Small modular reactors in the Dutch energy system

Combined heat and power production in industry

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Contents

1 Introduction

In addition to renewable energy sources such as wind and solar energy, nuclear energy can contribute to a CO_2-free energy supply. This is recognized by the Dutch government and has led to a policy change in which, in addition to a lifetime extension of the existing Borssele nuclear power plant, efforts are being made to realize two to four new large-scale nuclear power plants (EZK, 2023) (PVV, VVD, NSC, BBB, 2024). This concerns large-scale nuclear power plants (NPPs) of generation III+[1] with a power generation capacity of 1000 to 1500 MW.

Nuclear energy technology continuous to improve. Various innovative types of nuclear reactors are being developed, with a focus on small modular reactors (SMR's). The proposed expansion of nuclear capacity in the Netherlands can therefore partially take place with SMRs with a power generation capacity below 500 MW_e. In the development of SMRs a distinction can be made between generation III+ and generation IV reactors (also called advanced modular reactors) (IAEA, 2020). The development of SMRs of generation III+ is closer to market introduction. The first-of-a-kind (FOAK) SMRs are expected to be built this decade (Breijder, 2023).

SMRs are expected to have a number of advantages over large-scale nuclear reactors. Due to their smaller scale, most components can be made in a factory hall and the design can be simpler. This provides a cost advantage that largely offsets the disadvantage of the small scale[2] (Scheepers, G.J., Roelofs, H., & Gerdes, 2021). The smaller size of an SMR may also make this type of NPP more adaptable: due to less space and cooling water requirements than a large-scale NPP, in principle more locations are suitable to build an NPP. SMRs can also be operated as combined heat and power units, supplying process heat to industry or heat to district heating (Nuclear-21, DNV, Evocatie, Stork, 2022).

Using the integrated energy system model OPERA, TNO has conducted a scenario study into a future sustainable energy system for the Netherlands in which the Dutch energy system will be greenhouse gas neutral by 2050. In the scenario study also the role of nuclear energy was investigated (Scheepers, et al., 2024). In addition to the scenario study, TNO, in collaboration with NRG, conducted further research into the cost-effectiveness of SMRs from a system perspective. Analyses were conducted into the deployment of SMRs in industrial clusters in which SMRs supply heat to industrial processes in addition to electricity. This concerns further analyses of model results of the same scenarios and variants as in the aforementioned scenario study.

This report first provides a brief description of the approach to the scenario study (Chapter 2). Chapter 3 discusses the results of the analyses into the possible role of SMRs in the future Dutch energy system. In Chapter 4, the report concludes with conclusions and recommendations. For a detailed description of the scenario study, reference is made to (Scheepers, et al., 2024). In addition to the results of the scenario study, this reference also contains a detailed description of the assumptions for the scenarios and variants and input data used. Quantitative results for the scenarios and variants in the form of graphs and diagrams can also be viewed in the webtool http://energyscenarios.tno.nl.

[1] Nuclear reactors are divided into generations. The most modern reactor types on the market are Generation III+ with improvements in safety, operating life, fuel technology and efficiency compared to Generation II built in the 1970s and 1980s. Generation IV are reactor concepts in development from which further improvements are expected.

[2] By building larger nuclear reactors, the costs per megawatt decrease (economy of scale) but the construction time increases. With serial production, the cost per megawatt also decreases due to standardization and relatively shorter construction time (economy of numbers).

2 Approach

2.1 Scenarios and industry variants

Future transition paths for a sustainable Dutch energy system can be investigated using scenarios. Based on a coherent set of realistic assumptions and boundary conditions, scenarios describe the possible development of the energy system. Two scenarios drawn up by TNO were used for this study: ADAPT and TRANSFORM (Scheepers, et al., 2024). These scenarios are based on different visions of the future for the Dutch energy system. In both visions, the aim is to reduce greenhouse gas emissions by 55% by 2030 and to achieve greenhouse gas neutrality by 2050. Population growth and the development of the Dutch economy remain the same in both scenarios. The way in which the objectives are achieved is different. The two scenarios differ in particular in terms of intrinsic motivation and support for change among government, citizens and companies (see Box 1).

Of all energy-consuming sectors, the development of the industry sector is the most uncertain. If industrial production processes have to be made more sustainable, companies will probably build their new factories in places where sustainable energy (e.g. electricity, hydrogen) and sustainable raw materials (e.g. biomass) are available in sufficient quantities and at relatively low prices. The available amount of biomass in the Netherlands is small, but with the North Sea it does have great potential for generating electricity from wind energy and storing CO_2. Furthermore, the Netherlands is well situated in relation to European markets and has seaports and a well-developed transport infrastructure. The uncertainty about how four energy-intensive industrial sectors will become more sustainable (production of fertilizers, steel, liquid fuels and high value chemicals[3]) has been investigated using three industry variants compared to the TRANSFORM scenario (see Figure 2.1), whereby:

- The production volume in these four sectors is decreasing as a result of competition with foreign producers who have access to sufficient sustainable energy and raw materials at relatively low prices.
- Production in the Netherlands is maintained, but the energy-intensive part of the production chain in the Netherlands is (partly) being replaced by imports of semi-finished products[4].
- The production volume in the Netherlands is decreasing and the energy-intensive part of the production chain in the Netherlands is being replaced by imports of semi-finished products.

In order to investigate the sensitivity of the results with respect to boundary conditions and assumptions, a few what-if analyses were performed. These what-if analyses examined whether investment in and use of SMRs changes when input parameters are varied.

[3] High value chemicals (HVCs), i.e. olefins (e.g. ethylene, propylene and butadiene) and aromatics (e.g. benzene, xylene and toluene), and aromatics.

[4] Semi-finished products refer to:
- Refineries: bio-intermediates, such as bio oil, ethanol, hydrogen
- HVCs: bio/renewable-naphtha, bio oil, ethanol, bio/renewable methanol, plastic waste, hydrogen
- Fertilisers: ammonia, hydrogen
- Steel: hot briquetted iron (HBI), hydrogen.

Box 1 – Visions on the future (storylines)

ADAPT

- *Netherlands and EU will meet 2030 and 2050 GHG reduction targets.*
- *Society values the current lifestyle.*
- *EU countries have their own policies in achieving GHG reduction.*
- *Industrial production and economic structure remain basically the same.*
- *National and local government take the lead.*
- *Adapting and optimising the energy system and industrial processes.*
- *Planning for structural change post 2050.*
- *To abate CO_2 emissions, fossil fuels are expected to be utilised in combination with carbon capture and storage (CCS).*

TRANSFORM

- *The Netherlands and EU will meet 2030 and 2050 GHG reduction targets.*
- *Strong environmental awareness and sense of urgency in society.*
- *EU and Netherlands want to become an innovative power house.*
- *Individual and collective action by civilians.*
- *Government has a stimulating and enabling role.*
- *Ambitious transformation of energy system, transition of energy intensive industry, resulting in lower industrial production and energy use, increase of service sector output.*
- *Reduction in other GHG intensive activities (such as animal husbandry and international travel).*
- *A limited use of CO_2 storage.*

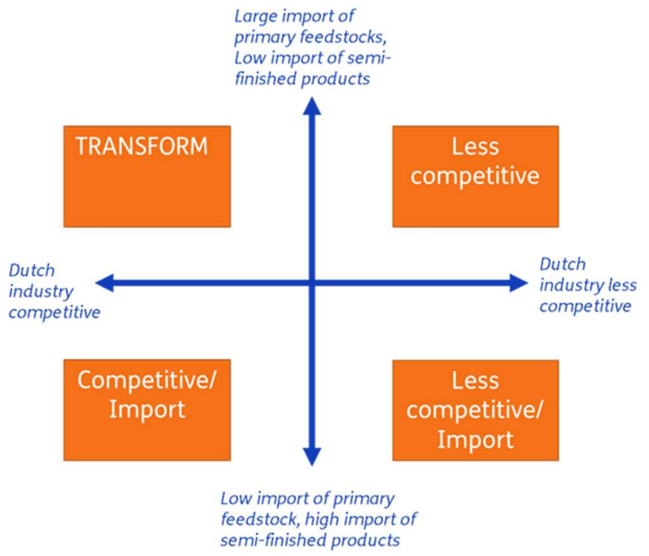

Figure 2.1: Matrix for the industry variants

2.2 OPERA model

The OPERA model was used to make quantitative projections of the scenarios, industry variants and what-if analyses. This integral energy system model for the Netherlands calculates an energy system for a specific year with which the energy demand can be met and industrial production can be realised while at the same time meeting the boundary condition for maximum greenhouse gas emissions. Using an optimisation algorithm, the model (endogenously) determines the technology deployment and the supply and demand mix. The model selects the technologies and energy sources that lead to the lowest social costs of the energy system.

The OPERA model is shown schematically in Figure 2.2. Input parameters used by the OPERA model are:

- Maximum greenhouse gas emissions.
- Energy demand, mobility demand and production of industrial products.
- Techno-economic data of the technology options.
- Price of imported energy and raw materials.
- Specific constraints on the use of technologies, such as maximum potential for wind and solar energy production, CO_2 storage and nuclear power plants.

The OPERA model provides the following results:

- Physical results: mix of energy supply and demand (total and per sector), technologies used (e.g. installed capacity, full load hours), import and export of energy (e.g. fossil energy, biomass, electricity, hydrogen), residual greenhouse gas emissions.
- Economic results: system costs and annual investments (total and per sector) and shadow prices (based on marginal costs for CO_2 reduction and production of electricity and hydrogen).

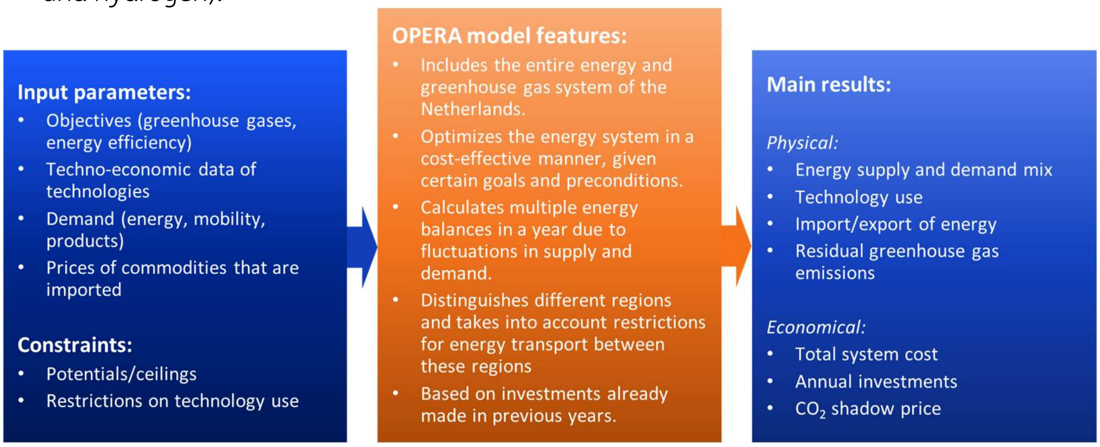

Figure 2.2: Schematic representation of the OPERA model

The model takes into account the fluctuating energy demand during a year and the variable energy production from wind and sun. In doing so, supply and demand are balanced for each time period, whereby options such as demand management and energy storage are also used and energy is imported or exported from and to neighbouring countries. The model distinguishes between different regions in the Netherlands: 7 regions on land (each industrial cluster falls into a separate region) and 7 regions on the North Sea with distinctive wind regimes and distances to the coast, see Figure 2.3. Heat cannot be exchanged between regions, because long-distance transport of heat is too expensive and leads to considerable heat losses. Electricity can be transported between regions and also to and from neighbouring counties. For transport over the high-voltage grid and over the interconnections with neighbouring counties, a capacity limitation is taken into account. The model uses a myopic approach: for each subsequent year for which an energy system is calculated, the model takes into account the assets already present from the previous period based on the technical lifetime of these assets. The model determines whether additional capacity must be invested to meet the demand.

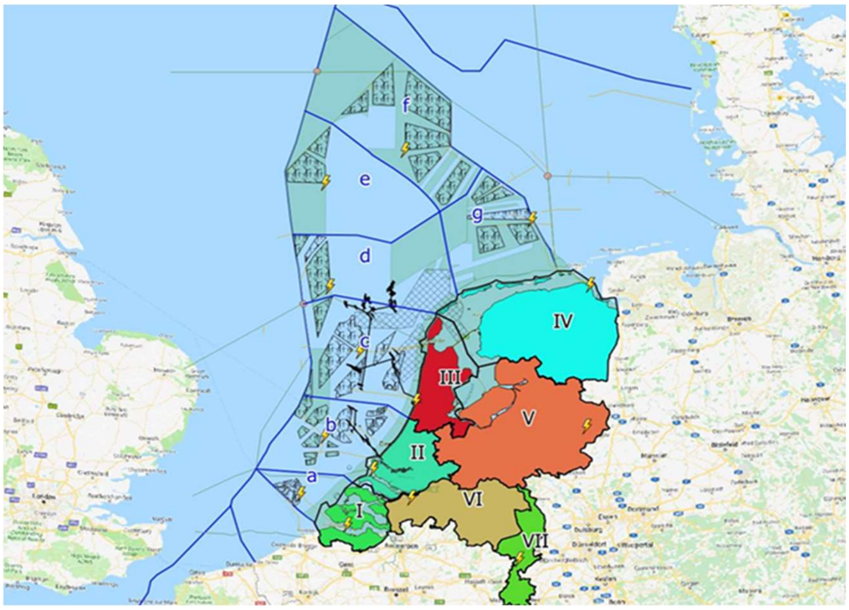

Figure 2.3: Onshore and offshore regions in het OPERA model

The energy-intensive industry in the Netherlands is concentrated in five industrial clusters, see Table 2.1. These industrial clusters largely coincide with the regions in the model, with the exception of Noord-Brabant. The industry in West-Brabant around Bergen op Zoom is included in the Zeeland region and the industry in Moerdijk in the Zuid-Holland region.

Table 2.1: Industry clusters in the OPERA model

Region	Indicated in OPERA	Industry cluster[5]
I	Zeeland	Zeeland-West Brabant
II	Zuid-Holland	Rotterdam-Moerdijk
III	Noord-Holland	Noordzeekanaal
IV	Noord-Nederland	Noord-Nederland
V	Midden-Nederland	-
VI	Noord-Brabant	-
VII	Limburg	Chemelot

2.3 Nuclear power plants

Assumptions have been made for nuclear power plants for the scenarios and industry variants. The OPERA model distinguishes four different types of nuclear power plants. The maximum permitted NPP capacity in which investments can be made differs by type (see Table 2.2). This is related to policy choices regarding the Borssele nuclear power plant (extending the operational lifespan up to 2042) and assumptions regarding commercial availability and realisation period of new nuclear capacity: two large-scale NPPs (generation III+) with a capacity of 1.5 GW_e each, a number of small modular reactors SMRs (generation III+) with a capacity of 0.15 GW_e each, one advanced NPP (generation IV) with a capacity of 0.2 GW. Except the Borssele NPP, the OPERA model determines which deployment of nuclear production capacity is cost optimal. The Borssele NPP will always be available in 2030, 2035

[5] As indicated in Cluster Energy Strategies (CES) 2022.

and 2040. If new nuclear production capacity is added in a particular year, this nuclear capacity will also be available in the following years.

Table 2.2: Maximum power output nuclear plants (GW)

	2030	2035	2040	2045	2050
Nuclear power plant Borssele	0,5	0,5	0,5	0	0
New built large scale power plants	-	1,5	3	3	3
Small modular reactors (SMRs)	-	-	0.45	0.9	2
Advanced nuclear power plant (generation VI)	-	-	-	-	0.2
Total	0,5	2,0	3,95	3,9	5,2

There are several SMRs in development, such as VOYGR, BWRX-300, UK SMR, SMART, SMR-160 (Breijder, 2023). For the OPERA calculations a generic SMR was assumed, based on characteristics as shown in Table 2.3 (Iovanovici, 2024). The investment costs and operational costs are equal to those of a large-scale nuclear power plant, whereby the investment costs are assumed to decrease over time. A technical lifespan of 60 years is assumed.

The SMR can be operated in full electricity mode (with an efficiency of 33%) or in a mode in which, in addition to electricity, SMRs also supply process heat in the form of steam at a temperature level of approximately 300 °C. In this heat mode, about half of the heat produced by the nuclear reactor is supplied as process heat. When supplying process heat, the conversion efficiency for electricity production drops to 18%. The OPERA model distinguishes five types of industrial heat demand: below 100 °C (hot water), 100-200 °C (steam), 200-400 °C (steam), 200-400 °C (direct heating), above 400 °C (direct heating). In the model analysis it was assumed that SMRs are only used to cover industrial heat demand of 200-400 °C (steam). However, SMRs can also supply heat at lower temperature levels. This has not been investigated further.

Table 2.3: Characteristics of a generic SMR

Parameter	Unit	2030	2050
Investment costs	€/kW$_e$	7097	6104
OPEX fixed	€/kW$_e$/a	100.4	100.4
OPEX variable	€/MWh$_e$	17.8	17.8
Max. thermal capacity	MW$_{th}$	500	
Max. electric output	MW$_e$	150	
Max. heat output	MW$_{th}$	250	
Capacity factor	%	95	
Minimum load	%	50	
Maximum ramping	%/hour	40	
T_{heat}	°C	300	
Technical lifetime	Year	60	

3 Results

3.1 Electricity demand and industrial heat demand

To understand the deployment of SMRs and the role this technology could play in the future energy system it is important to understand the demand for electricity and industrial heat (200–400 °C steam)[6] for the different scenarios, industry variants and what-if analysis. The total demand for electricity and industrial heat are given in Appendix 1, whilst the output in 2050 is represented graphically in Figure 3.1 for the readers convenience. TRANSFORM is taken as the default scenario for comparisons with industry variants 3, 4 and 5, because these variants are based on this scenario but with different industrial activity and imports of semi-finished products. What-if analyses 6 and 7 are based on TRANSFORM as well, but features doubled potential for SMRs. Additionally, in 7 potentials for offshore wind and solar are limited to the same level as in ADAPT (however, to have a feasible solution, the offshore wind potential was increased in 2050 to 60 GW)[7]. Although the scenario modelling is performed for the period 2030-2050 in steps of five years, the analyses for SMRs are limited to 2040, 2045 and 2050 as SMRs are deployed from 2040 onwards. For the analysis the focus lies on 2050, since the different assumptions, and their consequences on the energy system are expressed more explicitly in later years.

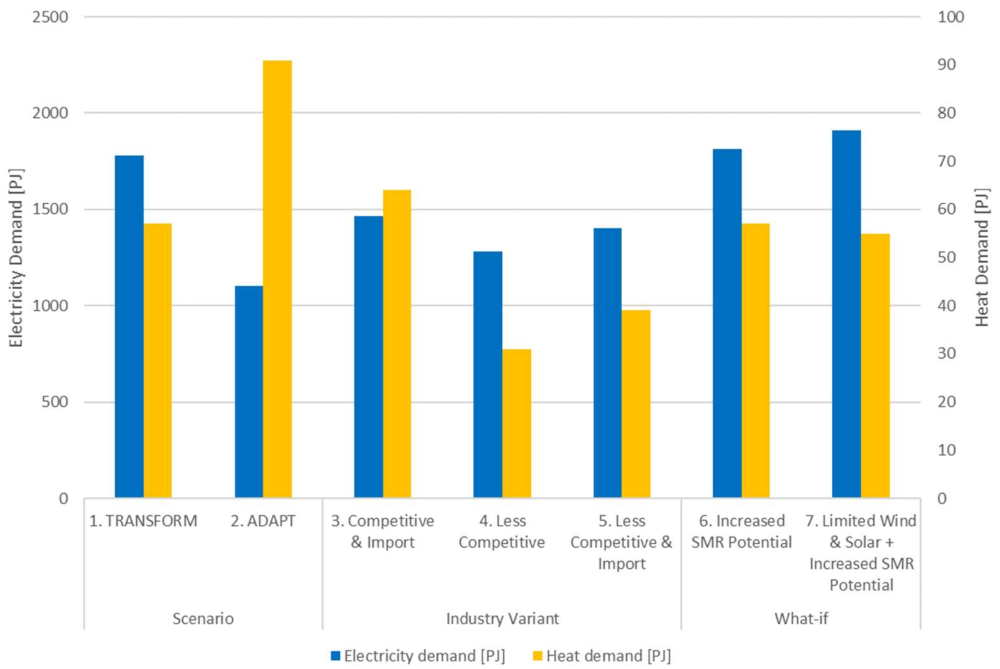

Figure 3.1: Electricity and industrial heat demand (200-400 °C steam) in 2050 for the different scenario's, industry variants and what-if analyses.

[6] For simplicity the specific 200–400 °C will be called (industrial) heat in the analysis.
[7] In TRANSFORM maximum capacities for offshore wind are in 2040, 2045 and 2050: 45, 58 and 70 GW respectively and for solar 84, 108 and 132 GW. In ADAPT these maximum capacities are for offshore wind 36, 38 and 40 GW respectively and for solar 69, 89 and 109 GW. (Scheepers, et al., 2024) The maximum capacity of offshore wind has been increased to 60 GW in 2050 in order to have a feasible result.

From Figure 3.1, it is observed that the electricity demand varies based on assumptions made for the scenarios, variants and what-if cases. TRANSFORM features a relative high level of electrification resulting in a high electricity demand. Therefore, in 2050, the potential for wind, solar and nuclear is fully utilised. The ADAPT scenario assumes a different transition path in which the electricity demand is lower than the TRANSFORM scenario for all years, whilst the opposite is true for the heat demand. Due to a less far-reaching decarbonisation of the energy system in ADAPT, fossil fuels are still used to some extent. In ADAPT, carbon capture and storage (CCS) is used on existing processes, which means that the greenhouse gas reduction is still met but heat demand for these processes is higher than in TRANSFORM. More specifically, there is higher continuation of fossil fuel refining activities in ADAPT, which feature a substantial industrial heat demand at 200–400 °C, because of the larger continuation of fossil fuel consumption. Another process that has significant impact on the industrial heat demand in the 200–400 °C segment is the production of aromatics via biomass. For this process the activity is larger in TRANSFORM than in ADAPT, where aromatics in the latter scenario are produced only partly on basis of biomass, but in general features lower heat demand than refineries, such that the total heat demand in TRANSFORM is lower than in ADAPT. The exact industrial heat demand for these two processes are given in Appendix 2, as these two processes constitute most of the industrial heat demand of the 200–400 °C heat segment under consideration.

Regarding the industry variants, the Competitive & Import variant features lower electricity demand (e.g. 1464 PJ vs. 1779 PJ in 2050) and a slightly higher heat demand (64 PJ vs. 57 PJ in 2050) than to TRANSFORM. Because of the import of semi-finished products there is more biomass available to produce biofuels and feedstock for the production of synthetic fuels and chemicals leading to higher heat consumption. More particular, there is more refining activity and less aromatics production observed. Hence, the heat demand level changes. In Zeeland heat demand from the refining sector remains at 12.4 PJ in 2050 as opposed to 0.2 PJ in TRANSFORM. On the other hand, aromatics production only features 3.7 PJ heat demand as opposed to 8 PJ. Impact on South Holland is more limited, with 16.2 PJ and 11.3 PJ as opposed to 17 PJ and 16.6 PJ for refineries and aromatics production, respectively.

The Less Competitive variant features lower electricity demand (e.g. 1279 PJ vs. 1779 PJ in 2050) as well as lower heat demand (30.6 PJ vs. 57 PJ in 2050) with respect to TRANSFORM, which is the result of less energy intensive industrial activity. More precisely, refineries largely scale down featured by 8.6 PJ heat demand in 2050 in South Holland and nothing in Zeeland

The Less Competitive & Import variant features lower electricity demand (e.g. 1400 PJ vs. 1779 PJ in 2050) and lower heat demand (38.6 PJ vs. 57 PJ in 2050) with respect to TRANSFORM, which is the result of less energy intensive economic activity. However, since primary products are imported, significant energy demand from the chemical sector remains, such that energy consumption levels are higher than the Less Competitive scenario.

In TRANSFORM, electricity production from wind, solar and nuclear is deployed to the maximum potentials. This constrains the electricity supply. In the what-if analysis with a doubling of the SMR capacity, this constrain is alleviated, with an increase of electricity demand, as a result of a new optimum between electricity demand and supply. Heat demand remains virtually the same. It is counterintuitive that limiting wind and solar potential increase the overall consumption of electricity, especially when comparing the two what-if scenario's amongst each other. However, the dynamics behind this result will be found when analysing the role of SMRs in the energy system in Section 3.3.

3.2 Nuclear energy

In this section the results of the deployment of different types of nuclear power plants are presented. These results are closely linked with the allowed capacities based on policy objectives, expected market availability and realisation periods, given in Table 2.2. That is, the potential of the deployment of nuclear power plants is modelled to be limited due to the scenario assumptions as described above. Therefore, the results cannot be interpreted as the economic optimum (in case of maximal deployment), but rather assess the impact of policy objectives and expected market developments. For two what-if analyses the potential capacity for SMRs has been doubled in order to get better insight into the influence of the maximum capacity on the optimal deployment from an economic point of view.

The results for the deployment of large scale NPPs (generation III+) are given in Table 3.1. Each large scale NPP has an assumed capacity of 1500 MW_e. For the years 2040 to 2050 the maximum potential for large scale NPPs is set at 3 GW, or two new build reactors. It is observed that for all scenario's and industry variants the maximum potential is reached in 2050. However, depending on the industry variant, there is a difference in the optimal timing for new nuclear power plants to become operational. For example, in 2040 the Competitive & Import electricity demand is lower than in TRANSFORM and the deployment of NPP's is smaller.

Table 3.1: Installed new build large scale nuclear power plants

Number of new Gen III (1500 MW_e each)	2040	2045	2050
1. TRANSFORM	2	2	2
2. ADAPT	2	2	2
3. Competitive & Import	1	2	2
4. Less Competitive	0	2	2
5. Less Competitive & Import	1	1	2
6. Increased SMR Potential	2	2	2
7. Limited Wind & Solar + Increased SMR Potential	2	2	2

In Table 3.2 the result of SMR deployment are presented. Each SMR represents a reactor of 150 MW_e. Note that the values refer to electric power output but the same reactor can at the same time supply heat as well. Each reactor can supply 250 MW_{th} of steam at approximately 300 °C, see Table 2.3. The next paragraph will elaborate further on the relative heat and power output of SMRs in the aforementioned scenarios and variants. Again, it is important to relate the OPERA output to the maximum allowed potential (see table 2.2) which was used as a boundary condition in the calculation.

Discretizing the maximum potential for the years 2040, 2045 and 2050 (0.45, 0.9, 2 GW respectively) leads to a maximal deployment of 3, 6 and 13 SMRs, respectively. Thus, in the TRANSFORM scenario, the maximum potential is deployed. The what-if analyses (6, 7) feature a doubled maximum potential, which explains higher deployment numbers.

Table 3.2: Installed number of SMRs

Number of SMRs (150 MW_e each)	2040	2045	2050
1. TRANSFORM	3	6	13
2. ADAPT	3	4	10
3. Competitive & Import	2	4	8
4. Less Competitive	1	3	4
5. Less Competitive & Import	0	2	2
6. Increased SMR Potential	6	10	27
7. Limited Wind & Solar + Increased SMR Potential	6	13	27

The results show that the deployment of SMRs is dependent of the assumptions made about the transition path and structure of the energy system and industry in the future. The number of SMRs in 2050 ranges between 2, for the Less Competitive & Import variant, to the maximum potential of 13 in TRANSFORM. If the cap on the maximum potential is doubled the optimal deployment may theoretically increase to 27. In the TRANSFORM scenario the maximum potential for wind and solar is deployed as well, as a result of the high electrification of the energy system. In this scenario there is sufficient electricity demand to install SMRs. The what-if with increased SMR potential shows that electricity production is a limiting factor in the system; by increasing the electricity production capacity, electricity consumption rises.

Electricity demand in ADAPT is significantly lower than in TRANSFORM. Wind and solar capacity potentials, which are lower than in TRANSFORM, are not fully utilised in 2040 and 2045. However, in 2050 the maximum potential for wind and solar is deployed (see (Scheepers, et al., 2024)). Compared to TRANSFORM, the industrial heat demand remains relatively high in ADAPT. This results in a deployment of 10 SMRs in 2050 for this scenario.

For industry variants the electricity as well as the heat demand is (significantly) less than for TRANSFORM, with the exception for Competitive & Import, which features slightly higher industrial heat demand. This reflects to the number of SMRs that the model deploys: in all cases less than in TRANSFORM. In general, it can be concluded that higher demand for energy (electricity and 200–400 °C steam) leads to higher deployment of SMRs.

The OPERA model divides the Netherlands in a set of regions. SMRs are only allowed to be installed in regions with industrial clusters, as described in Table 2.1. This is reflected in which regions the model deploys SMRs, see Figure 3.2. Especially South Holland and Limburg have a good fit with SMRs according to the results. Because of the large energy demand (from industry), multiple SMRs are assigned to these regions. Zeeland consistently gets appointed SMRs as well, two SMRs seem to be enough to cover the industrial energy demand for the energy types under consideration. Some capacity is also assigned to North Netherlands, but the threshold capacity of a single SMR (150 MW_e) is only exceeded in the Competitive & Import scenario.

Figure 3.2: Results of OPERA modelling for regions with an industrial cluster that have most fit with SMRs. A darker colour represents better fit.

3.3 Heat and power production SMRs

SMRs can produce both power and heat, see Table 2.3. In this section the relative power and heat output of SMRs is analysed and related to the entire energy system. The different scenarios and variants feature different assumptions about the future economy, energy system and transition path and result in different capacity deployment, as can be seen in Table 3.2. Both the electricity demand and the heat demand by itself are not sufficient to explain the differences in the future deployed capacities. Therefore, to identify the drivers of SMR deployment the behaviour of SMR energy production in relation with characteristics of energy demand will be thoroughly inspected. In particular, demand from industrial processes will be looked at, since SMRs can supply process heat, but are competing with other fuel based and electric heat supply options.

ADAPT and TRANSFORM

In Figure 3.3 the energy output from SMRs is given for the years 2040, 2045 and 2050 for the ADAPT and TRANSFORM scenario's. For the readers convenience, the share of total respective production is shown above the bars. This relates to the absolute energy output from SMRs related to the total demand, as given in Figure 3.1. As an example, in 2050, it can be observed that the share of electricity and industrial heat production in TRANSFORM and ADAPT is approximately the same, while absolute production levels differ vastly. In ADAPT SMRs produce significantly more heat compared to TRANSFORM in correlation with a larger heat demand in ADAPT. On the other hand, SMR electricity production in TRANSFORM is higher than in ADAPT, also correlated with a higher electricity demand in TRANSFORM.

Specifically, total heat demand is approximately the same in 2040, 2045 and 2050 at 90 PJ in the ADAPT scenario. With the continued but decreasing production of fossil fuels in the ADAPT scenario, heat demand is driven by the refinery sector [78%; 72%; 63%][8] and gradually replaced by aromatics production via biomass [14%; 20%; 27%], for the years 2040, 2045 and 2050 respectively. In the ADAPT scenario the uptake of aromatics production via biomass takes place in South Holland. Hence, industrial heat demand that is

[8] Shares of heat supply by SMRs as part of total heat demand for 2040, 2045 and 2050, respectively.

covered by SMRs concentrates in South Holland: [88%; 88%; 92%]. It is observed that in the ADAPT scenario all 10 SMRs in 2050 are placed in South Holland, for this reason.

Nevertheless, in the ADAPT scenario SMR potential is not fully utilised. SMR heat production is stable at 18.3 PJ in South Holland in 2040 and 2045. The user varies: in 2040 15.3 PJ of heat is supplied in the refinery sector by SMRs, while aromatics production relies on biomass CHP. In 2045, the refinery sector is heated almost fully by waste gas boilers and biomass CHP has been replaced by SMRs heating for the growing aromatics production. The change happens because biomass is more economically used as a feedstock to produce bio-fuels than for heating because of increased demand of biofuels in that year. In 2050 SMRs supply the majority of heat to both sectors, accompanied by waste gas boilers which account for 20% in refineries, 40% in aromatics production. The total amount of industrial heat supplied by SMRs accounts for 77.4% of national industrial heat demand.

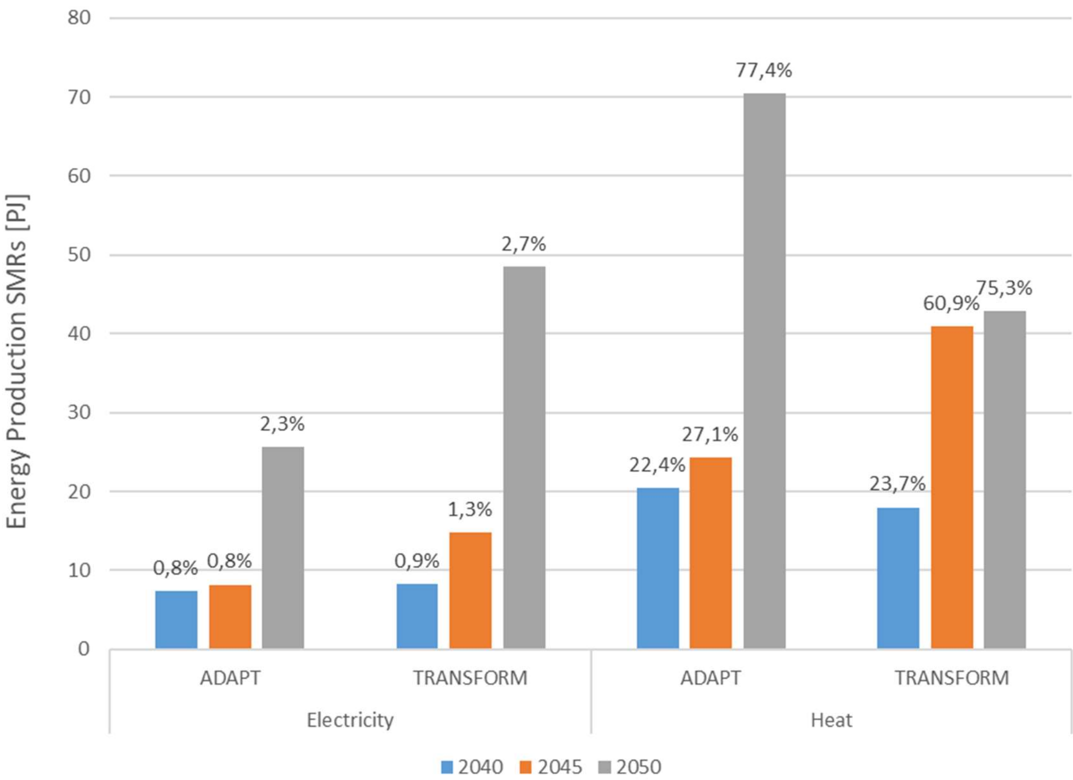

Figure 3.3: Electricity and heat supply from SMRs for the years 2040, 2045 and 2050 for ADAPT and TRANFORM. Above the bars the share of SMR electricity and heat supply in total national power and industrial heat production is given.

In the ADAPT scenario SMRs produce electricity as well, albeit in more limited amounts than heat. The electricity demand is lower in the ADAPT scenario in comparison to TRANSFORM. A large part of electricity demand is covered by wind and solar capacities. The produced electricity is a co-product of SMR operation in heat mode for the vast majority, as the SMR still uses 50% of its energy to produce electricity when the heat output is maximised, see section 2.3. In other words, in the ADAPT scenario the driver of SMR deployment is to produce industrial heat, of which demand can be covered cost-efficiently by 10 SMRs, whilst electricity demand can be covered by competing technologies.

The TRANSFORM scenario shows a different picture regarding the energy output of SMRs. In 2040 – with the same number of SMRs installed – somewhat more electricity is produced than in ADAPT, at the expanse of heat production. Subsequently in 2045, the maximum potential is installed for that year, resulting in a leap in industrial heat production. In 2050, the installed capacity further increases to the maximum potential, accompanied by a leap in electricity production, while industrial heat production only rises slightly. This is because the electricity demand rises sharply in the TRANSFORM scenario, see Figure 3.1. In fact, supply of electricity is constrained, as the maximum capacities for wind, solar and nuclear are installed. Under the circumstances of the TRANSFORM scenario it can be concluded that SMRs are initially installed to cost effectively supply industrial heat, but also produce a significant amount of electricity to cover the relatively large electricity demand.

In more detail, the uptake of SMRs starts in South-Holland [2; 3; 5][9] and Zeeland [1; 1; 1], for the years 2040, 2045 and 2045, respectively. The refineries located in South Holland replace natural gas CHP with CCS and waste gas boilers with SMRs. Heat demand from refineries in Zeeland phases out over time, but heat demand is replaced by the introduction of aromatics production via biomass.[10] Regional analysis shows that the SMRs provide 20% of heat demand in these sectors in 2040, 50% in 2045, growing to 80% in 2050, with the remaining heat supplied by waste gas boilers.

In Limburg SMRs are introduced later [0; 1; 6]. This is connected with the emerging aromatics production, for which SMRs produce the heat (e.g. 6.8 PJ or 98% in 2045). The SMRs introduced after 2045 are for electricity production purposes. In fact, in Limburg heat demand covered by SMRs drops to 5.8 PJ in 2050, whilst electricity production rises from 2.5 PJ to 27.5 PJ. The electricity market transcends regional boundaries. Therefore, regional analysis can only inform about the relationship between industrial heat demand and SMR heat supply. The SMRs that predominantly fulfil an electricity function – about 5 in Limburg in TRANSFORM in 2050 – are not bound to this region, but could in theory be spread over the Netherlands. The proximity of interconnectors to neighbouring countries, together with the boundary condition of industrial activity, is the reason that SMR deployment in Limburg gives rise to a slight competitive advantage on a systems level such that the model selects this region.

Industry variants

Figure 3.4 shows the SMR production per energy type for the industry variants and TRANSFORM, the reference scenario. As can be seen in Figure 3.1 and Table 3.2, the assumptions about industrial decarbonisation result in different energy demand profile and SMR deployment levels. In this section an assessment is made of how the different industry assumptions impact SMR energy production.

The *Competitive & Import variant* features significantly lower electricity demand and slightly higher heat demand with respect to TRANSFORM, which results in lower SMR deployment. Consequently, this results in a significant drop in electricity supply by SMRs, whilst heat supply increases slightly, see Figure 3.4. Regional analysis shows that the largest difference in SMR deployment takes place in Limburg: [0; 1; 1] vs. [0; 1; 6] of installed SMRs for 2040, 2045 and 2050, respectively. In TRANSFORM, the deployment of 5 SMRs in Limburg was indeed observed, mainly for electricity production, which are not installed with the lower electricity demand in this variant. The remaining SMR in Limburg provides heat for aromatics production (8.3 PJ in 2050) which features higher heat demand than in TRANSFORM (8.9 PJ vs. 5.8 PJ) by higher activity.

[9] Number of SMR units for 2040, 2045 and 2050, respectively.
[10] The analysis does not take into account the exact location of respective plants, but accumulates demand to a regional level, therefore it is not taken into account that refineries and aromatics production is located on opposite sides of the Schelde.

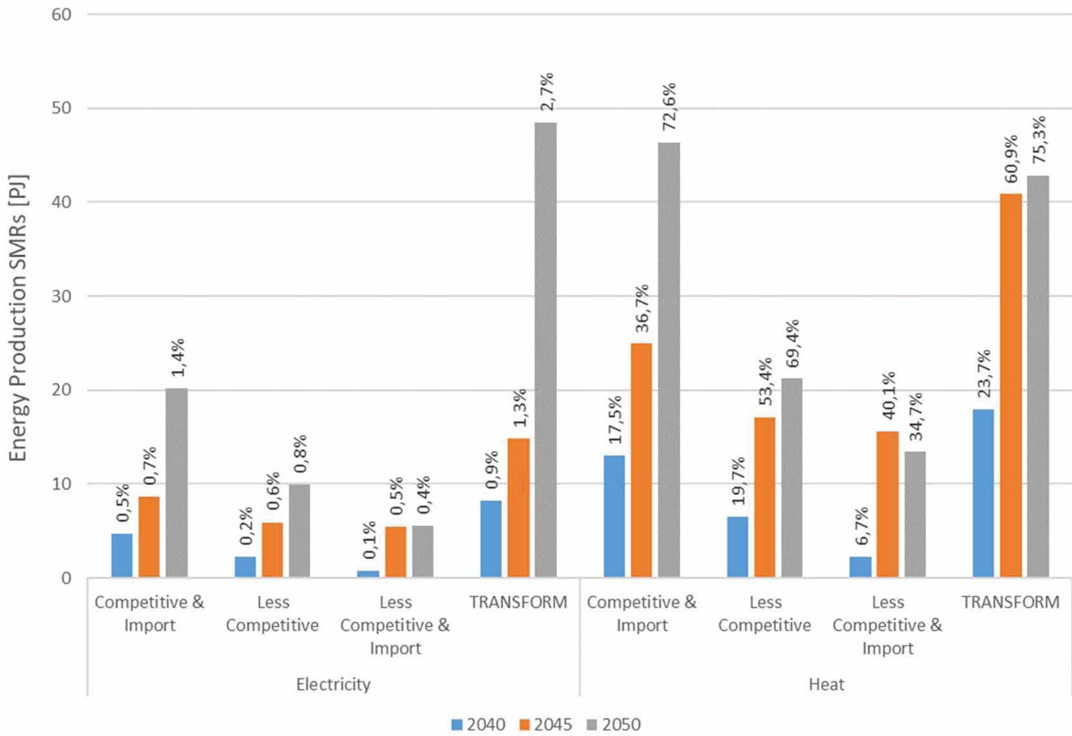

Figure 3.4: Electricity and heat supply from SMRs for the years 2040, 2045 and 2050 for the industry variants and TRANSFORM. Above the bars the share is given of SMR electricity and heat supply in total national power and industrial heat (200-400 °C steam) production.

The Competitive & Import variant has effect on industrial activity in South Holland and Zeeland as well. There is more refining activity observed and less aromatics production. This results in a change in the industrial heat demand profile. In Zeeland heat demand from the refining sector increases from 12.4 PJ in 2050 opposed to 0.2 PJ in TRANSFORM while demand from aromatics production decreases to 3.7 PJ instead of 8 PJ. The higher overall industrial heat demand causes more SMRs to be assigned to Zeeland, two in total in 2050 instead of one in TRANSFORM. Reversely, industrial heat demand in South Holland is slightly lower which result to one less SMR assigned to South Holland, adding up to four in 2050. Also, the introduction of aromatics production in North Netherlands together with heat demand of food and beverage activities cause one SMR to be installed in 2050 in this scenario. As a result, the lower amount of total SMRs in this variant are able to supply slightly more industrial heat in 2050 in Competitive & Import and is closely linked with heat demand from refining activity and the production of aromatics via biomass.

The correlation with heat demand also explains the later introduction of SMRs, which can be observed best by the lower heat supply levels in 2045, both absolutely and relative to the entire system. In Competitive & Import, the industrial heat demand from refining activities remains higher than in TRANSFORM. For the heat supply these activities rely on waste gas boilers until 2045 in this variant, while there is a transition towards steam supply from nuclear only in 2050. At that time however, there is relatively low industrial heat demand from refineries left. At the same time, industrial heat demand from aromatics production via biomass is less than in TRANSFORM, especially in 2040 and 2045, resulting in lower industrial heat supply from SMRs until 2050.

The *Less Competitive variant* features lower electricity demand and lower industrial heat demand than TRANSFORM, accompanied with lower deployment of SMRs. Naturally therefore lower electricity and industrial heat supply is observed. While the contribution to electricity production remains very limited, the contribution to serve industrial heat demand is still significant, with 21.2 PJ or 69.4% in 2050.

In more detail, refineries largely scale down in this variant and also industrial heat demand from aromatics production via biomass is lower than in TRANSFORM. As a result, industrial heat demand in South Holland and Zeeland drop drastically compared to TRANSFORM. Two SMRs are sufficient to cover most industrial heat demand in South Holland, supplying 12.8 PJ of 16 PJ heat demand. The aromatics production via biomass that takes place in Limburg, cause one SMR to supply the majority of industrial heat, 7.1 PJ with 7.6 PJ demand, consistent with TRANSFORM and Competitive & Import.

The ***Less Competitive & Import variant*** features lower electricity demand and lower heat demand with respect to TRANSFORM. Two SMRs are expected, which are located in Limburg. This can be linked with the aromatics production taking place in Limburg. More specifically, from 2045 onwards biomass aromatics production begins to take place in Limburg with 8.1 PJ heat demand initially and 10.1 PJ in 2050. This drives the SMR heat supply in this variant, producing 9.3 PJ of heat for both years (in 2045 there is additional heat demand from other industries as well, to complete the heat balance). This is somewhat higher than in Less Competitive.

The limited refinery sector, featured 10.1 PJ and 6.4 PJ of heat demand in 2050 for South Holland and Zeeland, respectively, is fully supplied by waste gas boilers until 2050, which remain competitive and abundant in this variant. Hence there is no heat supply from SMRs expected in these regions. In other words, in the Less Competitive & Import variant SMRs can be linked only to aromatics production via biomass, and not to refineries, this observation can be made for Competitive & Import as well, but not in Less Competitive and TRANSFORM, where both industries acted as a driver for SMR heat supply.

Increased potential for SMR
Since in TRANSFORM the installed SMR capacities equal the maximum potential allowed (2 GW in 2050), the OPERA model has also been run with the option of doubled SMR capacity (4 GW in 2050). In this what-if analysis, it was observed that again the maximum potential was installed, see Table 3.2. In another what-if analysis, in addition to the doubling of SMR capacity, the maximum wind and solar capacity in 2050 was limited to 60 GW (instead of 70 GW) and 109 GW (instead of 132 GW) respectively. This analysis shows again a maximum SMR deployment, but also a change in SMR output. The results for electricity and industrial heat production are given in Figure 3.5.

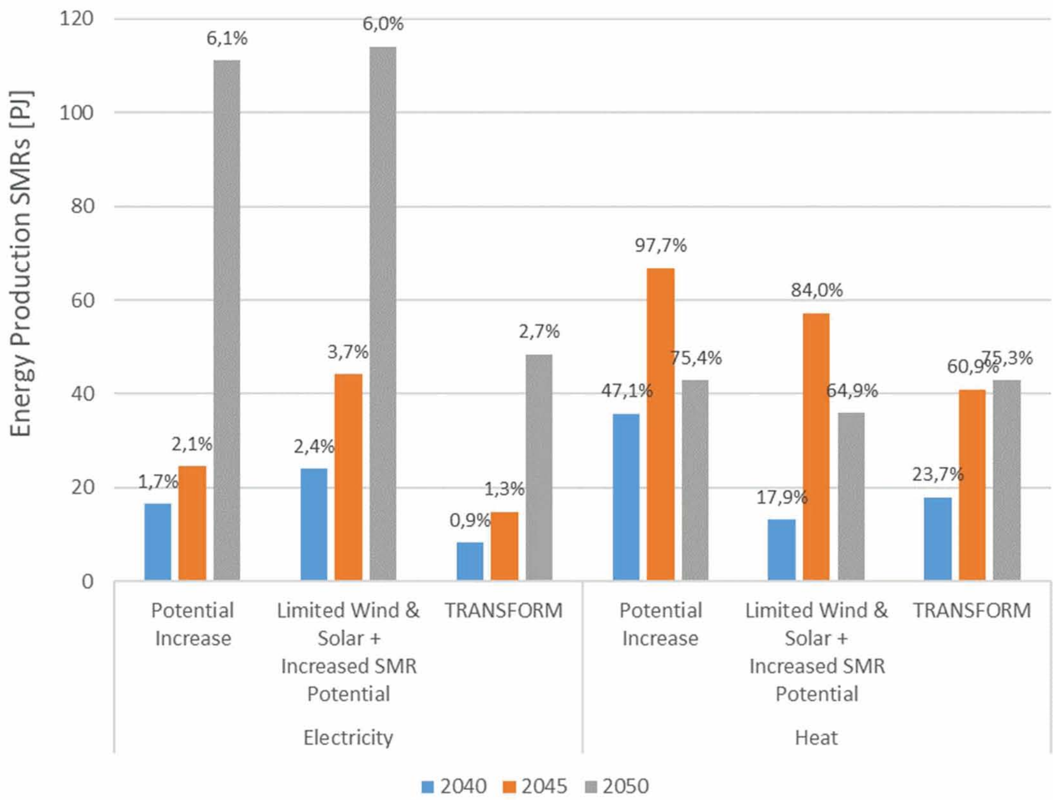

Figure 3.5: Electricity and heat supply from SMRs for the years 2040, 2045 and 2050 for the what-if analyses and TRANFORM. Above the bars the share is given of SMR electricity and heat supply in total national power and industrial heat (200-400 °C steam) production.

By increasing the number of SMRs in the what-if analysis Potential Increase, the constraint on electricity production in TRANSFORM is somewhat relieved and electricity consumption increases slightly. Heat consumption in 2050 is identical to TRANSFORM. This results in the deployment of the full potential of SMRs for 2040 and 2050, but not for 2045. Initially, the SMRs are appointed to South Holland [5; 6; 6] and Zeeland [1; 1; 1], while later a leap in deployment in Limburg [0; 1; 18] is observed, complemented with deployment in North Netherlands [0; 1; 1], for the years 2040, 2045 and 2050 respectively in brackets. In other words, the cap on SMR potential slightly limited deployment in South Holland and North Netherlands. The largest difference is observed in Limburg however, with an increase of 12 units in 2050.

In the supply data, it is observed that electricity from SMRs increases for all years, and rises from 48.5 PJ (TRANSFORM) to 111 PJ in 2050. This mainly has to do with the additional capacity installed in Limburg in 2050 which supply electricity, next to heat for aromatics production. The demand and supply of industrial heat is in balance in the local region, because long distance heat transport (i.e. outside the region) is not feasible (and not allowed in the model). Electricity transport to other regions and even abroad is possible and, therefore, electricity is supplied to a larger market. Regarding electricity the model does not aim to find the best-fit for the region. Moreover, the increase in national electricity supply from SMRs, 62.5 PJ, surpasses the increase in demand of 35 PJ. Therefore, with higher SMR potential, supplying electricity to the national and international electricity market is slightly more efficient.

For heat supply, it is observed that the larger SMR capacity causes heat supply to increase in 2040 and 2045, while being equal in 2050. In 2040 heat is exactly doubled, in line with the doubled potential. In 2045 industrial heat supply is less than doubled, but nearly all industrial heat is supplied to industry by SMRs. This indicates that SMR deployment is driven by the undersaturated heat demand initially up to a certain point of saturation, which is supported by regional analysis for refineries in Zeeland and South Holland. Only in 2050, when electricity demand increases sharply, and the industrial heat market can efficiently been served with a mix of SMRs and waste gas boilers, electricity supply becomes a main function of SMRs.

The what-if analyses Limited Wind and Solar features higher electricity demand and similar heat demand to TRANSFORM and the Potential Increase scenario. As a result of limiting the potentials for wind and solar (potentials in 2050 for offshore wind 60 GW instead of 70 GW and solar 109 GW instead of 132 GW, see also Section 3.1), it is observed that the maximum potential for SMRs are installed for all years. Also, a different use of SMRs can be observed. That is, for all years SMRs supply more electricity at the expense of supplying heat, relative to the Potential Increase what-if analysis. Moreover, in 2040 it is observed that more electricity is supplied than heat, something that has not been observed for any other scenarios and variants. Where the driver for SMRs in 2040 consistently was industrial heat demand, in this what-if analysis electricity demand is the main driver. Lower electricity production from wind and sun is compensated by more electricity production from SMRs at the expense of heat production. Nevertheless, SMRs still supply significant industrial heat. With lower availability of electricity sources, it is simply more effective, or necessary, to produce electricity with these assets. This changes slightly in 2045 and 2050, but still a shift from industrial heat production towards electricity production is observed with respect to Potential Increase. The relatively more important electricity function is reflected in the regional analysis as well. For all years, the most SMRs are located in Limburg, which goes at the expense of SMRs to be installed in South Holland. The results show an uptake of three SMRs in Limburg already in 2040, compared to one or zero for other scenarios and variants. This is consistent with electrical function driven SMR deployment in Limburg, besides supplying industrial heat for aromatics production, in the previous results. Nevertheless, it is also observed that the SMRs in South Holland and Zeeland, linked with refining activity and later aromatics production, relatively supply more electricity at the cost of heat production.

3.4 Discussion of the results

In this section the results presented in the previous sections are discussed. The emphasis on the results regarding the deployment and usage of SMRs, as for the large scale nuclear powerplants the capacity results have already been presented in Table 3.1, and these nuclear powerplants are modelled to only produce electricity. With some what-if analyses the robustness of model results has been investigated with respect to research approach and assumptions. This is also discussed in this paragraph.

Observations

Different assumptions for scenarios, scenario variants and what-if analyses can result in outcomes of an optimization model that sometimes differ little from each other and can therefore be sensitive to uncertainties in the assumptions. Taking this into consideration, a number of observations can be made. For all scenario’s under investigation deployment of SMRs is observed, however the number of SMRs in 2050 varies between 2 and 13, and with higher SMR capacity potential up to 27. This large bandwidth indicates that the optimal SMR capacity is highly dependent on the assumptions regarding the future energy system, and more precisely the future industrial activity taking place in the Netherlands. Nevertheless, the results indicate SMRs can cover industrial heat demand:

- 4 – 10 SMRs are sufficient to supply 80% of heat demand (200–400 °C) from refineries and the chemical sector, depending on the scenario or variant.
- SMR is the dominant technology for heat supply to industry (200–400°C) in 2050, with a share of 70+% on a system level.

- Only for the Less Competitive & Import other heat sources dominate, leaving SMRs to produce approximately 35% of industrial heat on a system level.

Heat demand from refining activities linked with nuclear heat supply is limited at first, while large scale aromatics production via biomass ramps up mostly after 2040. While economical attractive alternatives for heat supply to refining activities exist in some variants (e.g. waste gas boilers), aromatics production is always correlated with nuclear heat generation according to the model used in this work. This makes that the most suitable regions for this purpose, according to this model based on the current industrial market organisation, are South Holland, Zeeland, Limburg and North Netherlands.

In certain cases SMRs are used predominantly for electricity supply as well, although in most cases the electrical output of these systems is merely the co-product of SMRs when producing in heat mode, with the exception of moments of extreme electricity scarcity because of weather circumstances. Nevertheless, the model shows that there exists a threshold – at least over 1200 PJ electricity demand – after which SMRs are predominantly used for electricity production and SMR deployment reaches the maximal potentials. Under these conditions it remains unclear what the optimal potential is, as even in the Increased Potential what-if the maximal potential was installed. Additionally, under these conditions, SMRs are recognised to supply the majority of industrial heat in the 200–400 °C range. In a system with a constrained electricity supply (i.e. all electric power resources are deployed to their maximum capacity), direct heat supply is preferred over electrical heat (e.g. electric boilers).

Discretize SMR unit size

Although the SMR capacities have been presented in terms of unit size, the modelling has not been executed in a discretised fashion because of the LP algorithm of the OPERA-model. That is, a cut-off capacity was used to present the installed capacities. However, a model run was made were the SMR capacities were set to capacities of multiple unit size (150 MW_e), to check for robustness. It was found that fixing the unit sizes did not have a significant impact on the results, other than the omission of small capacities in North Brabant, North Holland and North Netherlands, which were already far below the cut-off capacity. The use the SMRs also did not mentionable change.

Discount rate

The OPERA model optimises the energy system based on national system costs. A discount rate of 2.25% is used to determine the cost of capital. It was also investigated what happens when the discount rate increases from 2.25% to 5%. This has obviously directly impacts the total system cost, which increases by 15.6%, 18.4%, and 17.3% for 2040, 2045 and 2050, respectively. However, deployment and production levels of SMR energy are very similar to the base case. The only noticeable effect is the omission of the one SMR placed in Zeeland, which is appointed to South Holland.

Delayed availability SMRs

SMRs are still under development and not yet commercially available in the (European) market, meaning the timelines for realisation are still uncertain. Therefore, it was investigated what the effect on the system is, when the introduction of SMRs is delayed by five years, that is, with a maximum potential of 0.2 GW in 2045 and 0.9 GW in 2050. It was found that biomass consumption by industry as a feedstock decreased sharply, in order to use that biomass for electricity generation. This also affected the deployment of SMRs in Zeeland and caused industrial heat demand to fall sharply in this region. Moreover, system costs increase sharply in 2045 and 2050, by 12% and 3.5% respectively.

No newly built nuclear power plants
It is conceivable that no new nuclear power plants will be built in the Netherlands, neither large nuclear power plants nor SMRs. This has been investigated in a what-if analysis in (Scheepers, et al., 2024) by setting the maximum capacity for new large-scale generation III+ nuclear power plants and SMRs to zero. A future Dutch energy system in which sustainable electricity production is almost entirely based on solar and wind is possible for both the ADAPT and TRANSFORM scenarios. In both scenarios, the production capacity for wind and solar energy does not change in 2050 because they are already used to the maximum capacity in the base case. Without new nuclear power plants, the demand for electricity is lower compared to the scenarios with new nuclear energy, because the electricity supply is even more constrained. Heat demand in industry is covered by electric boilers, waste gas boilers and biomass CHP. In an energy system without new nuclear power plants, the total system costs in 2050 are 1% to 2.5% higher, depending on the scenario, than in a system with nuclear energy.

Study limitations
This study has some limitations. Firstly, while a standard generic SMR was defined based on the best available insights (see Table 2.3), in reality, there are multiple (types of) SMRs being developed. These SMRs span a large capacity range and are developed with different deployment goals in mind. Although costs per unit of power are very likely to increase for small, or micro-, SMRs, the possible functions of these type of reactors were omitted by the cut-off capacity. In theory, smaller capacities that the model predicted to be installed in some regions could be met with these types of reactors. Moreover, in this study two energy categories are regarded - electricity and 200–400 °C steam. In practice, SMRs could also be used for other categories such as lower temperature industrial heat or district heating. Further investigation is needed to assess usefulness in those categories, possibly aligned with lower capacity SMRs. As a fact, large scale generation III+ reactors are thermal energy sources as well, but were excluded for heat supply as a whole. Hence, it is suggested to assess the contribution of large scale nuclear powerplants for heat supply as well, albeit that the thermal energy source is highly concentrated.

Also, the capital cost per unit of power of the standard SMRs are based on the modelled costs of the large scale generation III+ reactors due to pragmatic reasons. Due to the lack of economic track record caused SMRs having not yet reached the market, there is no empirical data to base our modelling on. In fact, SMR developers report lower costs than used in the modelling, lower than large scale generation III+ costs. Since the results show that large scale reactors are installed to the maximal potential, a lower cost for SMRs could have impact on the electricity system, for example by crowding out large scale powerplants, or reaching higher production and/or penetration levels, although it is doubtful that the electricity demand is a larger driver than heat demand for economical and efficiency reasons. It was also not investigated in-depth to what extent SMRs can fulfil a flexible function to cope with fluctuating electricity demand and supply from renewable sources, either by scaling up/down energy output or changing between industrial heat supply and electricity generation. Lastly, and connected to all of the above, this study's starting point was the possible relevance of SMR heat supply for industry. Indeed it was found that the relevance is clear, but this resulted in some imposing limitations. In this study, SMRs were only allowed to be deployed close to industry clusters to supply industrial heat and be connected to the electricity grid. The results therefore show concentrations of SMR units in the regions with industry clusters, while it would be worthwhile to consider a widespread availability throughout the country – especially when the SMRs are used primarily for their electrical supply function. The modelling also did not take into account additional boundary conditions, such as the availability of suitable locations and cooling water, which means that the undesirability of installing dozens of units in one region was not considered. Nevertheless, this study has shown light on the importance of SMRs for industrial heating purposes and their role in the electricity market when capacity limits for competing electricity sources come in sight.

4 Conclusions and recommendations

A scenario study investigated whether the changes in nuclear policy as announced by the Dutch government have any significance for realising a climate-neutral energy system. This mainly concerns the lifetime extension of Borssele, introduction of two new GEN III+ nuclear powerplants and SMRs. The results show that both the lifetime extension of Borssele and introduction of two new nuclear powerplants are economically viable from an energy system perspective.

Conclusions of this study
An in-depth assessment about the role of SMRs was performed, as the technology possibly offers functionalities for both electricity and heat supply. The results show that SMRs have a role to play in the Dutch energy transition. The optimal contribution of SMRs to 2050 was calculated for various assumptions about future society. The results show that 2 to more than 13 SMRs (à 150 MW_e) can be deployed with room for further expansion of this number in 2050. These results are contingent on policy objectives, expected market availability and realisation periods. If constraints on the potential deployment capacity are partially lifted, as is done in some of the what-if analyses, it is observed that there may even be room for more than 27 SMRs (of 150 MWe). This what-if analysis result can be interpreted as a more economically optimal solution, but is obviously conditional on the aforementioned aspects used to define the potential limits for the scenarios being sufficiently adjusted to allow for this to occur. On the other hand, with delayed introduction of SMRs or no nuclear at all, a carbon neutral energy system in 2050 is possible as well. The exact optimum depends mainly on the future of industry, and more specifically on the future heat demand from activities such as refineries and (bio-)aromatics production, and the degree of electrification in society. Nevertheless, it can be concluded that SMRs are an important option for decarbonisation of the industry by supplying process heat.

Recommendations
The following relevant topics have not yet been answered in this study and may be the subject of further research:
- Since recently the Dutch government has announced a further upscale of the nuclear programme it is recommended to continue these types of study, e.g. incorporating 6 GW of GEN III+ nuclear powerplants, i.e. a doubling of the foreseen new build capacity.
- In this study, the heat supply of SMRs is limited to one temperature category, i.e. 200-400 °C steam. It is recommended to also assess SMRs for other heating purposes, such as heat supply for 100-200 °C steam or heat demand in hydrogen production.
- In this study one type of generic SMR has been defined, whereas in practice a multiple SMRs are developed with different sizes and design applications. Further research could better estimate how different types of SMRs fit with different purposes by defining multiple sub-categories.
- This study has not performed an in-depth analysis about the interaction between nuclear power and other electricity generating technologies. It is recommended to take a closer look to the role the nuclear plays as a flexible electricity source, preserving net stability and reliability of supply, either by scaling production up or down, or changing the type of energy output.

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Appendix A
Total demand electricity and industrial heat

Table A.1: Total electricity demand in PJ for the different scenario's, industry variants and what-ifs

Total Electricity Demand (PJ)	2040	2045	2050
1. TRANSFORM	950	1155	1779
2. ADAPT	900	980	1103
3. Competitive & Import	1026	1197	1464
4. Less Competitive	904	1038	1279
5. Less Competitive & Import	919	1125	1400
6. Increased SMR Potential	950	1143	1814
7. Limited Wind & Solar + Increased SMR Potential	1013	1190	1911

Table A.2: Total industrial 200–400 C steam demand in PJ for the different scenario's, industry variants and what-ifs

Total Industrial Heat Demand: 200-400 °C steam (PJ)	2040	2045	2050
1. TRANSFORM	76	67	57
2. ADAPT	91	90	91
3. Competitive & Import	74	68	64
4. Less Competitive	33	32	31
5. Less Competitive & Import	33	39	39
6. Increased SMR Potential	76	68	57
7. Limited Wind & Solar + Increased SMR Potential	74	68	55

Appendix B
Industrial heat demand for TRANSFORM and ADAPT

Table B.1: 200–400 °C heat demand in PJ refineries 1 for the different scenarios and industry variants for2040, 2045 and 2050

Refineries [PJ]	2040	2045	2050
1. TRANSFORM	42.8	30	17.1
2. ADAPT	71.4	64.3	57.1
3. Competitive & Import	58.2	45.4	28.6
4. Less Competitive	21.5	15	8.6
5. Less Competitive & Import	25	22.7	16.4

Table B.2: 200–400 °C heat demand in PJ of the production of aromatics via biomass for the different scenarios, industry variants 2040, 2045 and 2050

Bio-aromatics [PJ]	2040	2045	2050
1. TRANSFORM	21.2	26.3	29.4
2. ADAPT	8.9	14.3	21.1
3. Competitive & Import	6.4	12.9	24.9
4. Less Competitive	3.5	8.8	14
5. Less Competitive & Import	0	8.2	14.5

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