Feasibility of Nuclear Energy in the Energy Mix of the Netherlands

Identifying the economic potential of nuclear energy in a system where wind, solar and green hydrogen dominate.

Master Thesis

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Preface

Before you lies the thesis on the feasibility of nuclear energy in the future energy mix of the Netherlands. It has been written to fulfill the master Sustainable Development graduation requirements with a specialization in Energy & Materials. I have written this thesis in the period from February to July 2021. This thesis and its research question are the result of my personal interest in combination with the interests of both my supervisors, Geert-Jan de Haas (NRG) and Gert Jan Kramer (Utrecht University). The technical part of this research has been challenging, but fortunately both Prof. Kramer and Mr. de Haas were always available and willing to help. I would like to them both for their patience and guidance during this process. Their critical view on my work has resulted in a motivator to perform at the highest of my capability. I want to thank my family and friends for assisting me in the last period of this thesis. Without their assistance and interest, I would not have remained as motivated as I have been.

I hope you enjoy your reading.

Pim Broekhuizen

Abstract

This research has contributed to the goal of decarbonizing the energy sector. Through the process of decarbonization, all types of electricity generation technologies are re-evaluated. The energy produced must be reliable, affordable, and sustainable. Nuclear energy is proven to be reliable and sustainable, but its affordability is questioned. This research tried to answer this by studying the potential role nuclear energy could play in an energy mix where and when solar, wind and, green hydrogen dominate. It has done so by extending the model created by Kramer & Koning - which was used to identify the optimal combination of hydrogen and VREs in an energy system – with a nuclear energy component. It was concluded that with the introduction of nuclear energy in the system, the potential production of hydrogen as an ESS was higher compared to a system without nuclear energy. The height of the OCC of an NPP was retrieved through a literature review to find the optimal combinations of hydrogen and nuclear energy capacity. While there was no consensus in the literature, a bandwidth of the most probable OCC was constructed. Three cost ratios of nuclear energy over electrolysers were created to perform a cost-optimization and find the most cost-effective way of decarbonizing the energy sector. The cost optima combinations of nuclear energy and electrolysers were not significantly different for the three scenarios and showed a potential role for nuclear energy. By introducing nuclear energy into the mix, the total system costs could be reduced compared to a scenario without nuclear energy, depending on the cost ratio. With the expected cost reductions in electrolysers, there is a need for cost reduction in the OCC of an NPP to retain the potential role nuclear energy has. Lastly, if the role of nuclear energy will be to produce hydrogen, the same capacity of electrolysers should be installed to limit the cost of production. Hence, this research has concluded that there is a role that nuclear energy could play in an energy mix when and where solar, wind, and green hydrogen dominate. It can do so by being a baseload supplier of electricity and, to a limited extent, as a purple hydrogen producer. However, it must reduce its OCC to be cost-competitive in the future to maintain this potential role. Further research into other components than system costs is recommended to fully identify nuclear energy's potential role.

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Abbreviations

CAPEX – Capital Expenditures

CR – Cost ratio

ESS – Energy Storage System

GHG – Greenhouse gas

LCOE – Levelized Cost of Electricity

LCOH – Levelized Cost of Hydrogen

NPP – Nuclear energy Plant

NPV – Net Present Value

OCC – Overnight Capital Cost

OPEX – Operational Expenditures

PtH – Power-to-Hydrogen

RES – Renewable Energy Sources

VRE – Variable Renewable Energy, in this report includes solar PV, on-, and offshore wind.

WACC – Weighted Average Cost of Capital

1. Introduction

1.1 Decarbonising the Dutch electricity sector

The Dutch government has set a goal to have a climate-neutral energy system by 2050 (Rijksoverheid, 2019b). From this goal, the Climate Agreement was formed (Rijksoverheid, 2019a) of which the aim is to reduce the greenhouse gas (GHG) emissions by 49% in 2030 compared to 1990. Goals have been set for every sector, one of which is the electricity sector. In 2019 the Netherlands consumed a total of 435 PJ of electricity, which is approximately 19% of the total energy demand (TNO, 2020b). The goal for the electricity sector is to have 70% generated by renewable energy sources (RES) in 2030 and to be fully climate neutral by 2050. To reach the 2050 goal, different kinds of energy sources are being (re)considered. One of these is the use of nuclear energy. In 2019, the Dutch Parliament started to explore the role of nuclear energy in the Dutch electricity mix in 2050 (Rijksoverheid, 2019b). From this interest, ENCO (2020) studied the role of nuclear energy in the Dutch electricity mix in 2050. Additionally, KPMG is studying the viewpoint of market parties on investing in a nuclear power plant (NPP), what public support is needed, and what areas in the Netherlands would be willing to have an NPP (Ministerie van Economische Zaken en Klimaat, 2020).

1.2 The realization of the 2030 goals

When looking at the current electricity generation mix, natural gas is still dominating. Figure 1 shows the electricity generation in the Netherlands in 2019 and the first half of 2020. On average throughout the year, electricity in the Netherlands was generated by natural gas (60%), coal (13%), fossil-fuelled sources (2%), renewables (21%), and others including nuclear (4%) (CBS, 2021). Renewables (RES) consisted of wind (45%), solar (26%), biomass (29%), and a small part of hydro (0.3%). The trend towards 2030 set by the Climate Agreement (Rijksoverhied, 2019a) results in the phasing out of coal and further penetration of solar and wind (VREs) with hydrogen as a storage system. Besides, the nuclear reactor at Borssele will run till 2030. Thus, nuclear energy will be part of the electricity mix till 2030.

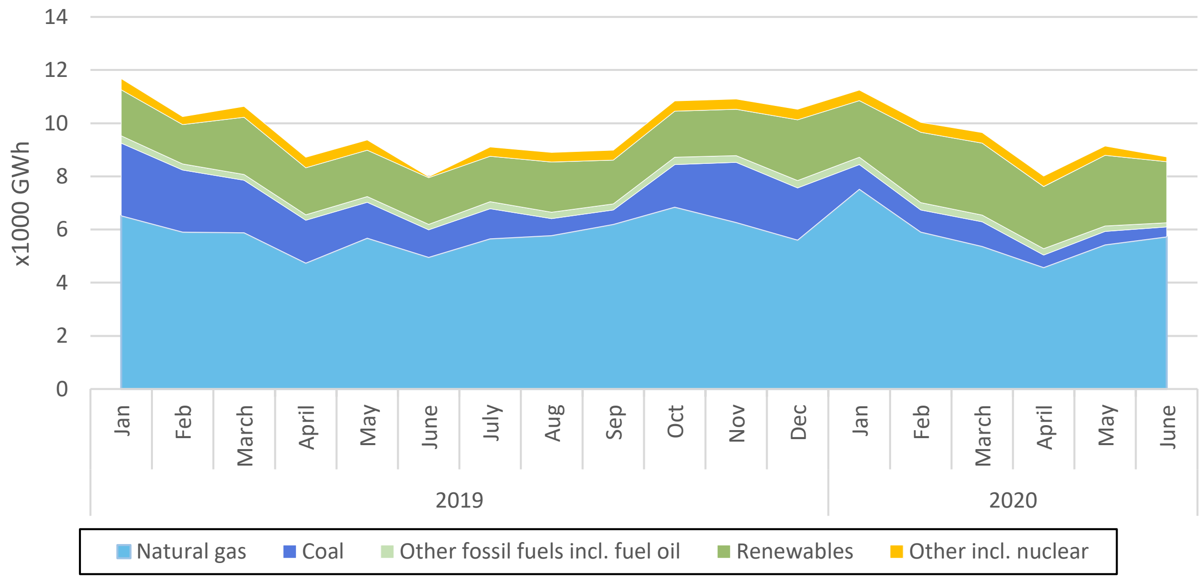

Figure 1 - Electricity generation per energy source in the Netherlands from January 2019 to June 2020 (CBS, 2020a)

Next to the decarbonization of the current electricity mix, the electrification from other sectors will result in even higher electricity demand. For example, cars will become electrically driven, and the industry will replace oil and gas with clean electric alternatives. Moreover, buildings will no longer be using gas but electricity for heating and cooking (Rijksoverheid, 2019a). It is estimated that in 2030, the Netherlands will need 49,000 GWh of electricity per year from offshore wind power and 35,000 GWh of electricity per year coming from solar and wind from land (Rijksoverheid, 2019a). Current production levels for solar and wind from both on- and offshore cannot supply this. Thus, the Climate Agreement suggests that investments in solar and off- and onshore wind are necessary. However, with the penetration of these VREs in the electricity mix, reliability becomes an issue as these forms of power are dependable on weather conditions. Due to this reliability problem caused by the intermittency, there is a chance that electricity generated by these VREs is high when demand is low and the other way around (Gowrisankaran et al., 2016; Milan et al., 2013). As a solution, technologies such as batteries and hydrogen-to-power (HtP) are foreseen in the Climate Agreement. The Dutch government currently encourages research into these storage capacities. Other solutions to the intermittency problem proposed in the Climate Agreement are smart charging of electric vehicles, stand-by reserve capacity, and smart grids for demand-side management. Therefore, it can be concluded that with the Climate Agreement, the pathway towards the reduction goals is known.

1.3 Towards 2050 goals

However, the transition towards renewable electricity does not stop in 2030. Electricity demand will keep growing because of a higher absolute electricity demand per person and the electrification of other energy sectors. According to TNO (2020b), the electricity demand in 2050 will likely be around 70% of the total energy demand. Den Ouden et al. (2020) indicate that the total electricity demand will be between 192 and 240 TWh. While the pathway to reach the 2030 goals has been fairly set, the path towards the 2050 goals remains to be carved. Aside from the goal to be climate neutral, no strict goals on the sources of electricity generation and types of storage have been set. What is set in the Climate Agreement, is that in 2050 energy must be clean, the costs must be kept as low as possible, and the reliability of the electricity system must be ensured at all times (Rijksoverheid, 2019a, p.157). The prognosis is that the development of solar, wind, and green hydrogen will continue from 2030 onwards. With the even further penetration of solar, wind, and storage systems such as green hydrogen, some challenges arise. Aside from the previously explained challenge of reliability issues due to the intermittency of VREs, the competition for land grows (van de Ven et al., 2021). Moreover, the affordability of the system is challenged as storage capacity limitations could result in high costs and resource use (Parra et al, 2017).

To meet the challenge at hand, another pathway is considered by the government. This is the addition of nuclear energy to the energy mix (May, 2016; Studiegroep Invulling klimaatopgave Green Deal, 2021; Berenschot & Klavasta, 2020). The recently revived interest in the potential of nuclear energy has resulted in various studies commissioned by the Ministry of Economic Affairs and Climate following resolutions in Parliament and the inclusion of nuclear energy in scenario studies. A scenario analysis of TNO (2020) concluded that the use of nuclear energy in the energy mix after 2030 is possible but states the uncertainty due to political and social debate and the higher system costs. Additionally, the *Studiegroep Invulling*

Klimaatopgave Green Deal (2021) states that by implementing nuclear energy, the pressure from VREs on land use is lowered.

1.4 Nuclear energy

Nuclear energy has contributed to electricity generation worldwide for over 65 years. In 2019, a total of 442 reactors were operational, with a capacity of over 393 GW of electricity in the world (WNA, 2021b). This accounts for over 10 percent of the total electricity supply globally (IEA, 2020). The EU has 106 operating reactors with a total capacity of over 104 GW generating 26% of the electricity (WNA, 2021a; FORATOM, 2020). One of these reactors is situated in the Netherlands in Borssele; the Borssele reactor has a capacity of 482 MW, delivering a total of 3.7% of the Dutch electricity supply (3,701 GWh) in 2019 (EPZ, 2019). Moreover, nuclear energy is a land-use efficient way of producing electricity. A nuclear reactor's average capacity worldwide is around 900 MW (WNA, 2021b). According to the U.S. Energy Information Administration (2021), this equals to 2.8 million solar PV panels or 388 wind turbines. The difference between an NPP and VREs such as wind turbines and solar panels is during construction. While solar panels and wind turbines can be deployed gradually over time, an NPP takes longer to construct and supplies the full capacity from the first day of operation instead of gradually developing its energy potential to overtime. So, nuclear energy has proven to be a matured and reliable technology in the world today.

In the transition to a decarbonized electricity sector in 2050, the topics reliable, clean, and affordable energy are central (UN, n.d.). In other words, energy should not only be carbon neutral, but also always available and with a fair price. An overview of different electricity generation technologies and their level of reliability, affordability, and sustainability is given in Table 1. Note that the colours represent the values in comparison with the other technologies. For example, VRE is labelled red for reliability, which implies that it has the worst reliability of the three technologies included. Here it can be seen that nuclear energy is the most reliable and sustainable technology of the three. However, VREs with a storage system are the least sustainable but average reliable and affordable. This suggests that there is not a single best option.

Table 1 - The reliability, affordability and sustainability of the different technologies discussed. Each score represents the value vis-á-vis the other, i.e. nuclear energy is the most reliable, then VRE with a storage system and lastly VRE without a storage system.

	Reliability	Affordability	Sustainability
VRE (solar & wind)			
VRE with storage (PtH/batteries)			
Nuclear energy			

1.5 The pathway towards a decarbonized energy system

The carbon-free electricity sector will most probably exist of a mix of VREs, storage systems, and a backup supplier of electricity (Kloosterman, 2019; Rijksoverheid, 2019a). Nuclear energy might be able to fill the role of backup supplier. Based on the literature, it can be concluded that nuclear energy could play a possible role in the decarbonized electricity sector in four different ways; as a baseload supplier, by purely load-following production, as a combined load-following and hydrogen producer, and lastly as a hydrogen producer (Costa et al., 2018; Berenschot & Klavasta, 2020; Olkkonen et al., 2018; Shropshire et al., 2012). MIT (2019) concluded that the main value of nuclear energy as a contributor to reach a carbon-neutral power sector is as a baseload supplier. For the Netherlands, the Borssele reactor has supplied a steady level of electricity as a baseload supplier. Recent literature on the costs for the Dutch electricity sector including nuclear energy in 2050 has contradictive outcomes (ENCO, 2020; Berenschot & Klavasta, 2020). Berenschot & Klavasta (2020) concluded that NPPs are merely economically feasible when nuclear energy has a certain baseload, even when the price of electricity is higher than those of VREs. While ENCO (2020) concluded that nuclear energy could play a cost-competitive role to VREs in the 2050 Dutch energy mix. Thus, the potential value of nuclear energy as a contributor to a decarbonized electricity sector is there, but the cost-competitiveness is questioned.

2. Problem definition and research aim

So, while there is sufficient information on the development towards the carbon reduction of the electricity sector of the Netherlands by 2030, the pathway towards full decarbonization is yet to be determined. The condition is that the system must be sustainable, reliable, and affordable. Nuclear energy is an option, but the affordability of it is questioned in the literature. This research aimed to determine the cost of developing a sustainable, reliable, and affordable electricity mix for the Netherlands to supply the 2050 demand. This research considered continuing on the decarbonization pathway as set by the Climate Agreement, which focuses on VREs development and hydrogen and battery storage. As the decarbonization of the electricity sector progresses, the costs for installing extra capacity of VREs and electrolysers and batteries increase. To clarify, decarbonizing the last ten percent of the electricity sector requires a greater amount of VRE and storage capacity compared to the first 10 percent. This could jeopardize the affordability of the system (Kramer & Koning, 2021). In their research, the energy storage system (ESS) used was hydrogen through electrolysers. Nuclear energy was until now not included in this model. This research has filled this gap using the model created by Kramer & Koning (2021) and extending it with a nuclear energy component. Hence, introducing nuclear energy in such a system might be cost-competitive to one without.

This research aimed to identify whether nuclear energy can play a potential role in the energy mix of the Netherlands in 2050, which is dominated by solar, wind, and green hydrogen. It has done so by identifying whether the system costs will rise or fall with the introduction of nuclear energy. As ENCO (2020) concluded, the system costs are very dependent on the distribution of the energy mix. Nuclear energy is reliable, though solar and wind are less reliable. Therefore, it is paramount to look at the electric potential needed to always supply the electricity demand. For example, when the capacity factor for solar is 10% and nuclear is 90%, the installed capacity must be 9 times larger. As nuclear energy is a reliable dispatchable source and VRE is not, the system costs must be considered for a useful comparison (ENCO, 2020). ENCO (2020) further stated that the system costs increase disproportionally if the share of VRE in the mix increases.

Since VREs, nuclear energy, and electrolysers are all capital-intensive technologies, the capital costs (CAPEX) are relevant when calculating the system costs. For nuclear energy, this can be expressed as the overnight capital costs (OCC). The OCC is the theoretical concept of constructing a power plant in one night, i.e., it does not consider the interest costs during the construction period and thus ignores financing costs (Berthélemy & Escobar Rangel, 2015; Timilsina, 2020). To achieve the aim of this research, the main question with sub-questions were formed, listed below

What role could nuclear energy play in an energy mix when and where solar, wind, and green hydrogen dominate?

I. How high are the overnight construction costs of an NPP in the Netherlands?
II. What is the hydrogen potential of a system with different levels of nuclear energy and electrolysers?
III. What are the cost optima combinations of nuclear energy and electrolysers capacity with a given amount of VREs?
IV. How does the introduction of nuclear energy impact the system costs for electricity generation in the Netherlands?

To answer the main research question, the OCC of an NPP was determined first. As a next step, the capacity of electrolysers that was feasible for different capacity levels of nuclear energy was calculated. An assumption made was that the capacity of VREs would not be further developed from 2030 onwards. By doing so, the impact nuclear energy has on the system costs could be isolated. When all feasible combinations of nuclear energy and electrolysers at a given capacity of VREs were calculated, the cost optima pathway towards a fully decarbonized system could be constructed. Subsequently, by comparing the conclusions from Kramer & Koning (2021) with the results from this research, the last sub-question was answered.

2.1 Relevance of the research

Due to the current Paris Agreement, EU directive, and Dutch Climate Agreement, VREs penetrate the energy mix to decarbonize the electricity sector. The exact configuration of the energy mix in 2050 is yet to be determined, just as the costs of such a system. Thus, alternative technologies such as nuclear energy are looked at. Limited studies have touched upon the specific system costs needed when one would add a nuclear component to a system of VREs and hydrogen storage, and when done, only in general (ENCO, 2020). Due to the long construction period (up to 15 to 20 years), the time to decide to invest in such a technology is imminent. By extending the model of Kramer & Koning (2021) and calculate the exact system costs, this research tried to give a better view of the development towards a carbon-neutral electricity sector with nuclear energy in the mix.

3. Concepts of cost of electricity

The cost for a technology to supply electricity consists of two parts: the cost of capital (CAPEX) and operation (OPEX). CAPEX is described as the initial investment required to build a specific generating asset, in this case, a power plant (Wu & Buyya, 2015, p. 598). The OPEX consist of the yearly costs of operating the power plant. This entails components such as fuel costs, employee costs, but also maintenance costs (Wu & Buyya, 2015, p. 598). The cost of electricity for nuclear, VREs, and electrolysers are dominated by their CAPEX, while for fossil generation the OPEX dominate (Kramer & Koning, 2021). Since the OPEX are yearly recurring costs, they are easy to calculate per year. However, calculating the CAPEX is more complex. For this, different methods are used.

3.1 Levelized Cost Of Electricity (LCOE) & Levelized Avoided Cost of Electricity (LACE)

A well-known metric for calculating the cost of electricity is the levelized cost of electricity (LCOE). The LCOE is the most common indicator for comparing different electricity generation technologies (Aldersey-Williams & Rupert, 2019; Timilsina, 2020). Here, the total cost of building and operating a power plant over its lifetime is divided by the total electricity output of that plant over the lifetime. When calculating the LCOE, one includes the cost for capital, operation & management (O&M) costs, and fuel costs. The LCOE is expressed as the costs per unit of energy, for example, €/MWh (WNA, 2020a). Here, the CAPEX and OPEX are combined into one single value. There are limitations to using LCOEs for comparing intermittent technologies with flexible technologies (Joskow, 2011; Sklar-Chik et al. 2016). Because, without storage, VREs cannot provide reliable electricity; therefore, the system will need other technologies to ensure this firm capacity. This would mean that the total system costs with VREs are higher than its LCOE summed. Thus, the use of LCOE might be of limited use when calculating the costs of the system. The EIA (2020) addressed the problem of the disjunction of the LCOE of intermittent and firm capacity by introducing the levelized avoided cost of electricity (LACE). The LACE includes the value of the power plant in serving the electricity grid. This is depicted as the costs it would have by generating from a new generation project as an estimate of the revenue available to the plant. Just as with the LCOE calculations, these costs are depicted as discounted and "levelized" over the plant its economic lifetime. A new power plant is thus economically attractive when the project its LACE exceeds the LCOE, in other words, when the value exceeds its costs.

3.2 System costs of generating electricity by Kramer & Koning (2021)

The different variables in the LCOE and LACE method are subject to variance. For example, the standardized operating assumptions for VREs can only predict future revenues to a certain extent. Likewise, the predictions in yearly irradiation, wind speeds, and technological developments can only be predicted to a degree. Therefore, the costs per generated energy output can differ more than calculated beforehand. Next to this, both methods calculate the general costs of electricity per technology and do not give insight in the share of OPEX and CAPEX. While the system addressed in this research is merely CAPEX intensive, the LCOE and LACE method can be regarded as not a perfect method.

A third option to calculate the system costs for generating electricity is developed by Kramer & Koning (2021). They examined the cost development of decarbonization of the power system by the penetration of VREs with power-to-hydrogen (PtH) storage using a different approach in calculating the costs of electricity. Kramer & Koning (2020) state: *"A pragmatic approach to 'calibrating' renewable and fossil costs relative to one another is to look at actual project costs."* Again, it is stated that the fossil electricity generation is determined by its OPEX, while the VREs are determined by its CAPEX. They acknowledge that the costs of decarbonization must be brought to a comparable footing to be competitive. Kramer & Koning (2021) indicate that this is not done by using the LCOE or LACE methods, since their model does not indicate, on the one hand, the cost developments of renewables and, on the other hand, fossil fuel prices. So, instead of calculating the LCOE or the LACE with the different components that could change over time, they approach it differently. When decarbonizing the electricity sector, the reference technologies that could substitute fossil electricity generation should be compared. As stated before, they compared the cost of capital of the different technologies. By doing this for the entire system, the system costs are calculated. Moreover, the model uses the cost ratio of VREs and electrolysers instead of the absolute CAPEX, which ensures a margin useful for calculating future scenarios. Since nuclear energy is a CAPEX-intensive technology as well, the model developed by Kramer & Koning (2020) is a useful tool to identify whether nuclear energy could be an affordable source of electricity which is necessary as aforementioned.

4. Methods

This chapter outlines the different steps taken to answer the sub-questions that in turn help to answer the main research question. First, a brief outline of the model is given, followed by a step-by-step explanation of the calculations and the data used.

4.1 Model framework

To define the role of nuclear energy in the decarbonization of the electricity sector, some steps needed to be taken. First, a model was constructed which had its foundation in the research of Kramer & Koning (2021). An overview of this model is given in Figure 2.

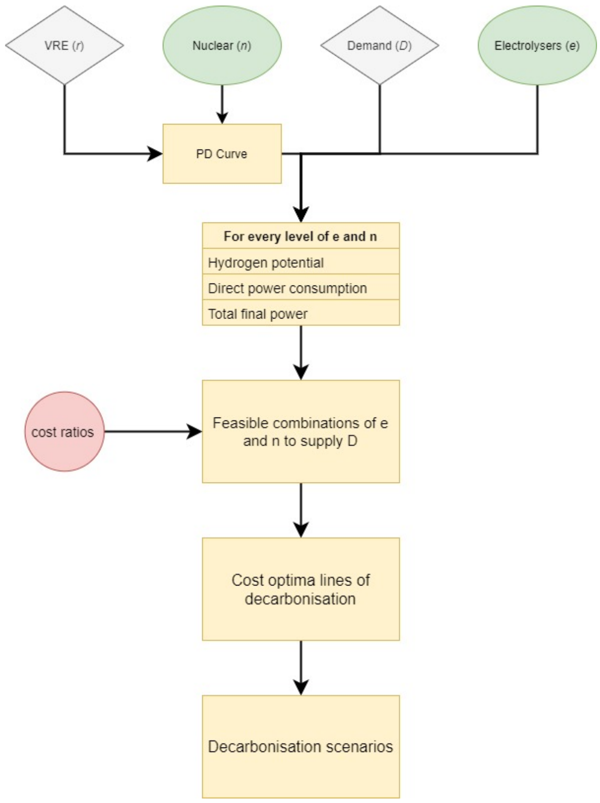

Figure 2 – An overview of the model created and used, which has its foundation in the model created by Kramer & Koning (2021). The grey diamond shapes represent variables that are unchangeable in this model. The green ellipses represent the variables that can be altered. The red circle is the assumptions made on cost ratios for the future, and the yellow boxes represent the calculations steps of the model.

4.1.1 Variable inputs

Firstly, the power-duration curve for this system was defined, visualized by the yellow box in the top left bottom of Figure 2 (PD Curve). A power duration curve is the time-ordered energy output in the year, which results in a continuously declining function, i.e., the ordered function from high to low power in a year. The steepness of the power duration curve is dependent on the generation by VRE, further referred to as variable r. The height of the power duration curve is dependent on the level of nuclear, further referred to as variable n. In this model, the values for r and n represent the average generation in a year. Furthermore, the data from Kramer & Koning (2021) on renewable energy generation was used, which consists of a mix of 75% on- and offshore wind and 25% PV solar. This is claimed to be a typical distribution for the

Netherlands. To illustrate this, a power curve and power duration curve are depicted in Figure 3. In the upper-right corner, one can see the electricity generation per hour for one year. The distinction has been made between VREs, in grey, and nuclear, in purple.

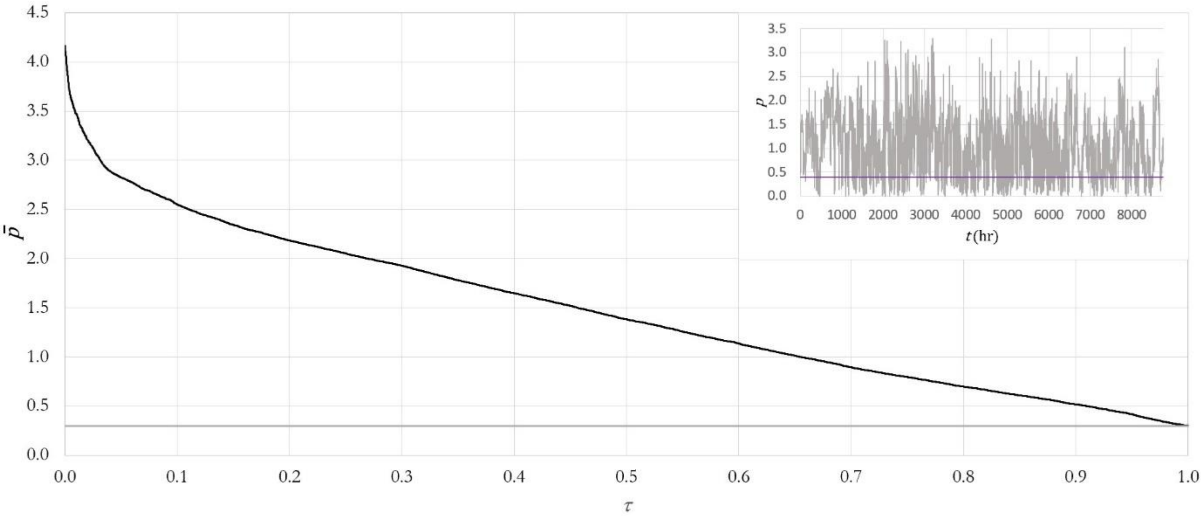

Figure 3 - An example of a power duration curve of a system including nuclear and VRE energy generation. The light grey line in the main graph represents the nuclear energy n, which is set to 0.4 in this example. In the upper right corner, one can see the electricity generation in a year.

4.1.2 The direct power consumption, hydrogen potential, and total final power

With the power duration curve constructed, the direct power consumption could be identified for the year. Needless to say, the direct power consumption equals all the generated electricity directly used for demand satisfaction, of which an example is visualized in Figure 4. Here the grey areas represent the direct power consumption. The dark grey represents the direct power consumption from r and the light grey from n.

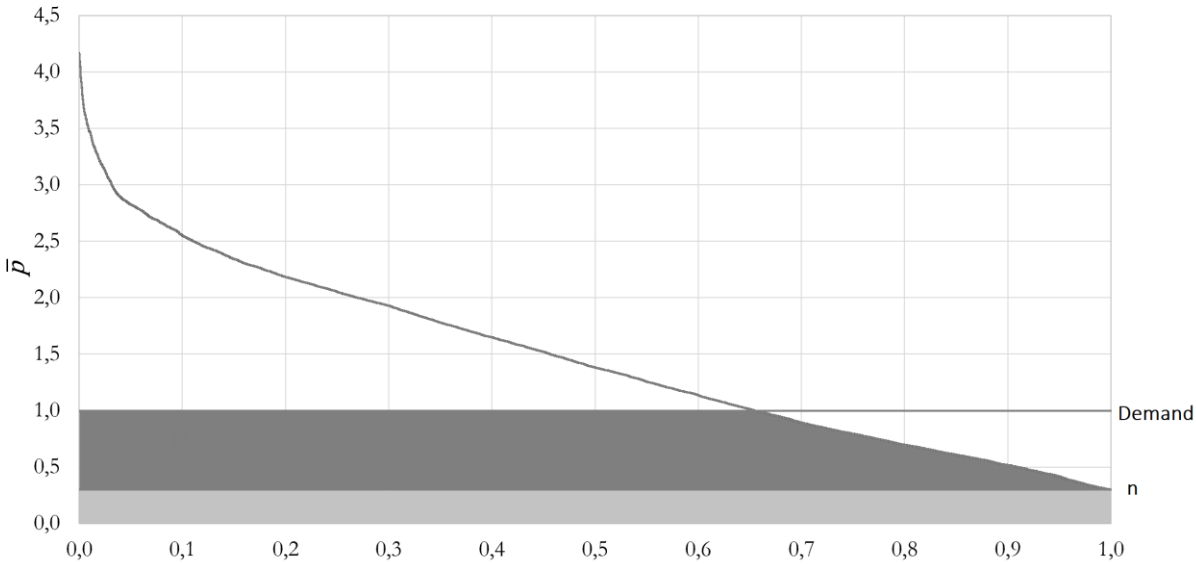

Figure 4 - An example of the direct power consumption of a system. The dark grey are represent the VRE direct power consumption, and the light grey represents the direct electricity consumption by nuclear.

Next, the hydrogen potential of a system was calculated. The variable e , which stands for the capacity of electrolysers, was added to the system to calculate the potential hydrogen production. With the addition of hydrogen storage, the system can be balanced to supply the demand throughout the year. A visual representation of balancing the system by hydrogen storage is given in Figure 5. To calculate the amount of hydrogen storage needed, some assumptions were made. One assumption is that hydrogen is cheaply storable and thus production and use of hydrogen throughout the year can be integrated. For this research, the long-term storage, of a maximum of one year, was studied. The amount of hydrogen produced depends on the available unserved energy. In the process of converting power to hydrogen and back to power, losses occur. Because of this, the efficiency drops. An overview of the efficiencies used in this model is given below.

Table 2 - Efficiency of hydrogen storage (Koning & Kramer, 2021).

Efficiencies	
η_e	70%
η_p	50%
$\eta_c = \eta_e \cdot \eta_p$	35%

η_e equals the efficiency from converting energy to hydrogen. η_p is the efficiency from converting hydrogen to power. It was assumed that the conversion back to power is displacing natural gas. Likewise, it was assumed that no additional costs are needed to switch from natural gas to hydrogen. The cycle efficiency – which is used for further reference – is depicted as η_c.

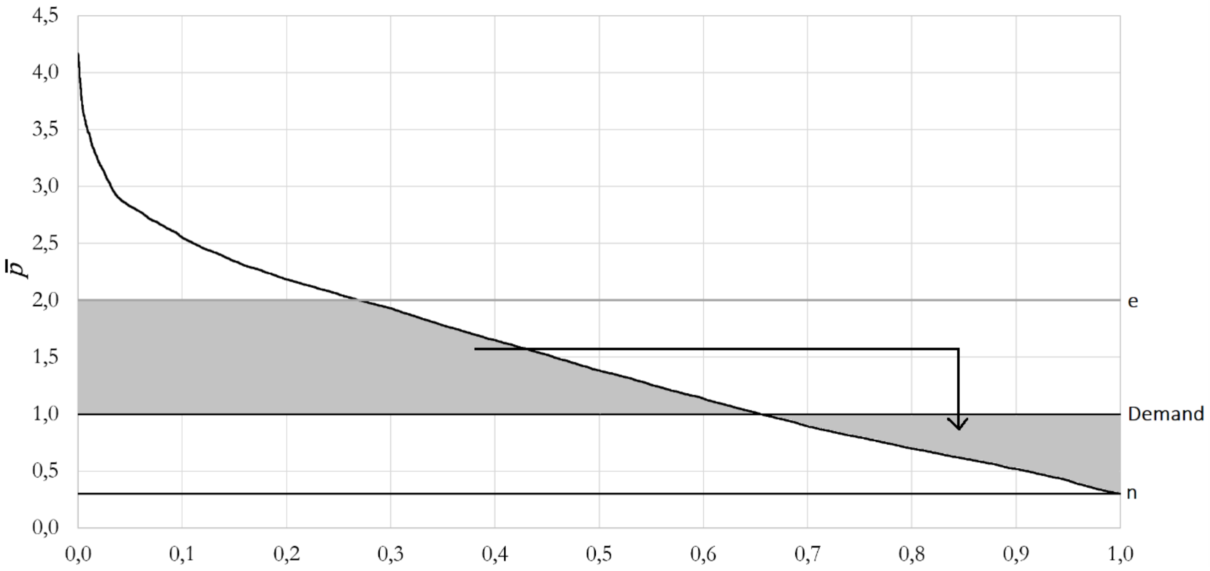

Figure 5 – An example of balancing the system. Here the system consists of 0.438 GW of nuclear, demand is flat at 1 GW and electrolyser capacity e of 1 GW.

Subsequently, an overview of all the different components is given in Figure 6. Here, one can see the power duration curve as the declining function, the levels of r, n and e as dotted lines. The grey areas represent the power-to-hydrogen (left grey area) and hydrogen-to-power (right grey area). Then, the total final power was calculated by adding the hydrogen production and direct power consumption.

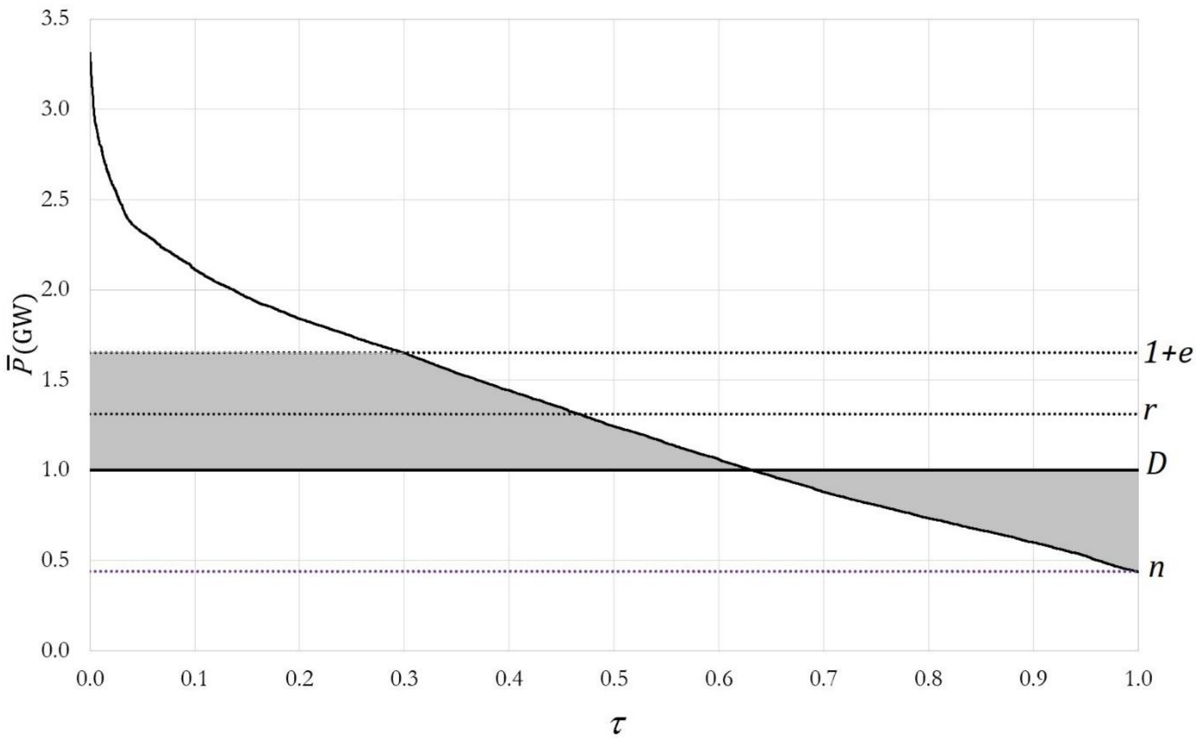

Figure 6 - The balancing of the system by hydrogen storage. This graph visualizes an example of the hydrogen storage needed to balance the system. To meet the average Demand of 1 GW, 0.438 GW of nuclear, 0.8731 GW of r and 0.65 GW of electrolyser capacity (e) must be installed.

4.1.3 Defining a decarbonised system in the (e, r, n, f)-space

With the system and its variables identified, the lines of equal production could be identified. When decarbonizing the system, the level of fossil energy production is being diminished. For every level of fossil-fuelled energy left, identified as variable f, the possible combinations of n and e with equal production were identified. Next, the cost of the system was identified. Two cost ratios were developed, nuclear over electrolysers and renewables over electrolysers. Since this model's options are to choose between the development of electrolysers and nuclear, the cost ratio between this is a useful tool to develop the costs. With the lines of equal production, in combination with the cost ratios, the cost optima lines of decarbonisation could be identified. This again was used to develop the decarbonisation scenarios for different cost ratios eventually. As the goal of this research was to decarbonize the electricity sector from 2030 onwards, the assumption was made that the goal for 2030 – which is a 70% reduction of fossil-fuelled electricity generation – is reached. The scenario of Kramer & Koning was used to identify the values of variable e, r for $f = 1$ till $f = 1$, which represents the 70% reduction since the system is normalized to 1 and has a flat demand of 1. An overview of this decarbonisation scenario is given in Figure 7. It can be seen that in this scenario, the use of hydrogen starts when there is 0.3 GW of fossil energy left in the system. This matches the starting point of this research.

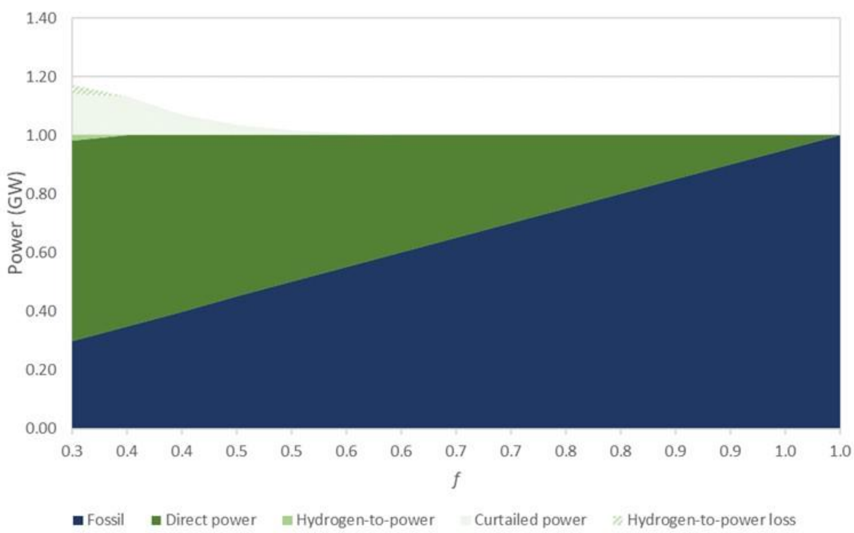

Figure 7 - Scenario for reaching the 2030 goals by Kramer & Koning (2021) with on the x-axis the level of fossil-fuelled electricity in the system and on the y-axis the power in GW.

For this analysis, a scenario was developed where solar, and wind investments are switched towards the investment in nuclear energy. At the point of 0.3 GW of fossil energy, 0.87 GW of renewables r and 0.13 GW of electrolysers e are in the system. Since the assumption is that there will be no more investments in r, the variable is set. Further decarbonization is thus reached by the development of nuclear energy, i.e., n, and electrolysers, i.e., e.

4.2 Mathematical framework

In this section, the mathematical calculations needed to construct the model are depicted. First, the mathematics used to calculate the VRE and nuclear electricity production are described, followed by the direct power production and hydrogen production potential. Lastly, the cost ratio calculations and cost optimization used in this research are depicted.

4.2.1 Renewable and nuclear electricity production.

First, the power duration curve was constructed, which consists of both nuclear and renewable power. Equation 1 was defined to calculate the energy generation per time t (in hours)

$$P(t) = r * p_r(t) + n * p_n(t) \tag{1}$$

Here, P is the total energy generated (in GW) for a system with VRE (r) and nuclear (n) energy sources. r and n equal the average renewable and nuclear energy respectively (in GW) in the system. p_r is the yearly VRE generation in GW. p is normalized, given in Equation 2

$$\langle(p_{\mathrm{r}}(\mathrm{t})\rangle = 1 \tag{2}$$

For nuclear power, p_n is equal to 1 throughout time t since it is a baseload supplier of energy in this model. Therefore, to simplify, the power function is given in Equation 3

$$P(t) = r * p_r(t) + n \qquad (3)$$

Subsequently, the power duration curve was formed. This was done by introducing $\bar{p}(\tau)$ as the power duration curve. This power duration curve is the time-ordered renewable and nuclear power in a year, where $0 < \tau \leq 1$, so that $\bar{p}$ is a continuously declining function as described in Equation 4.

$$\bar{P}(\tau) = r * \bar{p}_r(\tau) + n \qquad (4)$$

And

$$\langle \bar{p}_r(\tau) \rangle = 1 \qquad (5)$$

4.2.2 Direct power production

With the power duration curve and the demand set, the amount of power not directly served from VREs and nuclear were calculated. The power demand which is not served directly from VREs and nuclear energy is expressed in Equation 6.

$$\mathbb{I}_{\downarrow}(1, n) = \int_0^1 \big((1-n) - r * \bar{p}_r(\tau) \big) * \theta\big((1-n) - r * \bar{p}_r(\tau) \big) * d\tau \qquad (6)$$

Here, $\mathbb{I}_{\downarrow}$ is the integral of the unserved demand in GW, n the installed nuclear energy, r the installed VRE capacity, and θ is the Heavyside step function (0 when the argument is negative; 1 otherwise). Sine n and r are independent of time τ, the only variable that changes over time is $\bar{p}_r(\tau)$, which is the power-duration curve. Likewise, the excess power can be expressed as described in Equation 7.

$$\mathbb{I}_{\uparrow}(1, n) = \int_0^1 \big(r * \bar{p}_r(\tau) - (1-n) \big) * \theta\big(r * \bar{p}_r(\tau) - (1-n) \big) * d\tau \; P(t) = r * p_r(t) + n \qquad (7)$$

A visual representation is given in Figure 8Figure 4**Fout! Verwijzingsbron niet gevonden.**. Here, two different examples are given. One where $n = 0$, which is visualized by the light grey line, and another with the previous example with $n = 0.438$, which is visualized by the black line. Envisioned is the unserved power and excess power which is dependent on the power-duration curve $r * \bar{p}_r(\tau)$, demand level – which is set to 1 – and the level of n. For the system with $n = 0$, the area A is the excess energy and C + D the unserved energy. For a system with $n = 0.438$, the area A + B is the excess energy and D is the unserved energy. It is clear that with the introduction of nuclear energy, the need for hydrogen is reduced due to less unserved demand. Nevertheless, the excess energy is increased.

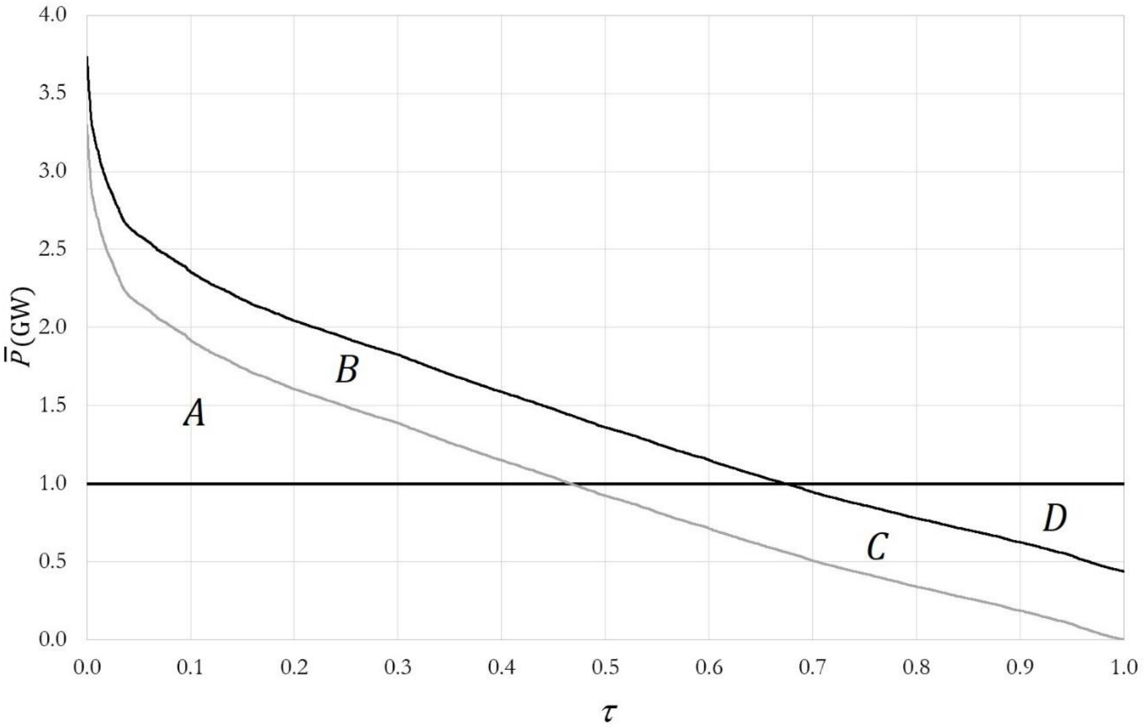

Figure 8 - Power-duration curves of a system with n=0 (light grey) and n=0.438 (black). The area of A and B represent the excess energy in the system and C and D the shortage of energy.

To make the calculations less complicated, the variable b was introduced. This variable b entails the variables which are consistent over time, i.e. demand and n. It results in an integral $\mathbb{I}$ which is merely dependent on one variable, as depicted in Equation 8 and 9.

$$\mathrm{i}_{\downarrow}(b) = \int_{0}^{1} \big(b - \bar{p}(\tau)\big) \cdot \theta\big(b - \bar{p}(\tau)\big) \cdot d\tau \tag{8}$$

$$i_{\uparrow}(b) = \int_{0}^{1} (\bar{p}(\tau) - b) * \theta(\bar{p}(\tau) - b) \ \cdot d\tau \tag{9}$$

Here, the variable, b, equals the demand – which is set to 1 GW – excluding the level of nuclear energy in the system, see Equation 10.

$$b = D - n \tag{10}$$

Where n can be a maximum of 1. The relation between $\mathbb{I}$ and i could then be expressed as depicted in Equation 11.

$$\mathbb{I}(b, r) = r \cdot \mathrm{i}\left(\frac{b}{r}\right) \tag{11}$$

Because the area under the curve of the integral is 1 (due to $\langle(p_{\mathrm{r}}(\mathrm{t})\rangle = 1)$, a simplification of the model could be realized as given in Equation 12.

$$\mathrm{i}_{\downarrow}(b) = i_{\uparrow}(b) + b - 1 \tag{12}$$

which allows expressing all that follows in terms of one integral, $\mathrm{i}_{\uparrow}(b)$, that needs to be evaluated numerically. Note that $\mathrm{i}_{\uparrow}(b)$ becomes one for b-values that exceed the maximum of the $\bar{p}(\tau)$-curve at $\bar{p}(0) = p_{max}$. For our particular choice of the power curve, $p_{max} = 3.29$.

4.2.3 Defining a power system in the (e, r, n, f)-space

With the level of r set, the different levels of e and n were calculated. This was done by defining the possible combinations of e and n for every level of f. Next, the cost-optimization was carried out to define the cost-optimum pathway into a decarbonized electricity sector. In this section, the assumptions made and the mathematical framework needed to conduct this is depicted. The amount of hydrogen produced in a system with e GW of electrolysers was as described in Equation 13.

$$\mathbb{I}_{\uparrow}(1 - n, r) - \mathbb{I}_{\uparrow}(1 - n + e, r) \tag{13}$$

Equation 14 depicts the calculated annual hydrogen production $\mathbb{H}$ for a system with e GW electrolysers.

$$\mathbb{H}(e, n) = \eta_e * r * \left[\mathrm{i}_{\uparrow}\left(\frac{b}{r}\right) - \mathrm{i}_{\uparrow}\left(\frac{b + e}{r}\right)\right] \tag{14}$$

Subsequently, by using the cost ratios as depicted in Figure 2 by the red circle, a cost-optimization for calculating the optimal combination of n and e was conducted. For this analysis, some reference numbers for the costs of the different energy generation technologies – namely e, r, and n – were used. The CAPEX of electrolysers and renewables was taken from the research of Kramer & Koning (2021), while the CAPEX of nuclear was retrieved from literature. The current cost for electrolysers is over 1000 €/kW, however, it is debated that in the future these costs could be reduced to between 250 and 300 €/kW. Kramer & Koning (2021) used the CAPEX of PV and Wind projects of 1000 \$/kW. As previously mentioned, the mix of Wind and PV for the Netherlands used is 3:1 (Wind:PV). With the average combined capacity factor of 30%, the CAPEX becomes 3000 \$/kW$_{\mathrm{a}}$ (average kW).

A small literature review defined the CAPEX of nuclear energy. Therefore, the OCC is used as an indicator for the CAPEX of nuclear energy in this research. The data for this was retrieved from two different sources. Firstly, data was delivered by NRG on the recent OCC of NPPs. Secondly, the data was gathered from the open database OpenEI. The data was corrected for inflation to correct for historical data, resulting in OCC in €$_{2021}$/kW. In total, 81 OCCs were found in 57 different studies reaching from 2002 till 2021. The distribution of the origin of these studies is given in Figure 9. Here, one can see that most of the studies are from the US or have no geographical specification. The unknowns consist of general studies into the OCC of NPPs.

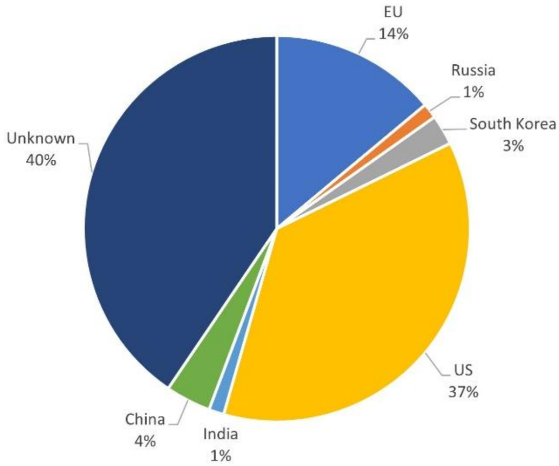

Figure 9 - distribution of origin of the studies

With the cost ratios found, the cost-optimization could be performed. This depended on the distribution of power sources. Therefore, the next calculations were used to calculate the power per source. For each level of f, the most cost-efficient levels of e and n are calculated for a fixed level of r. The level of f is thus equal to the demand minus the supply. Equation 15 depict the total power production, which is equal to the demand, set to 1

$$\mathbb{P}_{tot} = 1 \text{ (GWyear)} \tag{15}$$

$$\mathbb{P}_{dir} = 1 - r * i_{\downarrow}\left(\frac{(1-n)}{r}\right) + \text{n } P(t) = r * p_r(t) + n \tag{16}$$

Equation 16 depicts the direct power production, which represents the direct solar and wind production in combination with nuclear energy production.

$$\mathbb{P}_{H2P} = \eta_c * r * \left[i_{\uparrow}\left(\frac{1-n}{r}\right) - i_{\uparrow}\left(\frac{1+e-n}{r}\right) \right] \tag{17}$$

The annual hydrogen-to-power consumption calculation is given in Equation 17. Next, the annual production of f is given in Equation 18.

$$\mathbb{P}_f = f \tag{18}$$

By combining this, the total power generation was calculated as depicted in Equation 19

$$\mathbb{P}_{tot} = \mathbb{P}_{dir} + \mathbb{P}_{H2P} + \mathbb{P}_f = 1 \tag{19}$$

Which translates into Equation 20 and 21

$$1 = \left[1 - r * i_{\downarrow}\left(\frac{1-n}{r}\right)\right] + \left[\left(\eta_c * r * \left[i_{\uparrow}\left(\frac{1-n}{r}\right) - i_{\uparrow}\left(\frac{1+e-n}{r}\right)\ \right]\right)\right] + f(e,r,n) + n \qquad (20)$$

$$f(e,r,n) = 1 - \left[1 - r * i_{\downarrow}\left(\frac{1-n}{r}\right)\right] - \left[\eta_c * r * \left(i_{\uparrow}\left(\frac{1-n}{r}\right) - i_{\uparrow}\left(\frac{1+e-n}{r}\right)\right)\right] - n \qquad (21)$$

When we know that $i_{\downarrow}(b) = i_{\uparrow}(b) + b - 1$, then Equation 21 can be described as Equation 22.

$$f(e,r,n) = 1 - r * \left[(1-\eta_c) * i_{\uparrow}\left(\frac{1-n}{r}\right) + \eta_c * i_{\uparrow}\left(\frac{1+e-n}{r}\right)\right] - n \qquad (22)$$

Lastly, the stand-alone production of hydrogen by nuclear energy, $\mathbb{H}_{s.a.}$, was calculated as depicted in Equation 23.

$$\mathbb{H}_{s.a.}(e,n) = \eta_e * \mathbb{P}(e,n) = \eta_e * e, \text{ where } \eta_e * e \leq n \qquad (23)$$

The cost of stand-alone hydrogen is then equal to the formula given in Equation 24.

$$\mathcal{C}_{H_2 s.a.} = \frac{\mathbb{C}_{s.a.}}{\mathbb{H}_{s.a.}} = \frac{c_e * e + c_n * n}{\eta_e * \mathbb{P}(e,n)} = \frac{c_e * \left(\frac{e}{n} + CR\right)}{\eta_e * e} \qquad (24)$$

5. Results

This section depicts the results that have come from the steps taken in the previous method section. First, the power duration curves and the effect of the introduction of nuclear energy on the power duration curve are explained, followed by the potential hydrogen production. Next, the results from the literature review for determining the cost ratio of nuclear and electrolysers are described. Subsequently, the cost-optima pathways for combining n and e are depicted and the primary energy for every level of f. Finally, the model results and the impact of introducing nuclear energy into the system are described.

5.1 Power duration curves

The height of the power duration curve is dependent on the level of n, while the slope of the curve is dependent on the VRE production per hour. The latter has been set and the former has not. It is therefore in the range of $n = 0$ and $n = 1$. Visually, this is depicted in Figure 10. The lower power duration curve, visualized by the black line, is when $n = 0$ and the top line is at $n = 1$. The grey area in between represents the possible power curves depending on the level of n. The dotted line is the demand, which is set to 1. As one can see, the power at $\tau = 1$ does never surpass the demand. This is self-evident since there is no use in supplying more than the demand at every point of the year in an isolated system such as this. Furthermore, with the increase of n, the shortage of supply decreases, which is depicted by the grey area under the dotted line.

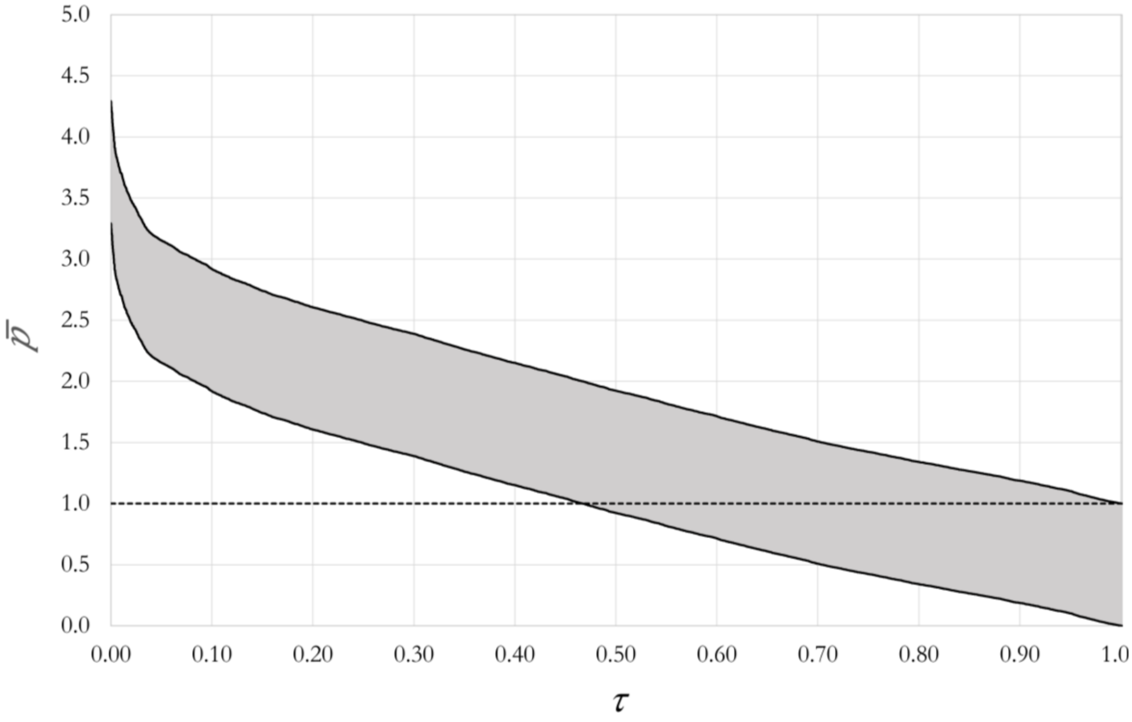

Figure 10 – The range of power curves the system can have, depending on the level of n. The lower black curve represents the power curve at n = 0. The upper black curve represents the power curve at n = 1. The dotted line represents the demand in the system.

5.2 Hydrogen production

With the power duration curves set, the potential hydrogen production at different levels of e and n are calculated. The hydrogen production is depicted in Figure 11. Again, the lower line is the hydrogen potential at $n = 0$ and the upper line is at $n = 1$. The grey area in between is the possible hydrogen production per level of capacity e. Since the hydrogen produced is the result of the surplus of r that is in excess over the demand, the total potential generation of hydrogen is dependent on r as well. Therefore, the higher capacity of n, the higher the surplus of r and thus the higher the hydrogen potential. It can be seen in Figure 11 that at $n = 0$, the marginal increase of hydrogen with the increase of e reaches zero near e capacity of 1 GW. The maximum hydrogen production at that point is approximately 0.13 GW. At $n = 1$, the marginal increase is almost zero at e capacity of 2 GW and the hydrogen production is here around 0.61 GW. This equals the r times the efficiency for conversion into hydrogen. Since r is fixed in this research, the maximum conversion and thus capacity of e is 0.61 GW. This equals the maximum conversion of all electricity generated by VREs, including the losses due to conversion.

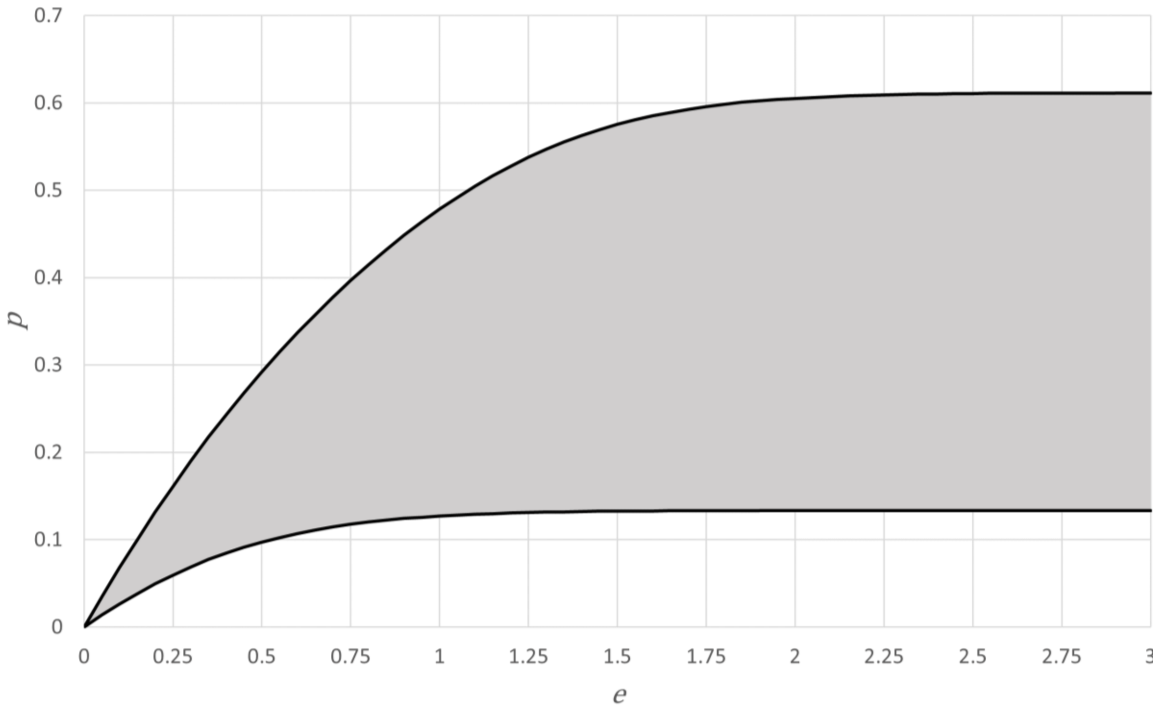

Figure 11 – The range of hydrogen production the system could produce. The lower black curve represents the hydrogen production for different levels of e at n = 0. The upper black curve represents the hydrogen production for different levels of e at n = 1.

5.3 Cost ratios

From an economic point of view, it is questionable to install the total capacity of 0.61 GW electrolysers. Thus, through a cost-optimization, the optimum combinations of n and e were identified. For this, the cost ratio of VREs over electrolysers and nuclear energy over electrolysers are used. As found by Koning & Kramer (2021), the cost ratio of VREs over electrolysers is equal to

$$CR_{r,e} = \frac{c_r}{c_e} \approx 3$$

The literature review resulted in a variety of values on the OCC of an NPP, of which an overview is given in Figure 12. The average value for the OCC of nuclear energy found in the literature is 4,496,25 $€_{2021}$/kW, with the lowest value of 1,492.59 $€_{2021}$/kW and the highest value of 11,700.00 $€_{2021}$/kW. Some studies identified a margin for the OCC instead of a single value. Therefore, an overview of the average values and their margins – if given – in Figure 12. It can be seen that the higher the OCC, the higher the uncertainty becomes. Since not all studies contained a minimum and a maximum price, it cannot be concluded that the uncertainty rises with an increase in price. The maximum average OCC – which is at percentile 100 – is 8,859.09 $€_{2021}$/kW.

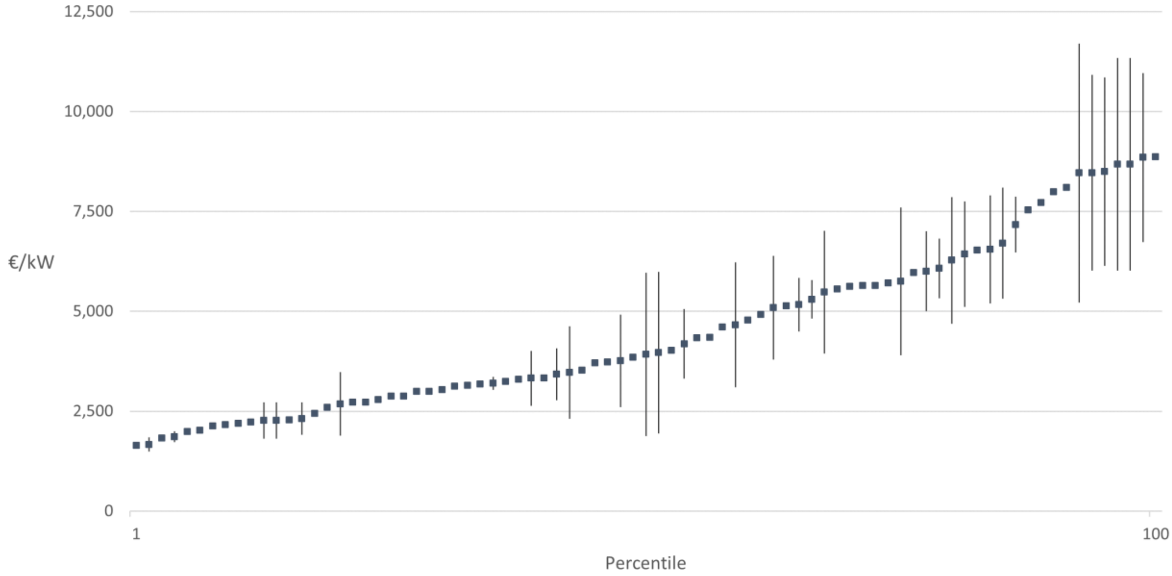

Figure 12 - The OCC of an NPP sorted from lowest to highest price with estimate margins in €2021/kW. The smaller bars represent the margins of OCC that some of the studies indicated.

Since this research is focused on the Dutch electricity sector, the OCC of western countries is the most representable. In Figure 13, the distribution of the same average OCC is given per geographical location. Here, it can be seen that up to around the first 50 percent of the studies found, the geographical location is unknown or from the United States (US). The values found for the EU, Netherlands, and France all have the higher OCC. These indicate that even though the globally average OCC could be low, European countries such as the Netherlands will have higher OCC than other countries.

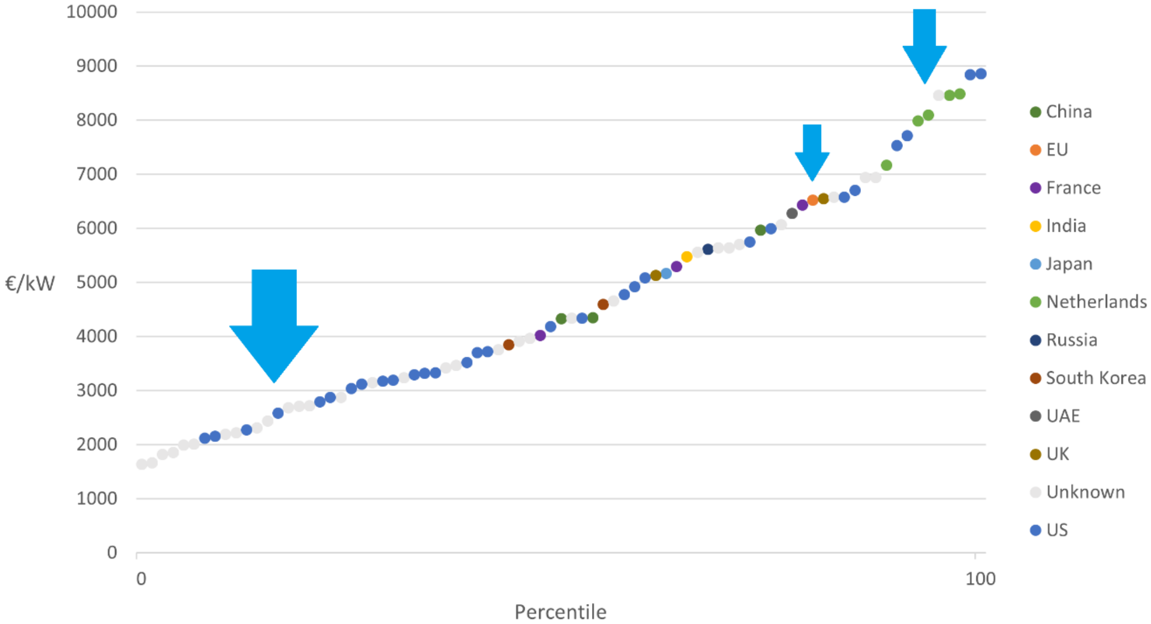

Figure 13 – The distribution of OCC per geographical location. The left arrow highlights the studies from the U.S. and unknown locations, the middle arrow the one from the EU and France, and the upper right the studies of the Netherlands. All in €2021/kW.

Next, the year of the research conducted has been compared. An overview of this is given in Figure 14. Here the R^2 of 12%, which indicates that time does not correlate with the OCC. In other words, there is no statistical proof that the costs of constructing an NPP increase over time. So there is no indication from this literature review that, over time, the OCC increase. What can be concluded is that throughout the years, the OCC of an NPP was between 3,000 and 8,000 €$_{2021}$/kW.

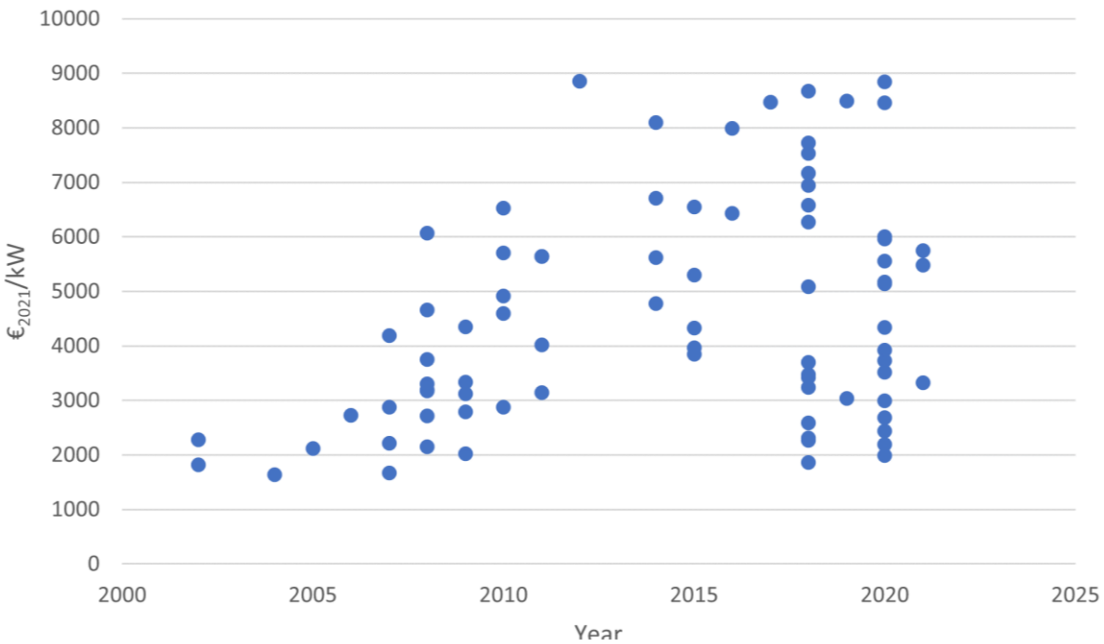

Figure 14 - Distribution of studies in the OCC of nuclear energy per year researched.

From these findings, it is concluded that there is no real consensus on the OCC of an NPP. Nonetheless, cost ratios for nuclear energy over electrolysers are needed for this research. With information on the probable OCC development in the future, which was gathered from NRG and the outcome of the literature review, the following different cost ratio scenarios are developed

$$CR_{A_{n,e}} \frac{c_n}{c_e} \approx 4$$

$$CR_{B_{n,e}} \frac{c_n}{c_e} \approx 5$$

$$CR_{C_{n,e}} \frac{c_n}{c_e} \approx 10$$

CR_A and CR_B represent the bandwidth of the probable case where the OCC will reach the value between 4,000 €$_{2021}$/kW and 5,000 €$_{2021}$/kW. The CR_C value represents an extreme scenario to see the impact of the cost ratio on the level of nuclear and electrolysers in the system.

5.4 Decarbonization strategies

With the cost ratios set, the decarbonization strategies could be formed. An overview of this is given in Figure 15. The indifference curves are given for different levels of f. It is limited by the technical maximum conversion, which is represented by the diagonal line starting from approximately 1.7, going up to 2.8 GW of e. In other words, when all excess energy produced by r and n would be converted to hydrogen. The CR4 and CR5 scenarios are relatively close together. The CR4 scenario at $f = 0$ has 0.45 GW of n capacity and 0.60 GW of e capacity. The CR5 scenario has 0.44 GW of n capacity and 0.65 GW of e capacity. When the cost ratio is doubled to the CR10 scenario, the ultimate combination at $f = 0$ equals 0.4 GW n capacity and 0.9 GW e capacity. Thus, by doubling the cost ratio, the capacity of electrolysers increases, but the nuclear capacity does not decrease as fast. This would suggest that there is a greater surplus of energy with an increasing cost ratio between electrolysers and nuclear capital costs.

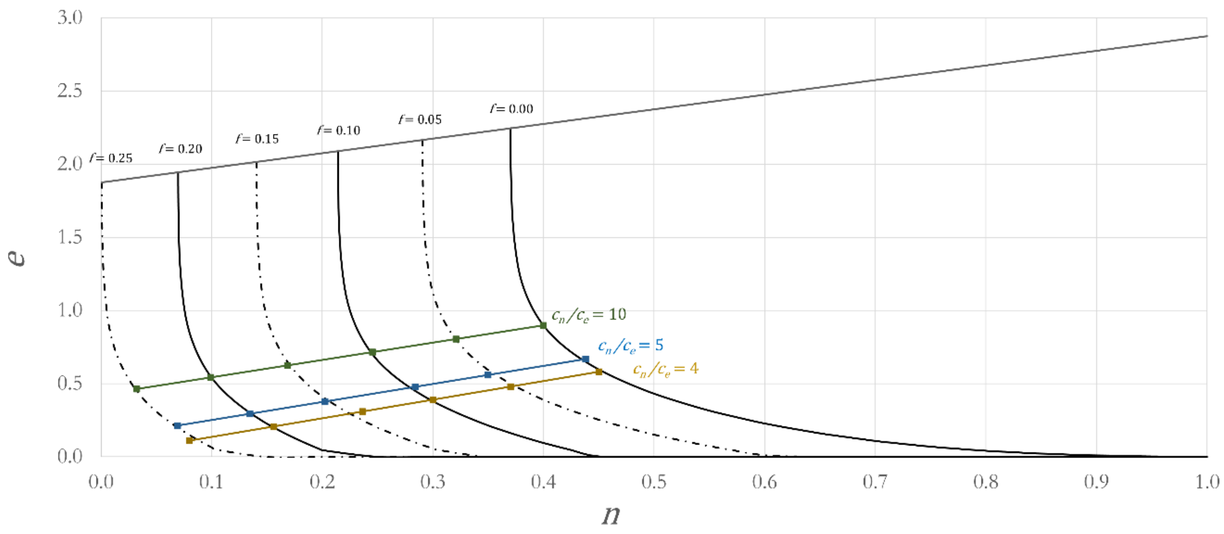

Figure 15 – Lines of equal renewable power production, which consist of direct power (nuclear and renewable) and H2P at a given level of f. The contour and dotted lines represent the combinations of n and e that are cost-optimal. The cost-optimum decarbonization pathway per cost ratio is depicted in brown (CR 4), blue (CR5), and green (CR10).

5.5 Pathways for decarbonization

With the (e, n)-combinations set for the different scenarios, the pathway for decarbonizing the energy sector was developed. The different pathways are given in Figure 16 and Appendix II. In Figure 16 the pathways of CR_A and CR_B are given since they are relatively similar. It can be seen that nuclear energy starts developing from roughly the same moment that hydrogen becomes relevant. This aligns with the expectations since the trade-off in this model is between electrolysers and nuclear energy. The CR5 scenario results in lesser curtailment compared to the CR4 scenario. This again is in line with the expectations where a higher cost ratio favours electrolysers over nuclear. With more electrolysers and thus more energy from VREs converted into hydrogen, the curtailment is lower. With the CR10 scenario, the curtailment is significantly lowered after the $f = 0.3$ mark, but the hydrogen-to-power loss increases significantly as well. Again, this is in line with the earlier explained expectations. The total energy in the system is fairly the same, with 1.32 GW for the CR_A, 1.31 GW for the CR_B, and 1.27 GW in the CR_C scenario. The decrease in total energy is the result of less nuclear energy in the system. This would suggest that with the introduction of nuclear energy in the system, the total energy rises. Another explanation for this could be that the fixed variable r results in unnecessary curtailment. Altogether, the impact of this is relatively small, which would suggest that the introduction of nuclear energy will not result in a significant increase in energy use in the system.

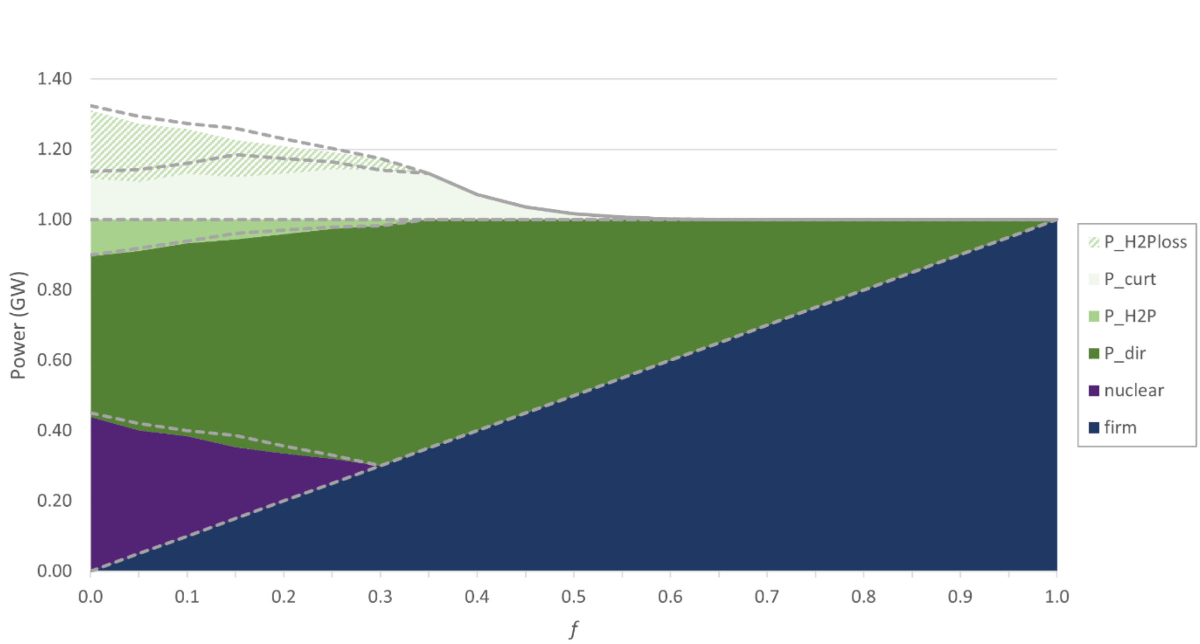

Figure 16 - Pathway to decarbonize energy sector for CR4 and CR5 scenario. The difference between the CR4 and CR5 scenarios is illustrated by the dotted line. This line represents the CR4 scenario.

The costs of the system are illustrated in Table 2. Here, the original scenario of Koning & Kramer (2021) is included in the second column. In the CR4 and CR5 scenarios, the system costs will decrease compared to the Koning & Kramer (2021) model. This would suggest that by introducing nuclear energy, with OCC between 4,000 to 5,000 €/kW, the total costs can be reduced. This can be since nuclear energy's marginal costs are lower than the marginal costs for electrolysers and VREs. However, for the CR10 scenario, the system costs are higher in comparison to the other scenarios. Here, the costs for nuclear energy are almost as high as with the CR4 and CR5 scenarios but uses more electrolysers. So, this would be economically unfavourable.

5.6 Cost reduction developments

The potential role of nuclear energy in this model is dependent on the cost developments of both electrolysers and the OCC of an NPP. There is a break-even point between the cost of installing solely VREs in combination with electrolysers and adding nuclear energy into the system. This break-even point lies at the cost ratio of nuclear energy over electrolysers of 5.77. The costs for both electrolysers and nuclear energy are given in Figure 17 - The break-even cost ratio for nuclear energy over electrolysers with a buffer of 10%. The break-even cost ratio is at 5.77. The cost of electrolysers and nuclear energy are in €$_{2021}$/kW. Figure 17, given in €$_{2021}$/kW. The diagonal line represents the cost ratio line of 5.77, with a buffer of 10%. Recent research into the cost of electrolyser resulted in 1,500 €$_{2021}$/kW for a GW-scale project (ISPT, 2020). This would suggest that the break-even point is currently at the OCC of an NPP at around 8,500 €$_{2021}$/kW. Therefore, the dots in the figure represent the current combinations, when assuming the OCC of nuclear energy is 4,000 €$_{2021}$/kW for CR_A, 5,000 €$_{2021}$/kW for CR_B, and 10,000 €$_{2021}$/kW for CR_C.

Kramer & Koning (2021) concluded that the costs of installing electrolysers would be subject to cost reductions in the future. They estimated that the costs of installing electrolysers would reach the level of 500 to 750 €$_{2021}$/kW, which is illustrated by the light grey box. What can be concluded is that the OCC of an NPP must reduce its costs to around 3,000 to 4,500 €$_{2021}$/kW to reach the break-even point. If the OCC is higher, it would be more beneficial to install electrolysers instead of nuclear energy.

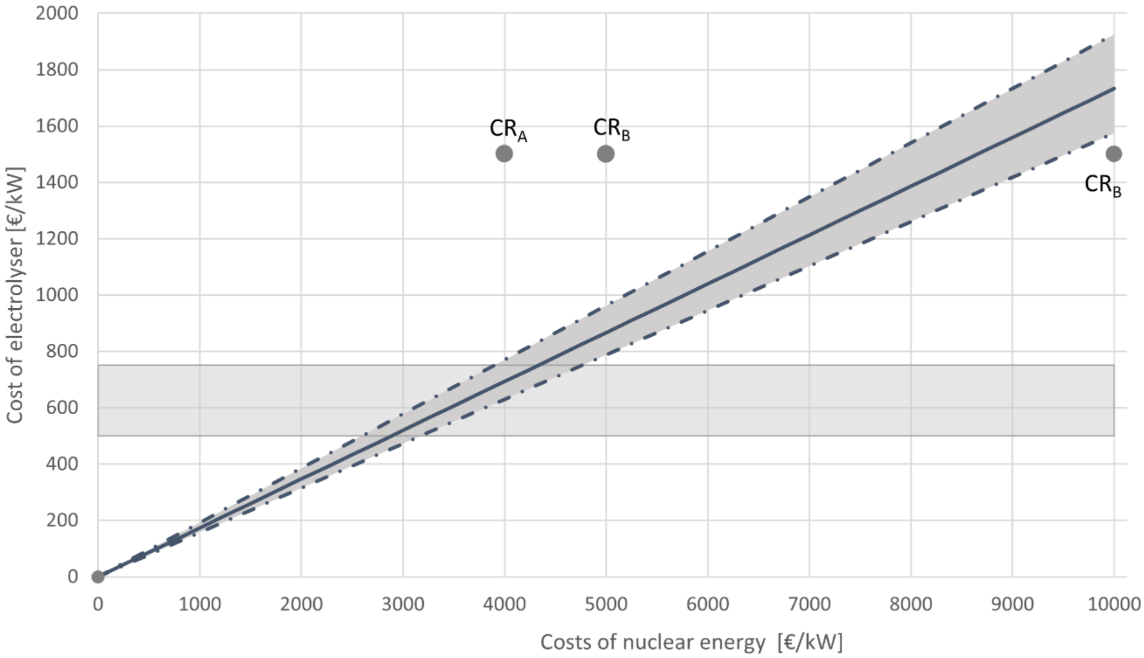

Figure 17 - The break-even cost ratio for nuclear energy over electrolysers with a buffer of 10%. The break-even cost ratio is at 5.77. The cost of electrolysers and nuclear energy are in €$_{2021}$/kW. The grey bar represents the prognosed cost of electrolysers in the future as identified by Kramer & Koning (2021).

5.7 Purple hydrogen production

As the decarbonization of the electricity sector progresses, hydrogen will be produced. Here, the role of nuclear energy to produce a baseload of electricity for demand satisfaction is extended with the role of producer of hydrogen, which is called purple hydrogen. The hydrogen produced could be used to balance the system or used in the non-power sector. For this, the costs of stand-alone hydrogen production by merely nuclear energy is calculated. Since electrolysers' cost is significantly lower than the cost of nuclear energy, the most cost-effective construction would be to fully convert the electricity produced by nuclear energy. Thus, in a system with 1 GW of nuclear energy, the capacity of 1 GW of electrolysers is the most cost-effective. This will result in a cost of purple hydrogen of 7,143 €$_{2021}$/kW for the CR_A scenario, 8,571 €$_{2021}$/kW for the CR_B scenario, and 15,714 €$_{2021}$/kW for the CR_C scenario.

6. Discussion

6.1 Discussion of the model

This research has built upon the already existing model of Kramer & Koning (2021). In this model, the proposed energy storage system (ESS) used is hydrogen storage through electrolysis. The storage of electricity will be needed due to the intermittency of electricity generation by solar and wind energy. The use of hydrogen as an ESS is also included In the Climate Agreement (Rijksoverheid, 2019a). As mentioned in Chapter 1.3, the development in the energy transition will most likely keep the same trajectory after the Climate Agreement's goals have been met. Thus, hydrogen storage, batteries, and demand-side management will contribute to decarbonizing the energy system (Rijksoverheid, 2019a). As Newbery (2018) mentioned, batteries have a niche value that could be useful in distribution networks where the costs of expansion are very expensive. However, for the more generic solution as investigated in this research, the use of batteries could be costlier (Newbery, 2018). Moreover, Haas et al. (2018) concluded that batteries its main role is supplying short-term storage, while hydrogen storage can be responsible for storing energy long-term. Since this research has focused itself on balancing the system in long-term periods, hydrogen as an ESS is plausible. However, other ESS should not be ruled out.

In addition, the model used the system costs as a proxy for the cost analysis. These system costs are described as the capital costs of the different technologies needed to supply the electricity for the system as a whole. As described in Chapter 3, the concept of the cost of generating electricity has multiple methods of calculating. By calculating the system costs, an indication of the capital costs of generating electricity is given. It is thus solely the costs of constructing the technologies needed to supply to satisfy the demand. The total final costs on which the LCOE is based are higher than the costs used in this research. The costs of constructing VRE technologies, NPPs, and electrolysers is dominated by its CAPEX. To compare these different technologies on a rudimentary level, the use of capital costs is thus plausible. It leaves out the speculation on interest levels of investment, which can be significantly higher for an NPP than a VRE technology. The total costs of this energy system, and with it the LCOE, will thus be higher than the costs identified by this research.

6.2 Discussion of results

The results show that there is a potential role for nuclear energy in the energy mix. This is somewhat in line with the research of NEA (2019). They concluded that the most cost-effective option for decarbonization is with a high share of nuclear power, and that the cost would rice over-proportionally with higher shares of VRE in the energy mix. They concluded, as in this research, that the share of renewables and nuclear energy remains the same with different scenarios. The same conclusion is made by ENCO (2020), where nuclear energy as a baseload supplier would deliver a big share of the needed baseload energy production in a cost-effective way.

The results have shown that nuclear energy is slowly developed as the decarbonization of the energy sector is progressing. In reality, the implementation of nuclear does not develop slowly over time. In the literature, there is speculation on the flexible use of nuclear energy and with this, a slow development of the share of nuclear energy in the energy mix (Shropshire et al., 2012). However, due to the very high upfront investment costs and the high interest to be paid, this is unlikely. It is thus most beneficial to run the NPP as much as possible, resulting in a higher capacity factor. So, as explained in Chapter 1.4, an NPP will supply its rated capacity of power from the first day of operation. This would imply that the shape of nuclear energy portrayed in Figure 16 will more likely look like a square rather than a triangle. In other words, there is no gradual implementation of nuclear energy as with the VREs. If managed incorrectly, this sudden implementation of a relatively high share of nuclear could result in either less fossil fuelled technologies or a higher level of excess energy. The first resulting in a successful decarbonization strategy and the latter leading to either higher curtailment.

Lastly, the role of nuclear energy in a stand-alone option with producing hydrogen has shown limited potential. This is in line with the research of Pinkey et al. (2020), where it was concluded that this technology is still in the pilot phase and needs more funding and policy assistance. The full potential role for nuclear as a hydrogen supplier would be found when this would be compared to other forms of producing hydrogen, such as green hydrogen. Further research in this could combine the values found by this research and the results of Kramer & Koning (2021) in combination with the costs of curtailment to find the most cost-effective way to produce hydrogen.

6.3 Limitations and recommendations

To be able to conduct this research, some simplifications were done to construct the model. This somehow limited the research in comparison to the reality. However, this is in line with the quote of George Box, who said, “All models are wrong, but some are useful.”

One assumption made in this model is the fixed level of r. By doing so, it is assumed that there will be no more development of VREs. The moment this development stops is at the mark of a 70% reduction of fossil-fuelled electricity generation. As previously explained, this corresponds to the 2030 goals of the Netherlands. Assuming no further development of VREs happens after this level, one limits itself on generating electricity from other energy sources. Thus, nuclear energy will be more likely to develop in the system. With the growing social and political debate about onshore wind and solar PV (AD, 2020), the assumption is not implausible. Bolwig et al. (2020) have proven that social acceptance significantly impacts the pathway scenarios. Therefore they concluded that the techno-economic, socio-technical, and political aspects should be analyzed when exploring the energy transition. Research into the techno-economic, socio-technical and political impacts of the different system scenarios from this research would be interesting to conduct in the future.

Another assumption made is that the system is isolated. In reality, this is not the case. As stated in the Climate Agreement, the import and export of renewable energy are solutions to the intermittency problem. Electricity can be exported during peak hours and imported during periods of shortage (Rijksoverheid, 2019a). Therefore, in reality, the system is more integrated than portrayed in this research.

Further, this research has focused on electricity production by an NPP. However, the role of an NPP for the energy mix might extend to merely electricity producer. The heat produced by an NPP could, for example, be used by industry (Rosen, 2020). Not only the electricity sector but the entire energy sector must decarbonize. Thus, by directly using the heat generated by nuclear energy instead of converting heat to electricity and back to heat, fewer efficiency losses might occur. Since this is out of the scope of this research, further research into this is recommended.

Lastly, this research its scope was to identify the role of nuclear energy in terms of economic feasibility. However, there are more factors in determining the potential role of nuclear energy in the future. Therefore, with the results of this research, it is recommended for further research to look into the social acceptability of nuclear energy, as well as its external effects. For example, as stated in Chapter 1.4, the ecological footprint in terms of land use is significantly lower for nuclear energy compared to VREs. Next, the storage of nuclear waste remains a problem to be solved. Altogether, further research in nuclear energy as a supplier of electricity and hydrogen is recommended to identify the potential role fully.

7. Conclusion

The energy sector must decarbonize. The Dutch government has constructed the Climate Agreement, where goals have been set to decarbonize the energy sector. This Climate Agreement states that all forms of electricity generation should be re-evaluated, one of which is nuclear energy. The source of energy must be reliable, affordable, and sustainable. Nuclear energy is proven to be reliable and sustainable, but its affordability is questioned. This research has tried to answer this by studying the potential role nuclear energy could play in an energy mix where and when solar, wind, and green hydrogen dominate. Here, green hydrogen would be used to balance the system and satisfy demand throughout the year. The level of VREs in the system was at a fixed level, corresponding with the goal set by the Climate Agreement. By doing so, the impact of nuclear energy on the system costs could be found. The role of nuclear energy was identified by adding a nuclear energy component to a model created by Kramer & Koning (2021). Firstly, it was concluded that with the introduction of nuclear energy in the system, the potential production of hydrogen as an ESS was higher than in a system without nuclear energy. Next, the optimal combination of nuclear energy and hydrogen storage with a given level of VREs was identified for the system. For it, the height of the OCC of an NPP was retrieved through a literature review. While there was no consensus in the literature on the OCC costs, a bandwidth of OCC was constructed to conduct this research. From these OCCs, different cost ratios of nuclear energy over electrolysers were created to conduct a cost-optimization and find the most cost-effective way of decarbonizing the energy sector. Three different scenarios were developed, two for the bandwidth identified and one extreme scenario for isolating the effect of OCC on the level of nuclear energy. What could be concluded is that the cost optima combinations of nuclear energy and electrolysers with a given amount of VREs were not significantly different for the bandwidth scenarios. While with the extreme scenario did not result in a significant change of the level of nuclear energy, the cost increased significantly. So, by introducing nuclear energy into the mix, the total system costs could be reduced compared to a scenario without nuclear energy, depending on the cost ratio. However, the expected cost reductions in electrolysers force a need for cost reduction in OCC of an NPP in order to retain the potential role nuclear energy has at the moment. When nuclear energy would be used as a producer of hydrogen, the equal capacity of electrolysers is recommended to be installed to limit the costs of producing hydrogen from nuclear energy. Hence, this research has concluded that there is a role that nuclear energy could play in an energy mix when and where solar, wind and. green hydrogen dominate. It can do so by being a baseload supplier of electricity and, to a limited extent, a purple hydrogen producer. However, to maintain this potential role, it must reduce its OCC to be cost-competitive in the future. Further research into other components than system costs is recommended to identify the potential role of nuclear energy fully.

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Appendices

I. Scenario Koning & Kramer (2021)

f	r	e
0.30	0.87	0.13
0.35	0.78	0.00
0.40	0.67	0.00
0.45	0.59	0.00
0.50	0.52	0.00
0.55	0.46	0.00
0.60	0.40	0.00
0.65	0.35	0.00
0.70	0.30	0.00
0.75	0.25	0.00
0.80	0.20	0.00
0.85	0.15	0.00
0.90	0.10	0.00
0.95	0.05	0.00
1.00	0.00	0.00

II. Pathway for decarbonization from Koning & Kramer (2021) and this study

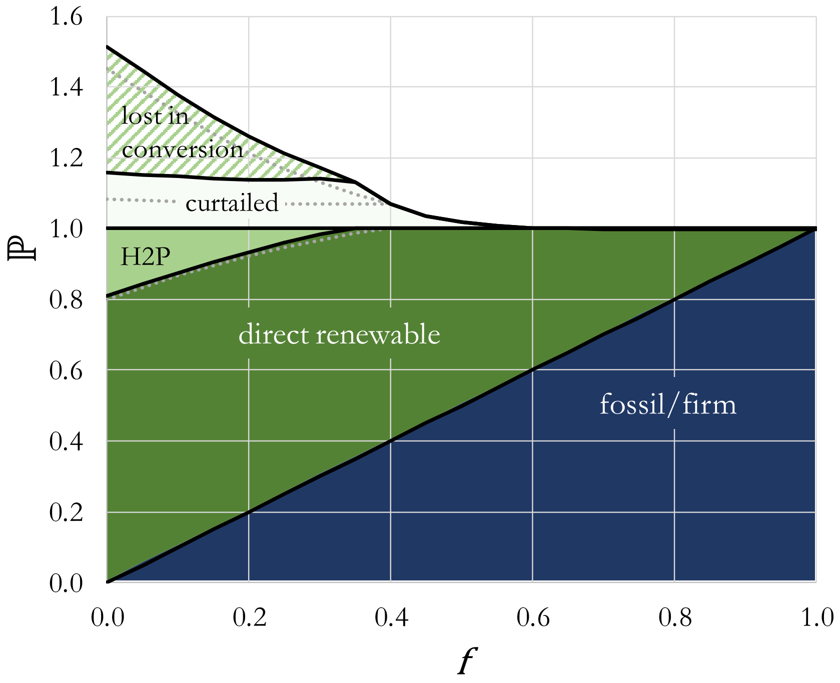

Figure 18 - The pathway for decarbonization with VREs and hydrogen storage (Koning & Kramer, 2021)

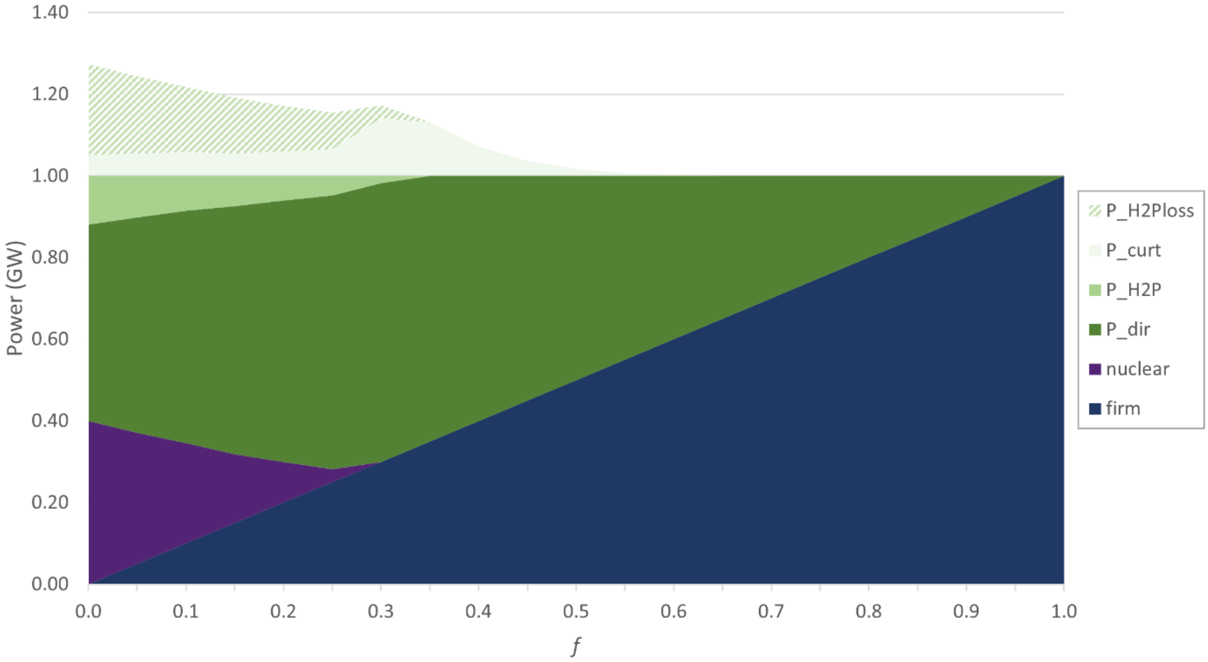

Figure 19 - Pathway to decarbonize the energy sector for the CR10 scenario.