the different scenarios and policy variants. Then, we compare the subsidy levels that are required. Finally, we look at the abatement expenditures of the various electricity generation techniques.

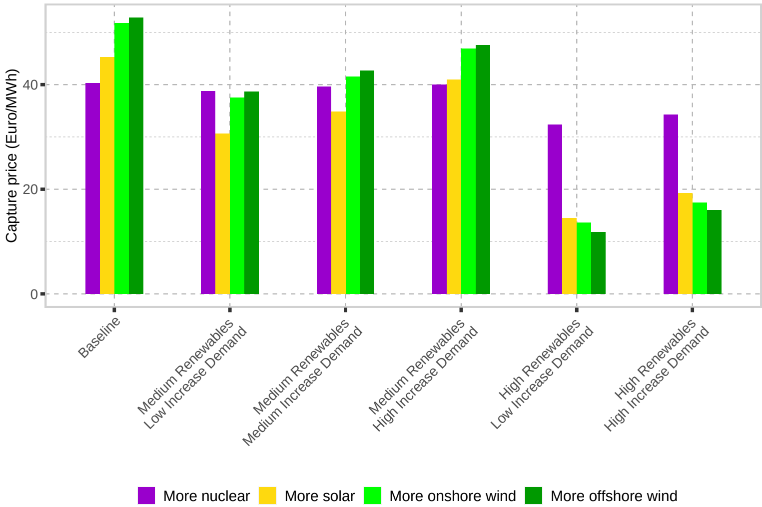
5.2 Capture price and capacity factor

Figure 5.1 shows how the capture price of nuclear power, solar PV, onshore wind energy and offshore wind energy changes over the different scenarios. This time, we add the 'capture price of green certificates' for solar PV, onshore wind and offshore wind energy. The capture price for renewable producers in Figure 5.1 is the sum of electricity and green certificate prices. For each technique, the bars in Figure 5.1 show the corresponding policy variant. That is, the *More nuclear*-bars shows the capture price of a nuclear power plant in the *More nuclear*-policy variants in the different scenarios. The other bars are defined in a similar way.

In the *Baseline*-scenario, the capture price of nuclear power is the lowest of the four considered electricity producers. The difference with Figure 4.3, where the capture price of nuclear power plants is the highest, is explained by the fact that we now add the price of green certificates for solar PV, onshore and offshore wind energy.

When we look at the other scenarios, we see that the capture price of nuclear power is more stable than that of the other electricity producers. Especially in the *High Renewables*-scenarios, the decrease of the capture price of solar PV, onshore wind and offshore wind is much larger than that of nuclear power. This can be explained by the large increase of capacity of solar PV, onshore wind and offshore wind energy and the decrease in gas-fired capacity. In hours at which there is much solar- and wind energy available, production of solar PV, onshore wind and offshore wind will be high, which leads to relatively low electricity- and green certificate prices. As a consequence, the capture price of solar PV, onshore wind and offshore wind decreases. However, during hours at which there is little solar- and wind energy available, the decrease in gas-fired capacity leads to scarcity and thus to higher electricity prices. As nuclear power plants can also produce during these hours, they can benefit from these relatively high prices.

Figure 5.1 Capture price per technology for different scenarios/policy variants (Euro/MWh)



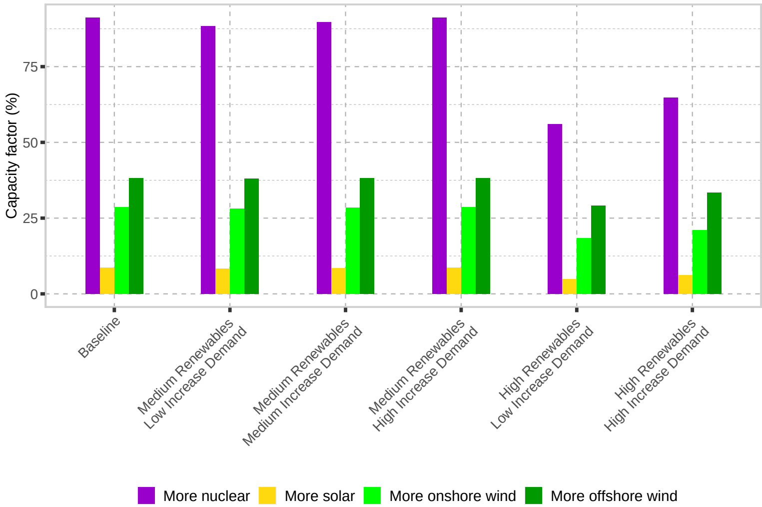
Notes:
Each color shows the capture price for technology X in the *More X*-policy variant, X = *Nuclear*, *Solar*, *Onshore wind*, *Offshore wind*.
For solar PV, onshore wind and offshore wind, the capture price contains both the electricity price as the green-certificate price.

Next, we look at the capacity factor of the four techniques. The bars in Figure 5.2 match again the techniques with their corresponding policy variants.

In the *Baseline*-scenario, the capacity factors of all four power plants are equal to their maximum availability level (see Appendix B). In the *Medium Renewables*-scenarios, only the capacity factor of the nuclear power plant shows a small decrease. This is caused by the merit order, which prioritizes the production of solar PV, onshore wind energy and offshore wind energy over the production of nuclear power. In these scenarios, the total hourly supply of solar PV, onshore wind and offshore wind is in general lower than the hourly demand, such that they can produce whenever energy is available. There are, however, (a few) hours at which the combined production of solar PV, onshore offshore wind wind and nuclear power plants exceed demand, such that the production of the nuclear power plant is diminished in order to prevent production against prices that are lower than the marginal costs.

However, when the installed capacities of solar PV, onshore wind and offshore wind further increase to the level described in the *High Renewables*-scenarios, also the capacity factors of these renewable producers decrease. During some hours, the available production of solar PV, onshore wind and/or offshore wind exceeds demand, such that production of these producers is reduced to prevent production against negative prices.

Figure 5.2 Capacity factor per technology for different scenarios/policy variants (Euro/MWh)



Note: Each color shows the capacity factor for technology X in the *More X*-policy variant, X = *Nuclear*, *Solar*, *Onshore wind*, *Offshore wind*

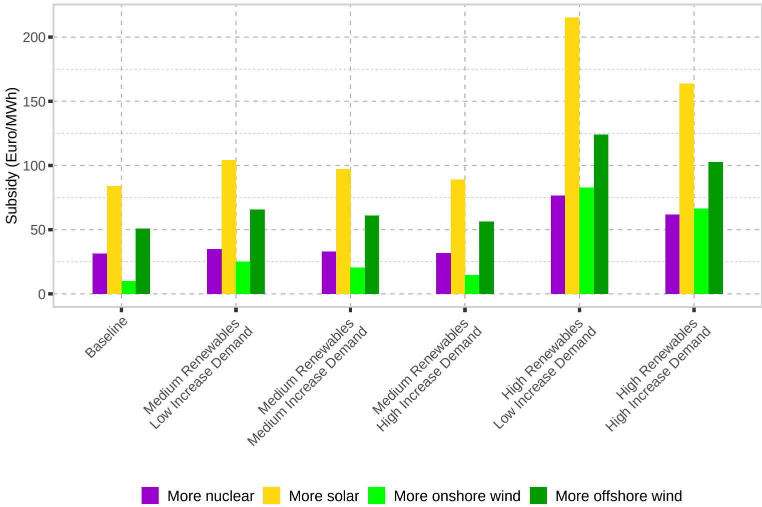
For the same reason, the capacity factor of nuclear power plants decreases in the *High Renewables*-scenarios. In absolute terms, the decrease of the capacity factor of nuclear power is largest. However, the relative decrease is similar to that of solar PV, onshore wind energy and offshore wind energy.

5.3 Required subsidy

With the information regarding the capacity factor and capture prices of nuclear power, solar PV, onshore wind and offshore wind energy, we now calculate the required levels of subsidy. Similar to Section 4, we calculate both the fixed annualized costs (based on the assumptions made in Tables 3.3 and 3.4) and the annual profits. If the former exceed the latter, the required subsidy level is calculated as the difference between the two. Again, we express the subsidy level in terms of MWh produced. Figure 5.3 shows the required subsidy levels for the considered power plants in all scenarios. The bars match the technique with the corresponding policy variant.

In the *Baseline*-scenario, onshore wind energy requires least subsidy to break even (10 Euro/MWh), followed by nuclear power (31 Euro/MWh), offshore wind energy (51 Euro/MWh) and solar PV (81 Euro/MWh). Despite the fact that the costs per MW of solar PV are much lower than that of nuclear power, the required subsidy level is much higher. This is mainly affected by the low capacity factor of solar PV, which is (in this scenario) only 10% of the capacity factor of nuclear power. First of all, this relatively

Figure 5.3 Required subsidy per technology for different scenarios/policy variants (Euro/MWh)



Note: Each color shows the required subsidy for technology X in the *More X*-policy variant, X = *Nuclear*, *Solar*, *Onshore wind*, *Offshore wind*

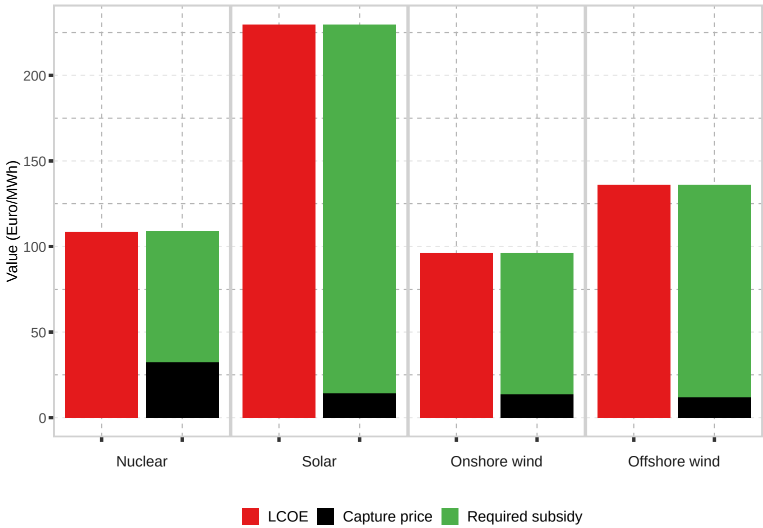
small capacity factor implies that the revenues per MW installed are lower for solar PV, such that a higher level of subsidy is required. Moreover, the subsidy level is divided over a smaller number of MWhs, increasing the required subsidy level (which is expressed per MWh produced). The same line of reasoning holds for offshore wind energy. However, as the capacity factor of offshore wind energy is larger than that of solar PV, the difference in required subsidy with nuclear power is smaller. Only onshore wind energy requires a smaller subsidy level in order to break even. Even though the capacity factor of onshore wind is lower than that of offshore wind, the construction cost of onshore wind is much lower, such that at the end less subsidy is required.

In Section 4, we saw how the required subsidy level of nuclear power increases as the installed capacities of solar PV, onshore wind energy and offshore wind energy increases, due to a decrease in the capture price and capacity factor. On the other hand, an increase in demand lowers the subsidy required, as it increases revenues. From Figure 5.3, we observe that the same applies to the required subsidy of solar PV, onshore wind and offshore wind. In fact, the reaction of the required subsidy level of these power plants to changes in supply and demand is stronger than that of nuclear power. This is in line with Figure 5.1, where we saw that the capture price of nuclear power differs less between the scenarios than the capture price of solar PV, onshore wind and offshore wind. Over all scenarios, the subsidy level required by solar PV and offshore wind exceeds that of nuclear power. Moreover, in the *High Renewables*-scenarios, even onshore wind energy requires a higher level of subsidy than nuclear power, such that nuclear power becomes the least expensive in terms of required subsidy per MWh produced.

5.4 LCOE, capture price and required subsidy

Above, we have shown that the required subsidy is directly related to the capture price: the higher (lower) the capture price, the less (more) subsidy is required to make an investment break even. This also implies that the sum of capture price and required subsidy are, by definition, equal to the total lifetime costs per unit, i.e. the Levelized Costs of Energy (LCOE). Figure 5.4 shows the contribution of both capture price and required subsidy to cover the LCOE for the various technologies in the scenario *High Renewables-Low Increase Demand*. It appears that for nuclear the contribution of the capture price is the largest, both in absolute and in relative sense, while solar PV is almost full dependent on subsidy in this scenario.

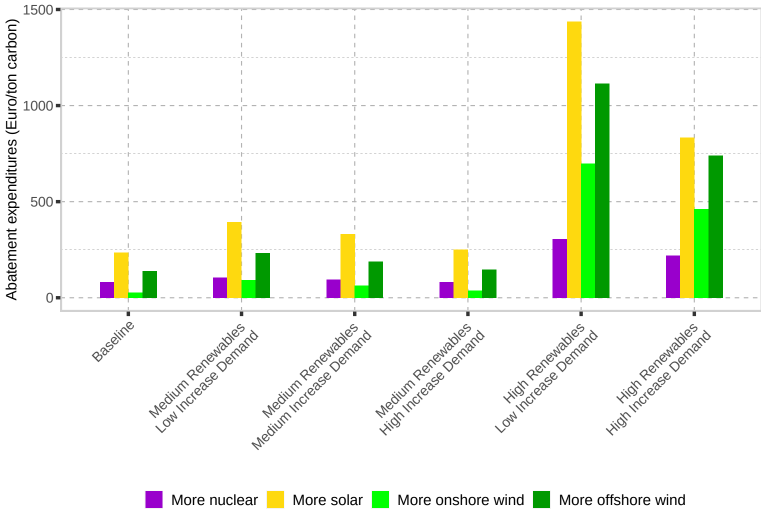
Figure 5.4 Contribution of capture price and required subsidy to cover the LCOE per technology in the *High Renewables- Low Increase Demand* scenario



5.5 Abatement expenditures

Next, we look at the abatement expenditures, or the cost of reducing carbon emissions by installing a nuclear power plant, solar PV installation, onshore wind energy turbine or offshore wind turbine. Similar to Section 4, we calculate the abatement expenditures as the ratio of total subsidy and the reduction in carbon emissions. Figure 5.5 shows the abatement expenditures of nuclear power, solar PV, onshore wind and offshore wind by looking at the subsidy that is required to make them break even. The abatement costs of the technologies that are based on the total welfare effects (social abatement costs) are not shown here, as the results are similar.

Figure 5.5 Abatement expenditures based on required subsidy per technology for different scenarios/policy variants (Euro/ton carbon)



Note: Each color shows the abatement expenditures for technology *X* in the *More X*-policy variant, *X = Nuclear*, *Solar*, *Onshore wind*, *Offshore wind*

In the *Baseline*-scenario, onshore wind energy has the lowest abatement expenditures (27 Euro/ton), followed by nuclear power (82 Euro/ton), offshore wind energy (141 Euro/ton) and solar PV (236 Euro/ton). As all considered power plants lead to a similar reduction in production of gas-fired power plants and thus to a reduction of carbon emissions, the abatement expenditures show the same ordering as in Figure 5.3, where we showed the required level of subsidy for the different power plants.

Just as the abatement expenditures of nuclear power, the abatement expenditures of solar PV, onshore wind and offshore wind increase as their installed capacities get larger. On the other hand, the abatement expenditures decrease when the demand for electricity increases. Both the increase and decrease can be explained by looking at the effect on the capacity factor, capture price and reduction in carbon emissions. The line of reasoning is the same as in Section 4.7.

In the *High Renewables*-scenarios, the abatement expenditures increase substantially compared to the other scenarios. The increase is relatively large for solar PV, onshore wind and offshore wind. In the most extreme scenario, the abatement expenditures of solar PV, onshore wind and offshore are equal to 1438, 698, and 1116 Euro/ton carbon, while the abatement expenditures of nuclear power is 305 Euro/ton carbon. This in in line with Figure 5.3, where we saw that nuclear power requires least subsidy in these scenarios.

6 Sensitivity Analysis

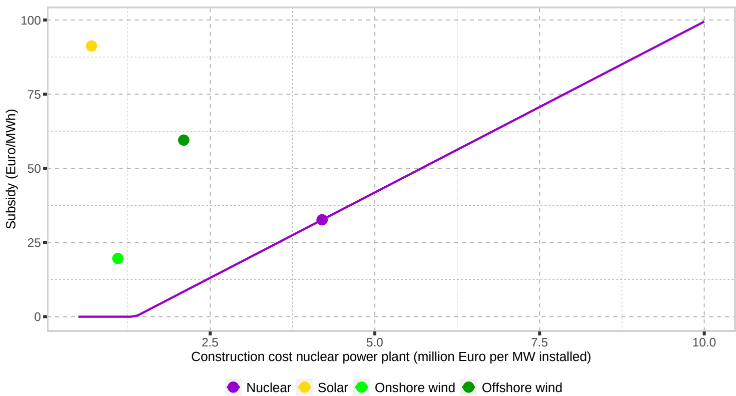
6.1 Introduction

In this section, we first test the sensitivity of our results with respect to the construction cost, lifetime, construction time and discount factor. We only show the results for the *Medium Renewables- Medium Increase Demand*-scenario. For the other scenarios, the results are similar.
We also consider the effect of more flexibility, as well as the effect of higher gas- and carbon prices on the required subsidy levels for all considered scenarios.

6.2 Construction cost

The construction cost is an important cash flow at the start of the capital-intensive project of building a power plant. Given revenues from selling electricity (and green certificates), a higher construction cost requires a higher subsidy in order to find a non-negative NPV. In our analysis, using external data sources, we assume that the construction cost (per MW installed) is highest for nuclear power plants, followed by offshore and onshore wind energy and is lowest for solar energy. Figure 6.1 shows the effect of the construction cost of a nuclear power plant on the required subsidy per MWh produced in the *Medium Renewables- Medium Increase Demand*-scenario. The yellow, light-green and dark-green dots represent the assumed construction cost and corresponding required subsidy per MWh produced of solar PV, onshore wind energy and offshore wind energy, respectively.

Figure 6.1 Sensitivity of required subsidy per MWh produced w.r.t. construction cost of nuclear power plant, Medium Renewables- Medium Increase Demand



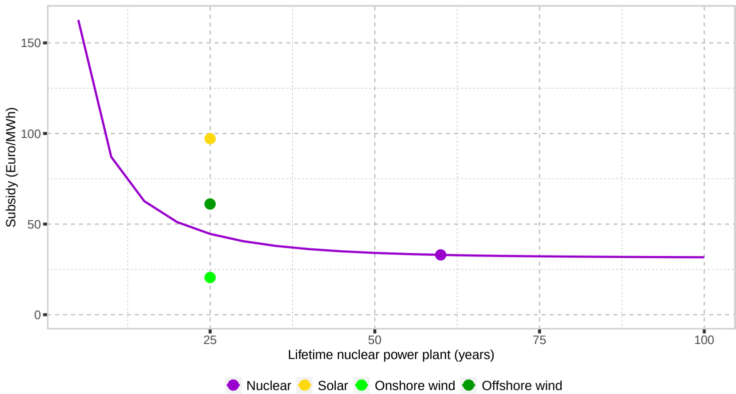
Note: The dots represent the level of assumed construction cost and corresponding required subsidy per MWh produced of solar PV, onshore wind energy and offshore wind energy and nuclear energy. The line shows the sensitivity of the required subsidy per MWh produced w.r.t. construction cost of nuclear power plant

From Figure 6.1, we observe how the required subsidy of nuclear power increases with the construction cost. With the initial set of assumptions, the required subsidy per MWh installed is lowest for onshore wind energy, followed by nuclear energy, offshore wind energy and solar energy. When the construction cost of a nuclear power plant is lower than 1.3 million per MW installed capacity (which is significantly below what is our baseline assumption), there is no subsidy required. In this situation, the revenues are high enough to compensate for the costs. If we consider higher construction costs for a nuclear power plant, we see that the required subsidy for a nuclear power plant exceeds that of offshore wind energy when the construction cost becomes larger than 6 million Euro per MW installed. Only when the construction cost exceeds 8 million Euro per MW installed, the required subsidy of nuclear power exceeds the required subsidy of solar energy. This implies that the economic feasibility of an investment in a nuclear power plants is very strongly related to the magnitude of the construction costs.

6.3 Lifetime

For a nuclear power plant, most costs (negative cashflows) are faced before production starts, while revenues (positive cashflows) are generated as long as the power plant is operating. As a consequence, a higher lifetime gives a longer period of revenues and thus lowers the amount of subsidy that is required. In Figure 6.2, we show the effect of the lifetime of a nuclear power plant on the required subsidy per MWh produced in the *Medium Renewables- Medium Increase Demand*-scenario. The dots indicate the initial set of assumptions.

Figure 6.2 Sensitivity of required subsidy per MWh produced w.r.t. lifetime nuclear power plant, Medium Renewables- Medium Increase Demand



Note: The dots represent the level of assumed lifetime and corresponding required subsidy per MWh produced of solar PV, onshore wind energy and offshore wind energy and nuclear energy. The line shows the sensitivity of the required subsidy per MWh produced w.r.t. lifetime of nuclear power plant

We observe how the required subsidy level decreases when the lifetime of a nuclear power plant increases. The decrease becomes smaller as the lifetime increases. This is explained by the discount factor that is used to weigh future cash flows. Due to this discounting, future cash flows have a smaller influence on the NPV than current cash flows.

When we compare the required subsidy level of nuclear energy with that of the renewable energy sources, we see that the required subsidy of nuclear energy is higher than that of onshore wind-energy, regardless of the lifetime of the nuclear power plant. When the lifetime of a nuclear power plant is 25 years and thus equal to the lifetime of the renewable power plants, the required subsidy for nuclear power is still lower than that of offshore wind energy and solar energy, though the difference with offshore energy is small. Only when the lifetime of the nuclear power plant becomes lower than 10 years, its required subsidy level exceeds that of solar energy.

6.4 Construction time

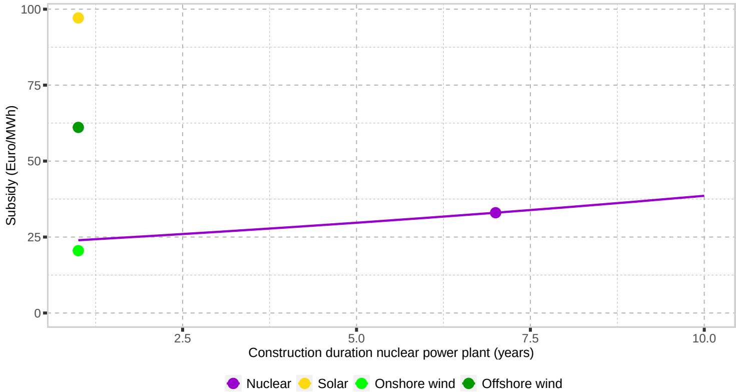
The length of the construction of a nuclear power plant affects the NPV of a nuclear power plant in both a positive and a negative way. On the one hand, a longer construction period implies that the construction costs are spread over a longer period of time. As a consequence, the total (discounted) construction costs get lower, resulting in a higher NPV. At the same time, a longer construction period delays the moment at which the power plant starts producing electricity. The revenues are therefore discounted more severe, such that the NPV decreases. In Figure 6.3, we show the overall effect of the construction time of a nuclear power plant on the required subsidy per MWh produced in the *Medium Renewables- Medium Increase Demand*-scenario. The dots indicate the initial set of assumptions.

From Figure 6.3, we see that the negative effect of an increase in the construction period is stronger than the positive effect, such that a higher level of subsidy is required to break-even. The effect is however modest: a change in the construction time does not change the required subsidy level much. For all considered lengths of the construction period, the required subsidy for nuclear power is lower than that of offshore wind energy and solar PV and exceeds the required subsidy of onshore wind energy.

6.5 Discount factor (WACC)

The discount factor is the factor by which a future cash flow is multiplied in order to obtain its present value. For (nuclear) power plants, most costs (negative cash flows) are incurred at the start of the project, while revenues (positive cash flows) are incurred at a later stage. A higher discount factor makes future cash flows smaller in terms of present value (in absolute sense). As a consequence, for the construction of a power plant, a higher discount rate comes with a higher required level of subsidy. In Figure 6.4, we show the effect of the discount factor on the required subsidy level. We do this not only for nuclear power plants, but also for solar PV, onshore wind energy and offshore wind energy. The dots indicate the initial set of assumptions.

Figure 6.3 Sensitivity of required subsidy per MWh produced w.r.t. construction time nuclear power plant, Medium Renewables- Medium Increase Demand

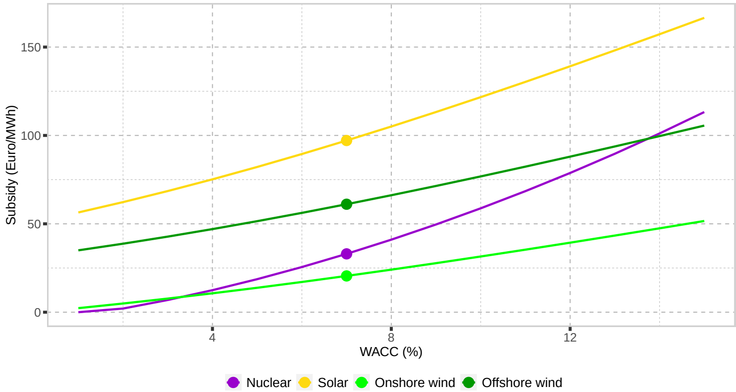


Note: The dots represent the level of assumed construction time and corresponding required subsidy per MWh produced of solar PV, onshore wind energy and offshore wind energy and nuclear energy. The line shows the sensitivity of the required subsidy per MWh produced w.r.t. construction time of nuclear power plant

From Figure 6.4, we can see that the required subsidy level of all considered producers increases with the discount factor, but that this effect is the strongest for nuclear power. This is explained by the fact that the lifetime of a nuclear power plant is much longer than the one of the other technologies. As a consequence, revenues are made during a relatively long period of time, such that a change in the discount factor has a relatively large effect on the NPV.

Overall, the original ordering of the required subsidies (lowest for onshore wind energy, followed by nuclear energy, offshore wind energy, highest for solar energy) remains the same for the considered range of discount factors. Only for discount factors exceeding 12%, the required subsidy of nuclear energy exceeds that of offshore wind offshore. On the other hand, the discount factor should decrease below 3% before nuclear power requires less subsidy than onshore wind energy.

Figure 6.4 Sensitivity of required subsidy per MWh produced w.r.t. discount factor, Medium Renewables- Medium Increase Demand



Note: The dots represent the level of assumed discount factor and corresponding required subsidy per MWh produced of solar PV, onshore wind energy and offshore wind energy and nuclear energy. The lines shows the sensitivity of the required subsidy per MWh produced w.r.t. discount factor of all considered power plants

6.6 Flexibility within electricity market

In electricity markets, the fluctuations in the electricity price partly depend on the ability of producers and consumers to respond to changing market circumstances. In the above analysis, we included several sources of flexibility, as gas-fired power plants, nuclear power plants, solar PV, onshore wind energy and offshore wind energy, and also demand and international trade respond to changes in market prices. In the following, we test the sensitivity of the model results for the flexibility by looking at a) a higher price elasticity of demand for electricity and b) more cross-border transmission capacity. Because of an increased interest in devices that can store electricity (e.g. batteries) and devices that can actively anticipate to changes in electricity prices (e.g. smart grids), it is expected that the demand for electricity will become more flexible in future electricity systems.

The flexibility of the demand for electricity can be expressed through the price elasticity, which is generally negative: when prices increase, demand increases and vice versa. The price elasticity of demand indicates how fast the demand for electricity changes when the electricity price changes. The higher the price elasticity, the more sensitive demand becomes, in the sense that an increase (decrease) in electricity price leads to a larger reduction (increase) in demand. An enhanced flexibility will make the demand for electricity more load-following: demand will be highest when there is a high production of solar PV, onshore wind and offshore wind (with low electricity prices) and lowest when these electricity producers produce little electricity (and the electricity price is high). As a consequence, the price duration curve as shown in Figures 3.3, 4.1 and 4.2 will become more flat: both the lowest and highest prices will be less extreme.

An increase in the available cross-border transmission capacity will have a similar effect on the price-duration curves. In hours with scarcity, for instance, prices will be relatively high on the Dutch electricity market. If this is not the case for the foreign electricity market, the international trader can generate revenues by buying electricity on the foreign market and selling it to the Dutch market. This will increase the supply on the Dutch electricity market and thus lower the electricity price. An increase in the transmission capacity will enlarge the possibilities of the international trader to trade, making the demand for electricity again more load-following. Increasing the magnitude of the available cross-border capacity is what likely will happen in the future, so it is relevant to explore the sensitivity of our results for that development.

Within our previous analysis, we assume a price elasticity of demand equal to -0.30 and a cross-border transmission capacity of 3000 MW, following Li and Mulder (2021) (see Appendix B). In Table 6.1 we show the effect of a) a higher price sensitivity of demand, b) a higher cross-border transmission capacity and c) a combination of the two on the required subsidy levels in different scenarios.

Table 6.1 Required subsidy per technology w.r.t. price elasticity and cross-border transmission capacity for different scenarios (in Euro/MWh)

Scenario	E_p	C_t	Nuclear	Solar	Onshore wind	Offshore wind
Baseline	*-0.30*	*3000*	31.32	84.10	9.81	50.87
	-0.45	3000	32.08	84.46	10.35	51.4
	-0.30	5000	31.43	84.56	10.39	51.18
	-0.45	5000	31.92	84.75	10.91	51.68
Medium Renewables- Low Increase Demand	*-0.30*	*3000*	34.86	104.36	25.16	65.47
	-0.45	3000	35.83	103.91	25.75	66.07
	-0.30	5000	34.89	99.82	25.29	65.4
	-0.45	5000	35.47	99.79	25.64	65.81
Medium Renewables- Medium Increase Demand	*-0.30*	*3000*	33.00	97.14	20.52	61.09
	-0.45	3000	33.95	97.23	21.17	61.68
	-0.30	5000	33.47	94.8	21.33	61.58
	-0.45	5000	34.05	94.97	21.83	62.05
Medium Renewables- High Increase Demand	*-0.30*	*3000*	31.70	88.89	14.72	56.18
	-0.45	3000	32.43	89.21	15.17	56.59
	-0.30	5000	31.97	88.97	15.37	56.57
	-0.45	5000	32.48	89.12	15.81	56.97
High Renewables- Low Increase Demand	*-0.30*	*3000*	76.37	215.24	82.72	124.20
	-0.45	3000	76.88	206.44	81.66	120.78
	-0.30	5000	71.44	194.38	76.32	116.54
	-0.45	5000	71.4	187.99	75.44	113.59
High Renewables- High Increase Demand	*-0.30*	*3000*	61.58	163.93	66.57	102.66
	-0.45	3000	62.22	160.26	65.79	100.84
	-0.30	5000	57.89	153.21	61.5	97.72
	-0.45	5000	58.09	150.3	61.13	96.17

Notes:
E_p: price elasticity of demand, initially assumed to be equal to -0.30
C_t: Cross-border transmission capacity (MW), initially assumed to be equal to 3000
Benchmark: $E_p = -0.30$, $C_t = 3000$

The effect of an increase in the price elasticity of demand and/or the cross-border transmission capacity on the required subsidy of electricity producers is ambiguous (see Table 6.1). On the one hand, less (extremely) low prices are observed, such that the revenues of all producers are expected to increase. However, (extremely) high prices are also observed less frequently, such that revenues during these hours get smaller.

For nuclear power plants, an increase in the price sensitivity of demand leads to an increase in the required subsidy level for all considered scenarios. Apparently, the reduction in the occurrence of (extremely) high electricity prices has a larger effect than the reduction of (extremely) low electricity prices, such that total revenues decrease and a higher subsidy is required in order to break-even. An increase in the cross-border transmission capacity also increases the required subsidy of nuclear power plants, except in the *High Renewables*-scenarios.

Overall, the effect of an increase in the price elasticity of demand and/or the cross-border transmission capacity is relatively small. The ordering of the different technologies regarding the required subsidy levels does not change.

6.7 Gas prices

In times of abundant generation capacity, the electricity price is determined by the marginal cost of the price-setting (marginal) plant. In the current electricity system, this plant is often an gas-fired power plant, but this may change when there is a large amount of renewables. Nevertheless, gas-fired power plants may remain the marginal plants for many hours in a year. Hence, their marginal cost remain relevant for the electricity price as well. These costs depend on both gas- and carbon prices (see Appendix A). As our model takes 2019 as benchmark, our analysis is based on actual gas prices in 2019. As a sensitivity analysis, we analyse the impact of significantly higher gas prices. In Table 6.5, we compare the required subsidy level for nuclear power, solar PV, onshore wind and offshore wind for different scenarios for two levels of gas prices.

Table 6.2 Required subsidy per technology produced w.r.t. various gas price levels, for different scenarios (in Euro/MWh)

Scenario	Setting	Nuclear	Solar	Onshore wind	Offshore wind
Baseline	p^G	31.32	84.10	9.81	50.87
	$p^G \times 5$	0	49.21	0	0
Medium Renewables- Low Increase Demand	p^G	34.86	104.36	25.16	65.47
	$p^G \times 5$	0	88.78	2.21	40.88
Medium Renewables- Medium Increase Demand	p^G	33.00	97.14	20.52	61.09
	$p^G \times 5$	0	74.69	0	24.1
Medium Renewables- High Increase Demand	p^G	31.70	88.89	14.72	56.18
	$p^G \times 5$	0	45.8	0	0
High Renewables- Low Increase Demand	p^G	76.37	215.24	82.72	124.20
	$p^G \times 5$	49.86	208.23	75.16	118.14
High Renewables- High Increase Demand	p^G	61.58	163.93	66.57	102.66
	$p^G \times 5$	18.66	149.94	52.09	90.44

Notes:
p^G: gas prices as in 2019.
$p^G \times 5$: gas prices of 2019 multiplied by a factor 5.

When the gas price is five times as high as the prices of 2019, electricity prices become higher, such that all types of generation require less subsidy. This effect is much stronger for nuclear power plants than for the renewable power plants, in particular in scenarios with high amounts of renewables. In these scenarios, solar PV, onshore wind and offshore wind only see a small reduction in required subsidy, while the subsidy required by nuclear is much lower compared to the situation with 2019- gas prices. The explanation for this is that solar PV and wind energy are utilized less when gas-fired power plants set the electricity price, such that they benefit less from higher electricity prices. Hence, higher prices of gas benefits investments in nuclear power plants more than investments in renewables, in particular when there is already a high share of renewables.

6.8 Carbon prices

Just as the gas price, also the carbon price affects the marginal costs of gas-fired power plants. Hence, it makes sense to analyse the sensitivity of our results for higher carbon prices. In the above analysis, we used the (daily) carbon prices of 2019, but for the future we may expect significantly higher values. Therefore, we have calculated the required subsidies when we assume that the carbon prices are 5 times and 10 times as high as in 2019. Just as in the case of higher gas prices, we find that the required subsidy for nuclear power benefits the most from higher carbon prices (see Table 4.6), as nuclear power plants are better able to produce and realize revenues when gas-fired power plants are needed in a scenario with a high amount of renewables.

Table 6.3 Required subsidy per technology w.r.t. various carbon price levels, for different scenarios (in Euro/MWh)

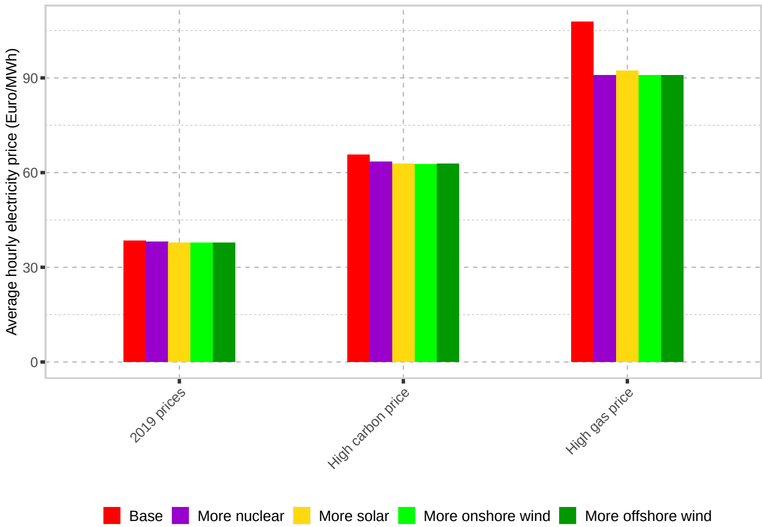
Scenario	Setting	Nuclear	Solar	Onshore wind	Offshore wind
Baseline	c^C	31.32	84.10	9.81	50.87
	$c^C \times 5$	0	62.99	0	20.18
	$c^C \times 10$	0	52.32	0	0
Medium Renewables- Low Increase Demand	c^C	34.86	104.36	25.16	65.47
	$c^C \times 5$	13.62	94.43	11.24	50.57
	$c^C \times 10$	0	90.05	4.1	42.97
Medium Renewables- Medium Increase Demand	c^C	33.00	97.14	20.52	61.09
	$c^C \times 5$	7	83.77	1.26	40.54
	$c^C \times 10$	0	76.76	0	27.87
Medium Renewables- High Increase Demand	c^C	31.70	88.89	14.72	56.18
	$c^C \times 5$	0	65.68	0	24.98
	$c^C \times 10$	0	49.52	0	0
High Renewables- Low Increase Demand	c^C	76.37	215.24	82.72	124.20
	$c^C \times 5$	63.71	210.84	78.35	120.58
	$c^C \times 10$	54.24	208.95	75.93	118.75
High Renewables- High Increase Demand	c^C	61.58	163.93	66.57	102.66
	$c^C \times 5$	43.36	156.04	59.28	96.34
	$c^C \times 10$	25.92	151.4	53.73	91.9

Notes:
c^C: carbon prices as in 2019.
$c^C \times 5$: carbon prices of 2019 multiplied by a factor 5.
$c^C \times 10$: carbon prices of 2019 multiplied by a factor 10.

6.9 Impact on average electricity price

Another, related issue is to what extent the various technologies reduce the vulnerability of the hourly weighted electricity price, i.e. the price consumers pay, to increases in gas and carbon prices. When the installed generation capacity is extended with additional capacity of nuclear power, offshore wind, onshore wind or solar PV, then the electricity price may be less often related to the gas price. Figure 6.5 shows that this is indeed the case. When there is more installed capacity of one of these technologies, the hourly weighted average electricity price responds less strongly to a higher carbon and gas price. Hence, with more other types of generation capacity which have low marginal costs, the electricity prices for consumers becomes less sensitive for increases in carbon and gas prices. However, there is not a real difference in the effect realized by a nuclear power plants and the effects of renewable technologies.

Figure 6.5 Average electricity prices with gas- and carbon prices from 2019 (left) high gas prices (middle) and high carbon prices (right), per policy-variant, Medium Renewables- Medium Increase Demand



Note: '2019 prices' refers to daily carbon prices and gas prices of 2019,'High carbon price' refers to carbon prices of 2019 multiplied by a factor 5, and 'High gas price' refers to gas prices of 2019 multiplied by a factor 5.

7 Conclusions

1. The economic value of a nuclear power plant basically depends on four factors: a) the plant characteristics, including its construction costs and construction duration, operational and maintenance costs, lifetime, ramping constraints, costs of handling and storing waste, and decommissioning costs b) the degree of utilisation (which is called the capacity factor), c) the capture price (which is the average electricity price the plant actually receives), and d) the contribution to reducing carbon emissions. While the first factor can be seen as an exogenous factor, the others are very much related to the characteristics and functioning of the electricity market. In this paper, we have analysed how both the utilisation of a new nuclear power plant and its capture price are related to the amount of renewable generation and the magnitude of the electricity demand. In addition, we have analysed the impact on the reduction of carbon emissions by the electricity system. In order to assess these effects, we compare the results with similar increases in solar PV, onshore wind and offshore wind, taking into account the differences in the respective capacity factors.

2. Using a partial equilibrium model of an electricity market, which is calibrated on the Dutch market situation in 2019, we find that the capacity factor of a nuclear power is strongly reduced, from about 90 to about 60 percent, when the electricity market is characterised by a high share of renewable generation. This effect is partially mitigated when the demand for electricity has increased strongly. In absolute terms, the reduction in the capacity factor of a nuclear power plant exceeds the reduction for a similar (additional) increase in solar or wind capacity, which is related to the fact that the capacity factors of renewables are significantly smaller. In relative terms, the decrease in capacity factors for these technologies is fairly similar.

3. The capture price of the nuclear power plant, however, is less sensitive to the amount of renewables in the system than the capture prices of solar and wind. In a scenario with a high amount of wind and solar generation, the capture price of a new nuclear power plant reduces from the current 40 to about 35 euro/MWh. The capture prices for solar and wind (also including the price for green certificates), however, decrease from about 50 to 10 euro/MWh when there already exists a high share of renewables in the market. The reason that the nuclear power plant experiences a much smaller reduction in its capture price when there is a high amount of renewables installed is that it is able to benefit from high (scarcity) prices when solar PV and/or wind turbines are not able to produce because of (adverse) weather circumstances.

4. Using external information on the construction, operating and decommissioning costs, duration and the lifetime, as well as the model results regarding utilisation rate and capture prices, we are able to determine the present value of an investment in a nuclear power plant and compare this with the similar metric for solar PV,

onshore wind and offshore wind. It appears that all these technologies need external subsidies in order to fully recoup their investment costs. This resembles the fact that all renewable sources are currently receiving subsidies for their exploitation. For the current characteristics of the (Dutch) electricity market, we find that a nuclear power plant needs more subsidy than an onshore wind turbine, but less than a solar PV installation and an offshore wind park. In a scenario with a high share of renewables, also onshore wind turbines require more subsidies than a nuclear power plant, which is related to the strong decline in the capture price of renewable power plants.

5. From these results it also follows that without any governmental support, commercial investors will likely not invest in a nuclear power plant as in all scenarios such an investment is loss making.

6. As the promotion of renewable generation and possibly also nuclear power is related to climate policy objectives, we express the required subsidies per technology in terms of the realized reductions in carbon emissions (the so-called abatement expenditures). This reduction results from the replacement of gas-fired power plants by one of the other techniques (nuclear, solar PV, onshore wind or offshore wind). It appears that in a scenario with a high amount of (already) installed renewables, the abatement expenditures (in euro/ton carbon) for nuclear are significantly lower than for wind and solar generation. This is related to the relative strong decline in the capture price for the renewable technologies.

7. Although providing subsidies for a loss-making technology forms a cost to society, there are some groups which benefit, such as electricity consumers who benefit from lower electricity prices. When we sum up all the economic effects in society, we obtain the overall welfare effects. By expressing these welfare effects in terms of the realized reduction in carbon emissions, the social abatement costs result. The conclusion from the social abatement costs is similar as the previous conclusion: the costs per ton of carbon emission reduction for nuclear are lowest in a scenario with high amounts of renewable capacity.

8. It also appears that nuclear power plants benefit more from higher gas or carbon prices than wind turbines and solar PV. Because of their high availability factor, nuclear power plants are able to produce electricity when gas-fired power plants set the electricity price, and hence, they experience higher electricity prices when the costs of gas-fired power plants increase.

9. From the perspective of electricity consumers, however, there is not a clear difference between the technologies in protecting them from high gas and carbon prices. Renewable technologies appear to be equally helpful as nuclear power plants to make the hourly average electricity price, i.e. the price consumers pay, less sensitive to (extreme) fuel prices, Hence, investing in both nuclear and renewables as wind and solar make the average electricity price less strongly related to these prices.

10. The results are, of course, sensitive to the assumptions made. When the construction and decommissioning costs of nuclear are twice as high as assumed, the required subsidy for nuclear power exceeds the subsidy needed for solar PV. Less dramatic increases in the assumed construction costs, however, do not change the above conclusions. We also find that the construction costs of solar PV should reduce by more than 50 percent in order to arrive at a similar required subsidy level as a nuclear power plant. Changing the assumption regarding the lifetime of the nuclear power plants does not really affect the outcomes. The results appear also to be robust for various values of the discount rate. Moreover, the results do not change significantly when we assume a higher amount of flexibility within the electricity market, which may happen in the future because of investments in storage and further international integration of markets.

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Appendices

A Mathematical model

The mathematical formulation of our model of an energy system is based on Li and Mulder (2021).

A.1 Electricity market

We denote an hour of the year by $h \in \{1, 2, ..., 8760\}$. Participants in the electricity market are modelled as follows:

Renewable producer. For every hour, a renewable producer $R \in$ {solar, onshore wind and offshore wind} decides how much electricity to sell. The hourly generation is bound by the installed capacity and the availability factor. The corresponding optimization problem is given by

$$\max_{q_h^{E,R}} \sum_{h=1}^{8760} (p_h^E + p_h^{GC} - c^R) \cdot q_h^{E,R},$$

subject to

$$0 \leq q_h^{E,R} \leq K^R \cdot A_h^R.$$

In this optimization problem, $q_h^{E,R}$ is the generation of a renewable producer, p_h^E is the electricity price per unit of electricity; p_h^{GC} is the green-certificate price per unit of electricity and A_h^R is the availability factor between 0 and 1, which depends on weather circumstances and follows an exogenous hourly pattern. The marginal cost of the renewable producer c^R and the installed capacity of the renewable producer K^R are assumed to be constant.

Gas-fired producer. For every hour, the gas-fired producer decides how much electricity to sell. The hourly generation is bound by the installed capacity. The corresponding optimization problem is given by

$$\max_{q_h^{E,G}} \sum_{h=1}^{8760} (p_h^E - \frac{p_h^G + \gamma^C \cdot c_h^C}{\gamma^G}) \cdot q_h^{E,G},$$

subject to

$$0 \leq q_h^{E,R} \leq K^G.$$

In this optimization problem, $q_h^{E,G}$ is the generation of the gas-fired producer, p_h^G is the gas price, resulting from an international gas market and c_h^C is the carbon price for each ton of emission. Both are treated as exogenous variables. The conversion efficiency from gas to electricity γ^g, the emissions of burning one unit of gas (in MWh) γ^C and the available installed capacity of the gas-fired producer are assumed to be constant.

Nuclear producer. For every hour, the nuclear-fired producer decides how much electricity to sell. The hourly generation is bound by the installed capacity, a minimum- and maximum output rate and a minimum- and maximum ramping rate.[8] The corresponding optimization problem is given by

$$\max_{q_h^{E,N}} \sum_{h=1}^{8760} (p_h^E - c^N) \cdot q_h^{E,N},$$

subject to

$$\begin{aligned} K^N \cdot O^{N,\min} \leq q_1^{E,N} &\leq K^N \cdot O^{N,\max}, \\ \max\left\{O^{N,\min}, q_{h-1}^{E,N}/K^N - R^N\right\} \cdot K^N &\leq q_h^{E,N}, \quad h = 2, \ldots, 8760, \\ \min\left\{O^{N,\max}, q_{h-1}^{E,N}/K^N + R^N\right\} \cdot K^N &\geq q_h^{E,N}, \quad h = 2, \ldots, 8760, \\ q_h^{E,N} &\leq K^N \cdot A_h^N \quad h = 1, \ldots, 8760. \end{aligned}$$

In this optimization problem, $q_h^{E,N}$ is the generation of the nuclear-fired power plant and a_h^N is the availability factor between 0 and 1, which depends on (planned) outages of the power plant and follows an exogenous hourly pattern. The variable cost of the nuclear producer c^N, installed capacity of the nuclear producer K^N, ramp rate of the nuclear power plant R^N and the lowest (highest) fraction of capacity at which the plant can operate $O^{N,\min}$ ($O^{N,\max}$) are assumed to be constant.

International trader. We model the international trader as a net importer. For every hour, the trader decides how much electricity to import or export. The net import is bounded by the available transmission capacity. The corresponding optimization problem is given by

$$\max_{q_h^{E,I}} \sum_{h=1}^{8760} (p_h^E - p_h^{F,E}) \cdot q_h^{E,I},$$

subject to

$$-K^I \leq q_h^{E,I} \leq K^I.$$

In this optimization problem, $q_h^{E,I}$ is the net import of the international trader and $p_h^{F,E}$ is the electricity price in the neighbouring country, treated as an exogenous variable. The available transmission capacity K^I is assumed to be constant.

Electricity demand. We assume the demand for electricity is represented by the following linear demand function

$$l_h^E = \alpha_h^E - \beta_h^E \cdot (p_h^E + t^E). \tag{1}$$

[8] As discussed in Section 2, nuclear power plants are increasingly able to operate in a flexible way. They are able to ramp up or down one or twice per day in a range of 20 to 100 percent of its rated capacity (see OECD (2011); Morilhat et al. (2019); Lokhov (2011); MIT (2018)). In our modelling, we take these output rates and ramping rates into account, but for simplicity reasons we ignore the constraint that this flexibility is limited to two periods per day. Including that constraint would make the model way more complicated as this would require intertemporal optimization. However, we conduct a sensitivity analysis in which we limit (and increase) the flexibility ability of nuclear power plants (see Appendix B.2).

In this function, l_h^E is the electricity consumption; t^E is the electricity tax for consumers. The intercept α_h^E and the slope β_h^E are both positive. The intercept changes over periods and follow an exogenous hourly pattern, but the slope is the same for all hours.

Electricity market-clearing constraint. Given the derived total demand for each period, the price p_h^E clears the electricity market by meeting the following condition:

$$\sum_R q_h^{E,R} + q_h^{E,G} + q_h^{E,N} + q_h^{E,I} = l_h^E.$$

A.2 Green-certificates market for electricity

A green certificate, also called a renewable-energy certificate, is a tradable asset that proves energy has been produced from a renewable energy source. In a green-certificate market, renewable producers receive certificates for each megawatt-hour (MWh) of produced energy and the certificates can be sold to consumers/retailers, which may result in extra income for the renewable producers depending on the price of the certificates. In our model, the supply of the green-electricity certificates equals the production by the renewable producer. The demand for green-certificates of electricity (in MWh) is represented by the following linear demand function

$$l_h^{GC} = \alpha_h^{GC} - \beta_h^{GC} \cdot p_h^{GC},$$

where the intercept α_h^{GC} and the slope β^{GC} both are positive and the intercept α_h^{GC} is less than the total electricity demand. The certificate price p_h^{GC} clears the green certificate market by meeting the condition

$$\sum_R q_h^{E,R} = l_h^{GC}.$$

B Data and parameter assumptions

B.1 Data

In our model we use data on gas prices, carbon prices, foreign electricity prices, demand and production, which we treat as exogenous. In the following we briefly discuss our sources and how we used the data for our analysis.

- We collect data on Dutch TTF gas-prices and EUA (carbon) prices. For the foreign electricity price, we collect data on day-ahead electricity prices in the German electricity market in 2019 from ENTSOE (2021a).

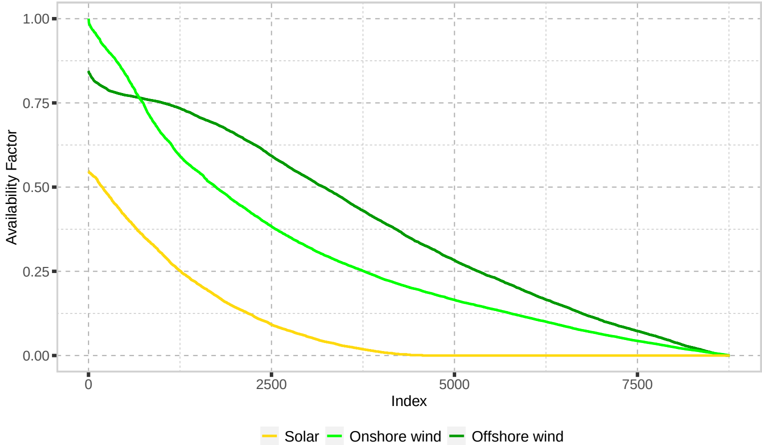
- We collect data on day-ahead electricity prices and scheduled generation in 2019 from ENTSOE (2021a,b). We assume that the slope coefficient β_h^E in equation (1) does not change over time. We calculate it, using the definition of the price elasticity and equation (1) as:

  $$\beta_h^E = \frac{-\bar{p}}{E_p \times \bar{q}},$$

  where E_p is the price-elasticity of demand, $\bar{p}$ is the average day-ahead electricity price and $\bar{q}$ is the average level of scheduled generation in 2019.
  The intercept coefficient α_h^E is then calculated using equation (1).
  The demand for green certificated is constructed in a similar way. We assume that the average demand for green certificates is equal to 50% of average electricity demand and that the average price for a green certificate is equal to 10 Euro/MWh.

- For each of the three considered techniques, we collect data on renewable electricity generation in 2019 from ENTSOE (2021a). Combined with the installed capacities we construct a so-called hourly availability factor, indicating what part of installed capacity can be used. This factor fluctuates between 0 and 1 with an average of 0.09, 0.28 and 0.38 for solar energy, onshore wind energy and offshore energy. These averages are based on the realized capacity factors per technology in the past years IEA (2019). Figure B.1 shows the duration curves of the availability factor of the three techniques.

Figure B.1 Duration curves of availability factor of solar energy, onshore wind energy and offshore wind energy, based on actual production data.



- We use data on U.S. nuclear plant outages from EIA (2018). We model a scheduled outage in September, when there is relatively little demand for electricity. The outage is assumed to last 31 days, equal to the average refueling outage in 2018.

B.2 Parameters

Table B.1 lists the values of other parameters in our model.

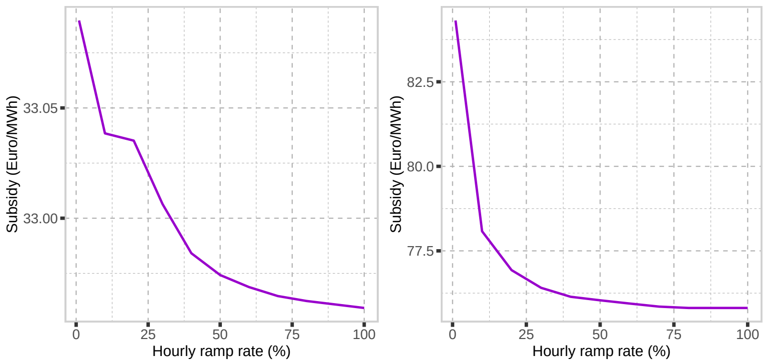
Table B.1 Assumptions technology parameters and other relevant variables

Parameter (unit)	Value	Reference
Carbon emission of burned gas (ton/MWh)	0.2	Li and Mulder (2021)
Conversion efficiency gas to electricity	0.5	Li and Mulder (2021)
Electricity tax (Euro/MWh)	20[1]	MFTD (2021)
Price elasticity of demand	-0.30	Li and Mulder (2021)
Mean load in 2019 (MWh)	12942	CBS (2021)
Price elasticity demand green certificates	-1	Li and Mulder (2021)
Average price green certificates (Euro/MWh)	10	Li and Mulder (2021)
Variable cost of renewable electricity (Euro/MWh)	0	Own assumption
Variable cost of nuclear electricity (Euro/MWh)	12.42	Own assumption [2]
Lowest fraction of output of nuclear power plant	0.25	OECD (2011);Morilhat et al. (2019)
Highest fraction of output of nuclear power plant	1	OECD (2011);Morilhat et al. (2019)
Ramp rate nuclear power plant (%/hour)	31	OECD (2011);Morilhat et al. (2019)

1: The tariffs differ a lot among various groups, depending on the size of electricity consumption. We just take a number in between the actual range.
2: Calculated as the sum of variable O&M costs, fuel costs and cost of waste processing.

Ramp rate nuclear power plant In our model, we assume an hourly ramp rate equal to 31% (OECD, 2011; Morilhat et al., 2019). In Figure B.2, we show the effect of this assumption on the required subsidy per MWh. Similar to Section 6, we consider the *Medium Renewables- Medium Increase Demand*-scenario (left). Moreover, we show the sensitivity in the *High Renewables- Low Increase Demand*-scenario (right). In this scenario, most flexibility is required as the installed capacities of solar PV and wind energy are relatively high and the increase in electricity demand is relatively small.

Figure B.2 Sensitivity of required subsidy per MWh produced w.r.t. hourly ramp rate, *Medium Renewables- Medium Increase Demand* (left) and *High Renewables- Low Increase Demand* (right)



The ramp rate imposes a constraint on the flexibility of the production of a nuclear power plant. Therefore, a higher ramp rate can be seen as a relaxation of the optimization problem of the nuclear producer given in Appendix A, potentially leading to higher revenues and thus to a lower required subsidy level. When a lower ramp rate is considered, the action space of the nuclear producer is limited, such that its revenues might decrease.

In Figure B.2, we observe how the required subsidy of nuclear power decreases when the hourly ramp rate increases. Especially in the *Medium Renewables- Medium Increase Demand*-scenario the effect of the hourly ramp rate is modest. In this scenario, the nuclear power plant will produce at full capacity most hours of the year, such that only little flexibility is required. As a consequence, a change in the ramp rate has only a modest effect on the reveneus and thus on the required subsidy level. In the *High Renewables- Low Increase Demand*-scenario the impact of the ramp rate is larger. In this scenario, there are relatively many hours at which solar- and wind energy electricity producers can satisfy demand (almost) completely. In these hours, the nuclear power plant wants to reduce its production to prevent production against prices that are lower than marginal costs. With a low ramp rate this is, however, not possible, such that total revenues decrease. As a result, the required subsidy for nuclear power increases. The increase in the required subsidy remains, however, fairly small. When the nuclear would only be able to operate in the base-load mode (with constant production), its required subsidy is 5 euro/MWh higher.

C Model outcomes, High Renewables- Low Increase Demand

In Figures C.1 and C.2, we give an overview of our model output for the *High Renewbles-Low Increase*-scenario in the *Base*-policy variant. We consider the production of the different techniques and the load per hour (Figure C.1) and per month (Figure C.2). The lines indicate the average value, while the coloured areas give a measure of deviation from this average.

Figure C.1 Hourly variability of production and load within a year, *Base*-policy, *High Renewables- Low Increase Demand*-scenario

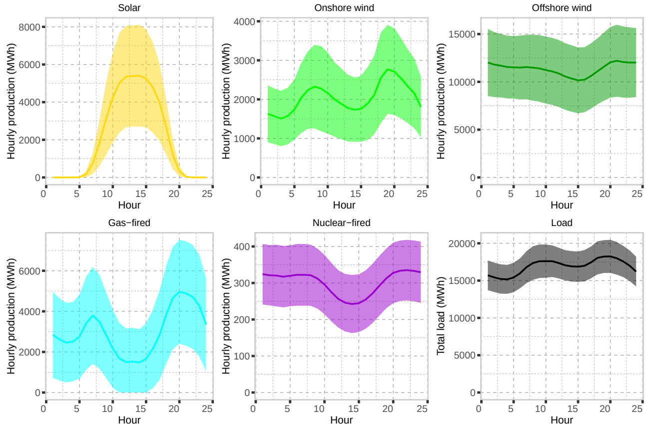
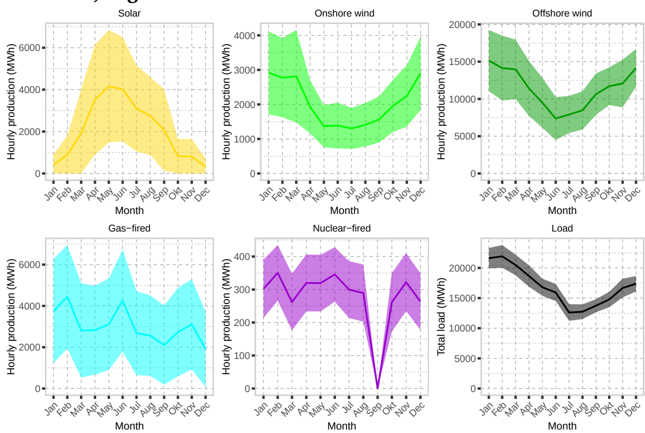


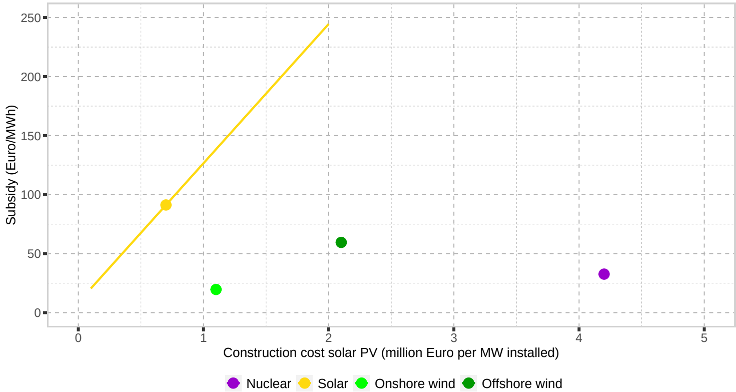
Figure C.2 Monthly variability of production and load within a year, *Base*-policy variant, *High Renewables- Low Increase Demand*-scenario



D Sensitivity analysis construction cost solar PV

In Figure D.1, we show the effect of the construction cost of solar PV on the required subsidy level per MWh produced in the *Medium onshore wind Medium Increase Demand*-scenario. The dots indicate the current set of assumptions.

Figure D.1 Sensitivity of required subsidy per MWh produced w.r.t. construction cost solar PV, Medium onshore wind Medium Increase Demand



This shows that the construction cost of solar PV should be significantly lower in order to require lower subsidies than nuclear.

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As the growth in renewable electricity is likely not sufficient to realize zero-carbon electricity systems, nuclear power may be useful to realize climate-policy objectives. Nuclear power is, however, highly debated, because of its perceived safety, security and environmental risks. Next to that, it may economically not be efficient to have such a type of power plant in future electricity markets which are dominated by high shares of renewable generation. In this paper, the authors tested this hypothesis for various scenarios regarding the future amount of renewables and magnitude of electricity demand. This analysis is solely directed at the economics of a nuclear power plant in an electricity market, which implies that they do not go into other (equally) relevant aspects of the societal discussion of nuclear power, such as safety, security and environmental issues, and societal acceptance.

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