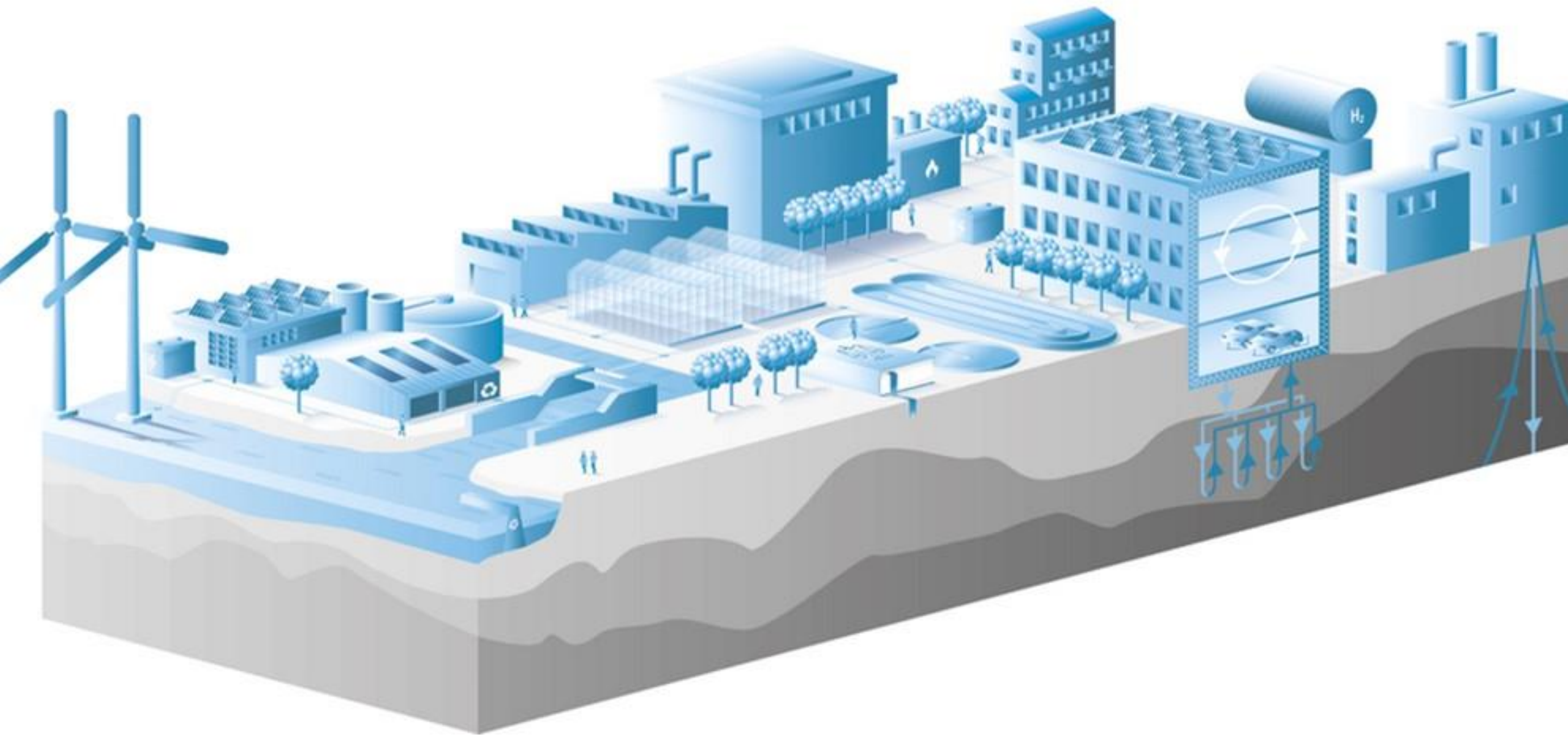

Scenario study nuclear energy

Conclusions and summary

Ministry of Economic Affairs and Climate Policy

26 September 2022

Project	Scenario study nuclear energy
Client	Ministry of Economic Affairs and Climate Policy
Document	Conclusions and summary
Status	Final version 02
Date	26 September 2022
Reference	130675/22-013.680
Project code	130675
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CONCLUSIONS AND SUMMARY

1.1 Objective of this scenario study

The objective of the study is to find out how nuclear energy can be part of the future energy mix of the Netherlands and Northwest Europe and what the costs thereof would be. In addition to the question of whether there is an economic role for nuclear power in the electricity system, this study also looks at raw materials and the use of space. The results of this scenario study can be incorporated into a comprehensive social assessment of nuclear energy, whereby aspects such as public support, safety, non-proliferation and the processing and storage of nuclear waste are also relevant.

1.2 Conclusions

The scenario study of nuclear energy draws a number of conclusions. These apply under the assumptions made for the future cost expectations of the technologies that are central to the energy transition, such as the costs of wind turbines, solar PV, batteries, various flexibility options and electrolysers, and for this study, also nuclear power plants. In addition, sensitivity analyses were also made with regard to the most important assumptions.

The impact of nuclear energy on the total cost of the Northwest European energy system is less than 1 %
This study first examines the effects of two new nuclear power plants in the Netherlands in 2035, taking into account the implementation of energy transition policies in Northwest Europe and the Netherlands until 2035. It then examines whether there is still an economic role for new nuclear power plants in the electricity mix by 2040, 2050 and 2070. The costs of nuclear power plants currently under construction in Europe are much higher than expected. If these costs were to be included, the optimisation would show that the use of nuclear energy is not cost-optimal at the system level. The energy system optimisation shows that, if large-scale nuclear energy can be realized without exceeding budget and construction period and if SMRs achieve their cost ambitions, nuclear energy can play a significant role in the Dutch energy system, both large scale plants and in the longer term SMRs.

If nuclear energy is not part of the electricity generation mix in the Netherlands, the dependence on energy imports will increase
Nuclear power plants in the Netherlands contribute to the Netherlands having an annual surplus of electricity. The analysis shows that if no nuclear plants are built in the Netherlands, it will be cost-optimal to import electricity.

Nuclear power helps to reduce dependence on imports of rare raw materials
The demand for direct and indirect (in the form of products) raw materials in the Netherlands is large. These raw materials are mainly necessary to produce the large amounts of wind energy, solar energy, batteries, electrolysers and electric cars. Nuclear energy needs similar raw materials, but significantly less per kWh. If we look at 2035, we could have realised 3 GW of nuclear energy by then, compared to 38 GW of wind and 56 GW of solar energy and 15 GW through electrolysis. In the longer term, the relative impact of nuclear energy may increase and thus reduce dependence on these raw materials.

Nuclear energy reduces the amount of space needed to produce electricity in Northwest Europe
Nuclear power plants have a significant safety profile that prevents them from being located in densely populated areas, which results in indirect use of space. The energy density of a nuclear power plant is high. This means that the direct use of space per quantity of electricity generated is high. Net use of space (direct+indirect) decreases in the scenarios with nuclear power in the energy mix.

Active participation of central government is essential for the development of nuclear energy
Nuclear power plants require significant investments and the total development period, during which no income is generated, is long. The analysis of the various financing models shows that it leads to lower costs for electricity consumers if the government not only ensures long-term purchase as a contracting party, but also actively participates in the development phases. This will ensure that financing costs, in particular, will be lower.

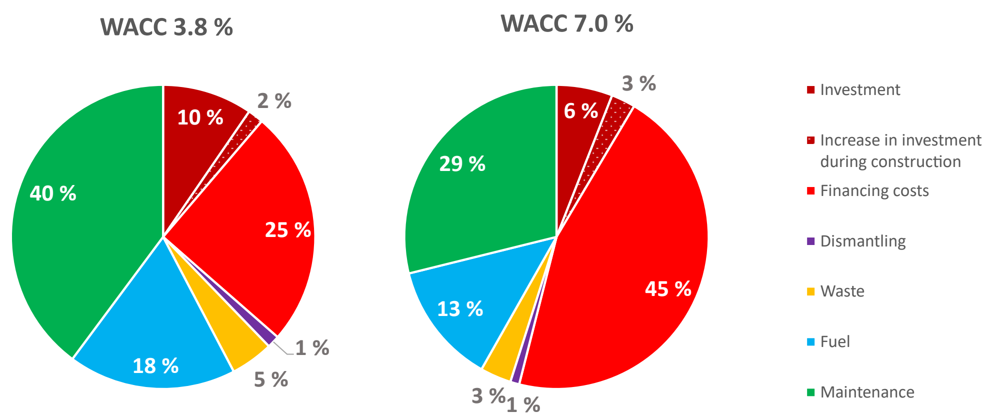
1.3 Costs and financing

'Costs and Financing' discusses the relationship between the costs of nuclear power plants, financing structures and the role of government and technology.

The LCOE of nuclear energy
The scenarios and the financing structures are strongly linked. A model can correctly calculate that adding nuclear energy can be beneficial or detrimental to the energy system, however, this is based on assumptions. These assumptions translate into the LCOE: the average price per MWh at which a power plant can produce. A specific LCOE can only be achieved within a specific financing structure. This applies even more to a nuclear power plant than to other technologies. Developing and building a nuclear power plant requires a considerable investment and generally takes at least 10 years. The plant must then operate for approximately 60 years and recoup the investment and all other costs over this long period.

Depending on how great a risk the financiers consider the development and operation of a nuclear power plant, the financing costs will be higher or lower. These financing costs are expressed as Weighted Average Cost of Capital (WACC). As shown in the figure below, the influence of the WACC on the LCOE is significant.

Figure 1.1 Cost allocation at low and higher WACC



Given the relatively large size of the financing costs in relation to the total costs, it is obvious that investors might be willing to invest in nuclear power only in a stable environment (regulation, government) with revenues from reasonably secure energy prices. It is in the period prior to the operational phase, during which no income is generated, that the greatest risks are incurred. The three projects currently under construction in Europe have suffered setbacks, which increased the construction time considerably. This means that the period during which no income is generated to offset a large part of the investments is even longer. The resulting additional financing costs significantly increase the LCOE.

Within the current market context with uncertain energy prices, it is therefore recommended, in the event that the government opts for nuclear energy as part of the energy system, that the government is closely involved in the development and financing of nuclear energy projects. Co-investment will increase the confidence of market players and can keep financing costs down, resulting in lower energy prices. Even if the government acts as a co-investor, it is still important, given the uncertain energy prices during the operational phase, to offer a certain revenue guarantee (this can be achieved by creating a structure in which a price is agreed at which a plant can deliver all or part of its production).

Nuclear energy technology

The literature and studies of reference projects consulted for this study make it clear that at present only large-scale, 3rd generation nuclear power plants (generally larger than 1 GW per reactor) have reached a mature stage and can scale up from FOAK (First Of A Kind) to NOAK (Nth Of A Kind). All other technologies still need to realise a first working power plant based on their design and get the functioning and approval of local legislators. The technologies of the more advanced options (4th generation and nuclear fusion) have yet to demonstrate themselves or at least demonstrate themselves at scale. In addition to large-scale plants, SMRs are also regularly discussed. An SMR, Small Modular Reactor, is generally understood to be a nuclear power plant smaller than 300MW of electrical capacity, which can be mass-produced and has a short construction period. While a number of 3rd generation SMRs are promising and getting close to realisation, these projects will also face technical challenges associated with first versions (FOAK). It is expected that these problems will be solved by the early 2030s and that SMRs will become available as a competitive alternative to large-scale power plants from the second half of the 2030s. This is too late for the first power plants that may be built as a result of the current Coalition Agreement. The NEA report 'Meeting Climate Change Targets: The Role of Nuclear Energy' from 2022 draws similar conclusions. For the 4th generation of SMRs, challenges still need to be overcome to scale up to commercialisation. In the short term, the role and success of the first demonstration projects will be crucial, not only to attract the interest of investors, but also to get a selection of concepts that work, as the GEN IV International Forum concluded in its 2020 Annual Report. For nuclear fusion, the conclusion can be drawn that, despite positive developments in various initiatives, a significant, large-scale contribution can only be expected between 2040 and 2070. In the energy system optimisation, nuclear fusion is therefore included in the 2070 horizon.

Construction time

Based on the sources consulted for this study, a total development and construction period of 11 years is considered realistic for a large-scale 3rd generation power plant in the Netherlands. The development and construction period per phase is roughly divided into: 3 years for the first phase of exploration and contract award, 2 years for the second phase in which the design is finalised and another 6 years for the actual construction (third phase).

Financing structures

The financial risk level of a nuclear power plant varies greatly depending on the phase of the plant's life cycle. The risk is highest in the first 2 phases of a project because it is still uncertain whether the project will generate the revenue required to make interest payments. Due to the high risk, these phases will often need to be financed with equity (or possibly with grants) in exchange for a share of the potential profit of the project after completion. In these phases, the capital requirement is still limited. In phase three, the construction phase, the capital requirement increases sharply. With the start of construction of the plant, the likelihood that the plant will produce energy is increased, and with it the certainty of income. As a result, more capital providers will want to meet the capital requirement. Lastly, the length of the fourth phase, during which the power plant is operational and subject to price risks, is substantial (this study assumes an economic lifespan of 60 years).

The transfer of parts of these risks during the first 3 phases of a project to the government will, all other factors being equal, reduce the risk compensation and thus the financing costs of the project. This reduces the risks for private investors, as they can achieve their desired returns even at relatively low selling prices.

The following financing models have been analysed for the construction of nuclear power plants:
- Regulated Asset Base (RAB).
- Public Private Partnership.
- Mankala (Finnish cooperative model).
- SaHo (Polish variant of the Mankala model).

Furthermore, a number of supporting instruments are described, such as a Power Purchase Agreement (PPA), a Contract for Difference (CfD), government guarantees and loans, export credits and supplier financing.

With a Regulated Asset Base (RAB) model, a Public Private Partnerships (PPP) model and combinations of both, government funding can be leveraged, leading to the lowest cost of capital for projects. In addition, these models can generate revenue as early as during construction and offer relative clarity on compensation, risk distribution and returns as previously concluded. The PPP model is suitable, however, risk and return distribution between private and public parties must be considered. Using a regulator may ensure that private parties focus more on the creation of long-term social value (security of supply, social and welfare results).

It is assessed that for the necessary mutual trust and dependency in the competitive Dutch business environment and the uncertainty in the electricity market, the application of the Mankala and SaHo models is likely to be difficult, as is also indicated in the KPMG market consultation. For the Mankala model, low cost of capital still depends on cheap external capital such as vendor and export credit. The SaHo model has not yet been tested in practice and it remains to be seen whether it will not be viewed by the EU as a vehicle for granting unlawful state aid.

Apart from the volume and price risk, the RAB models or a combination of RAB and PPP seem best suited for the Netherlands, due to the relatively low capital costs and the possibility for the government to make adjustments. The financing cost advantage of the RAB model identified in the analysis is in line with the findings of analyses made by the Department for Business, Energy & Industrial Strategy (BEIS) in the UK. These analyses show that the low cost of finance of the RAB model can deliver a cost saving for end-users compared to other nuclear power plant financing models used in the UK. The fact that there is already income during construction and that there is relatively clarity on compensation, risk distribution and returns makes the RAB model or RAB/PPP model attractive to private financiers, as is also noted in KPMG's market consultation.

For a nuclear power plant to be profitable, power purchase contracts remain essential in the operating phase. This despite opportunities to reduce financing costs in the development and construction phase thanks to government instruments. The Contract-for-Difference model lends itself well to this, also for the Dutch situation. When applying the CfD model, a trade-off must be made between a more private project with a significantly higher CfD price and a project in which the government takes over considerable risks with a much lower CfD price, especially in the first three phases prior to the operational phase. It must be avoided that an eventual private project needs a high CfD price as investors demand a return that does not reflect the government's risk mitigation.

1.4 Modelling and scenarios

1.4.1 Analysis of the year 2035

The analysis for 2035 for different variants (including demand generation capacities) and weather years (weather year is defined as simulating the supply and demand of the base year using historical weather data) shows how the demand for electricity is met by a production mix of solar, wind, nuclear, gas and hydrogen power plants. Based on the assumptions made, the Netherlands will be well equipped to deal with the strongly fluctuating supply of electricity in 2035. The large capacity of electrolysis, batteries and the electrification of a substantial part of the energy demand play a vital role in this. The model also takes into account different types of demand flexibility from heat pumps, industrial power to heat and electric transport.

The year 2035 was chosen because it is considered by experts to be the first year in which it is realistic for nuclear power plants from the Coalition Agreement to be built on commercial terms. For the energy system in 2035, the basic principles and a number of variants are based on a number of studies by, among others, PBL, Berenschot, Guidehouse and TenneT. These form the starting point for long-term optimisation.

For 2035, a model (PPSGen[1]) was used that plots the electricity demand against the options for generating electricity from dissimilar sources. This is done for the Northwest European market (Belgium, Germany, France, Luxembourg, the Netherlands and the United Kingdom). Imports and exports from and to the countries surrounding this Northwest European market are also taken into account. The electricity demand and the options to exercise influence thereon (by using batteries, for example) is met by renewable generation options, particularly sun and wind, natural gas and hydrogen power plants and, possibly, nuclear power plants. A number of minor technologies also play a role. The model calculates hourly prices in different countries and whether, under all variants, enough or too little electricity is supplied to meet demand in all countries. Because the model performs this analysis for Northwest Europe, it also includes the extent to which Dutch electricity production supplies other countries and when the opposite occurs.

The results show that all interconnectors (the electricity transmission cables between the countries) are used intensively and both nuclear power plants are used extensively. It should be taken into account that this is taking place in a playing field in which Germany and Belgium, for instance, have shut down a large part of their capacity (both nuclear energy and, in Germany, also coal and lignite-fired power stations). The electricity system as a whole always needs a backup, despite the maximum dispatch of other flexible capacities such as batteries, to cope with periods of prolonged lack of sun or wind. In the baseline situation for 2035, the Netherlands will have 15 GW of gas-fired power plants. These power plants operate on natural gas or on hydrogen gas and are important suppliers of flexibility in the Northwest European market, which is a consequence of the advanced interconnection of the European electricity markets.

A difference between variants with and without new nuclear energy is that without nuclear energy, the Netherlands will need to import electricity annually and with nuclear energy, it will become a net exporter (albeit both to a limited extent). The hydrogen and natural gas power plants in the Netherlands, which are necessary as backup anyway, will produce more (and thus be used more efficiently) for the neighbouring countries if nuclear power is realised in the Netherlands. On the other hand, if our neighbours ultimately opt for a different strategy, the results may of course be different.

Another direct consequence of the connections (interconnection capacity) the Netherlands has with its neighbouring countries is that any new nuclear power plants can operate for many hours in an open market. Due to the high electricity demand, which consists partly of electrolysis and partly of industrial electric boilers that can absorb a large part of the fluctuation of wind and solar energy, the nuclear power plants will achieve a high production under these assumptions.

1.4.2 Energy system optimisation for 2040 and 2050

Model approach

This analysis is based on brownfield 2035. In other words, the sustainable technologies that are already planned until 2035 serve as a starting point for the analysis. Subsequently, the question is answered whether, with further electrification towards 2040 and 2050, there is still an economically optimal role for new nuclear power plants, on top of the assumed 3 GW. For this optimisation, a specific optimisation model (PyPSA[2]) was used that was developed by scientists from TU Berlin and other European universities and is available open

[1] PPSGen is a fundamental merit-order model of the Northwest European electricity markets developed by the eRisk Group.

[2] Python for Power System Analysis https://pypsa.org/.

source. In a cost-optimal energy system, the annual expenditure on meeting the demand for electricity and hydrogen, including transport and storage of electricity and hydrogen, is minimised.

PyPSA makes it possible to investigate the optimal deployment and investments in energy generation, storage, conversion and transmission. The purpose is to gain insight into the cost-optimal investment for meeting our growing electricity demand and at the same time achieve a 100 % CO_2 reduction target in 2040 and 2050 with net negative emissions towards 2070. When implementing these components, the model optimises the use of energy technologies for all hours of the year and thus ensures that the energy demand is met for all hours. This relates to the investments in the generation, storage and transport of hydrogen and electricity at high voltage level.

Northwest Europe is modelled such that the model can build power plants within different regions. Electricity and hydrogen can be transported between regions, and PyPSA can invest in network expansion and the construction of hydrogen pipelines. The Netherlands is divided into six regions, which makes it possible to examine whether, from an energy system point of view, nuclear energy is more advantageous in certain regions than in others. The model provides an optimisation for Northwest Europe, so the results are partly determined by restrictions imposed, such as not being able to realise nuclear power in Belgium and Germany.

The electricity demand of the 6 regions in the Netherlands is based on the II3050 scenario Nationale Sturing. The electricity demand of neighbouring countries is prepared in PPSGen based on authoritative reports for each country. Flexible use of power-to-heat and smart vehicle charging to accommodate solar and wind peaks are already included in these electricity demand profiles. PyPSA optimises the use of batteries and electrolysers. The hydrogen demand to be supplied by the electrolysis units concerns an assumed base-load demand from industry in particular and the hydrogen needed for hydrogen power plants determined by PyPSA.

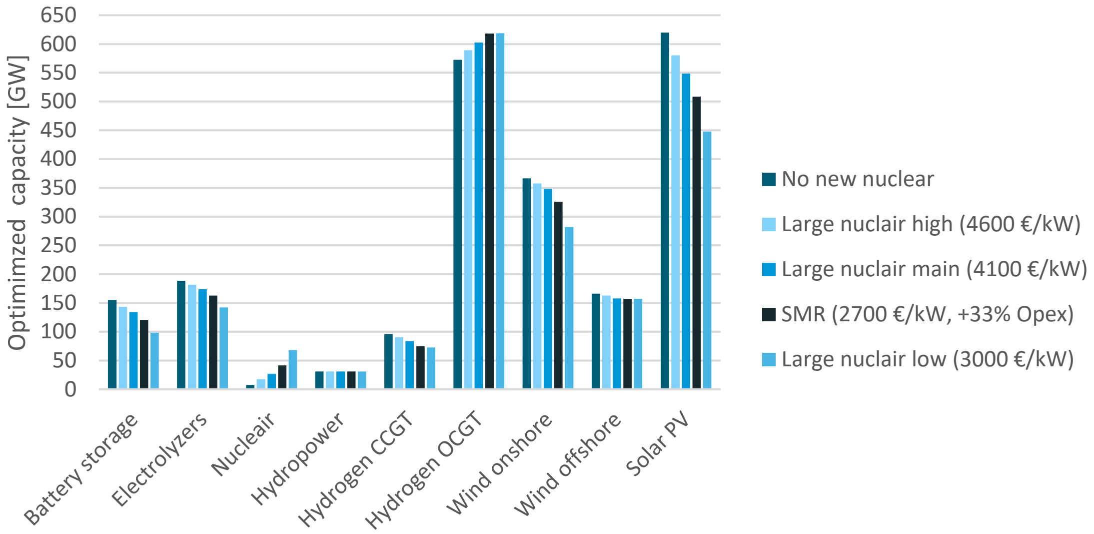
Energy system optimisation results

The energy system optimisation shows that, if large-scale nuclear energy can be realised without exceeding the budget and construction period, and if SMRs live up to their cost ambition, there may be a significant role for nuclear energy in the Dutch energy system. In 2050, for large-scale nuclear energy, at a price of EUR 4,100 per kW for the construction costs plus interest costs over the construction period at 3.8 % WACC, a cost-optimal expansion of 5.5 GW in nuclear energy in the Netherlands is anticipated on top of the 3 GW. With lower nuclear energy costs, more nuclear energy becomes cost-optimal. In the SMR scenario, for instance, a cost-optimal role for SMRs of 14.5 GW can be achieved in the Netherlands by 2050, if it can deliver on a cost of EUR 2,700 per kW.

That the reduction of risk, and the corresponding WACC has a major impact, is shown by the sensitivity analysis for the costs of nuclear energy. For large-scale nuclear power at the high cost variant of EUR 4,600/kW at 7 % WACC (without varying the WACC for other technologies) there is no longer a cost-optimal role for nuclear power. The turning point is between EUR 4,100 and EUR 4,600 per kW.

In general, an increase in nuclear power in Figure 1.2 shows a decrease in solar and wind power generation on a Northwestern European scale. The amount of batteries, electrolysers and hydrogen storage also decreases. In the case of hydrogen power plants, an increasing amount of nuclear energy results in a shift from efficient CCGT type plants to peak OCGT plants.

Figure 1.2 Optimised capacity [GW] for Northwestern Europe in 2050 for the different cost variants



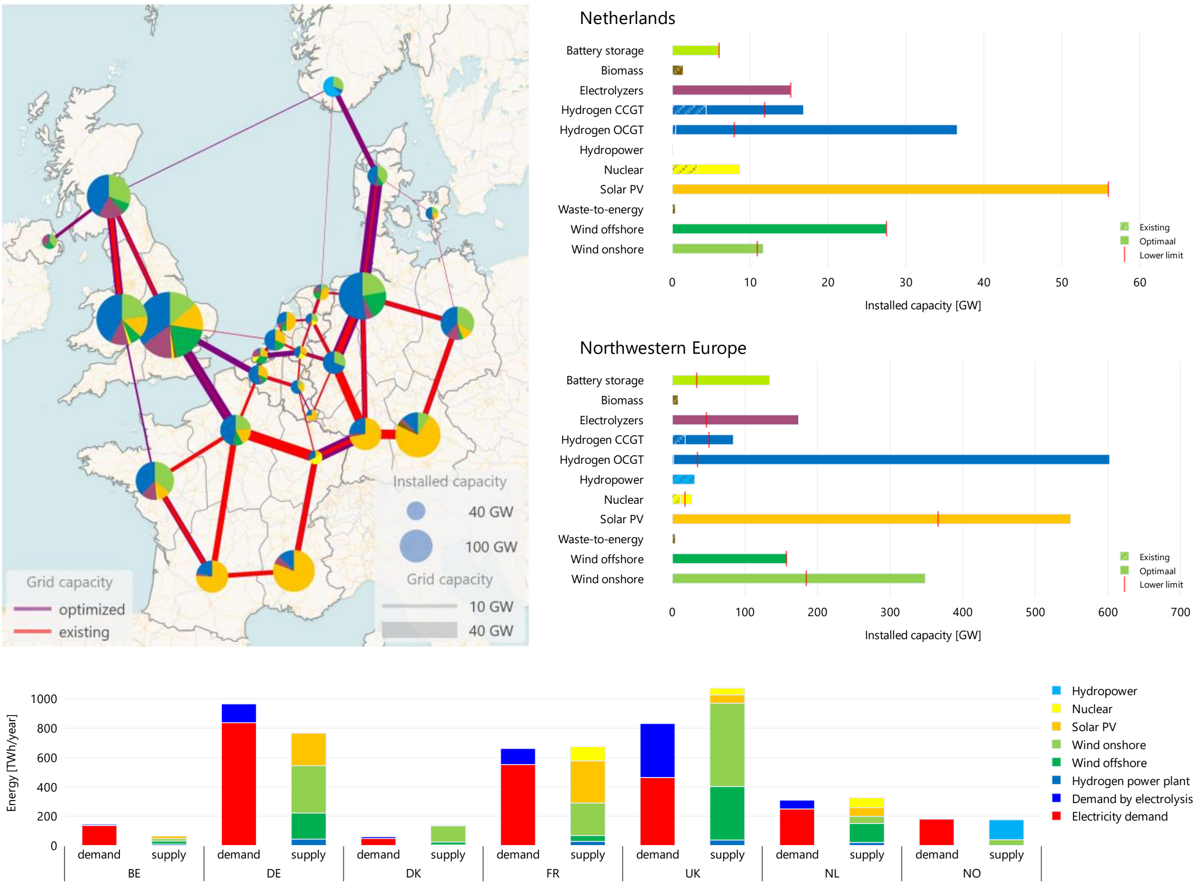
By 2050, the energy demand in the Netherlands will be 250 TWh plus 56-64 TWh for hydrogen production. The Netherlands will go from 39 TWh (13 %) net electricity imports in the scenario without nuclear energy to 16 TWh (5 %) net exports in the large-scale nuclear scenario, and to 83 TWh (26 %) net exports in the SMR scenario. The optimisation with nuclear energy results in less solar and wind power, especially in Germany and Belgium, because more nuclear energy can then be imported from the Netherlands and Northern France.

The calculations show that the lowest costs will be achieved if nuclear energy is installed in the south-east of the Netherlands first and in the east after that. This can be explained, on the one hand, by the fact that these regions are the only ones where there is no offshore wind. On the other hand, these regions are connected to the eastern part of Belgium and the western part of Germany.

Strong sensitivity to neighbouring countries' policies

In addition to the sensitivity to the cost of nuclear energy itself, other preconditions of the optimisation are also quite sensitive. The policies of neighbouring countries are particularly influential. The energy system optimisation was conducted from a brownfield 2035 point of departure for Northwest Europe, i.e. based on the existing policies of the Netherlands and surrounding countries and the amount of renewable generation that would be in place by 2035. Subsequently, the question is answered whether there is still a cost-effective role for nuclear power by 2040 and 2050 with further electrification and full decarbonisation of electricity. If we take the energy transition until 2030 (brownfield 2030) or even greenfield as a starting point rather than the planned and foreseen energy transition until 2035, achieving cost-optimisation will require the installation of considerably more nuclear energy in the Netherlands. However, this increase is mainly due to additional net exports and at the expense of less solar and wind power in Belgium and Germany. What stands out about greenfield without nuclear energy is that it is optimal in the Netherlands to realise 46 GW of offshore wind (more than the 28 GW established in brownfield 2035), which suggests that the Netherlands has relatively favourable offshore wind and landing conditions.

Figure 1.3 Installed capacity (above) and energy (below) for 2050 with large-scale nuclear energy



The Netherlands will export less in net terms and come closer to an import/export balance if it is assumed that countries want to become at least 80 % self-sufficient in electricity. This would reduce the cost-effective expansion of nuclear energy beyond the 3.2 GW in the Netherlands in 2050 to 2.4 GW for large-scale nuclear power plants and 8 GW for SMR. If SMRs are not only installed in the Netherlands, France and the UK but in all countries, then 1 GW would still be cost-optimal in the south-east of the Netherlands. In such a case, SMRs would be installed in far inland regions, with moderate wind conditions and relatively high demand, such as in the south and west of Germany, east of Belgium and Luxembourg.

For 2040, the energy system optimisation results in a greater role for nuclear energy than for 2050. This is the result of the assumption that the costs of solar, wind and storage continue to fall while the cost of nuclear energy is based on the same cost scenarios in both years. It should be noted that the costs for the SMR scenario for 2040 are ambitious and may not be met until 2050. This greater role for nuclear power in 2040 applies to both Northwest Europe, as shown in Figure 1.4 and the Netherlands, shown in Figure 1.5. In the scenario without nuclear energy, France will still have 40 GW in existing nuclear power plants by 2040 and the UK 6 GW.

Figure 1.4 Optimised energy production [TWh/year] for Northwestern Europe in 2040 and 2050 for the 3 scenarios

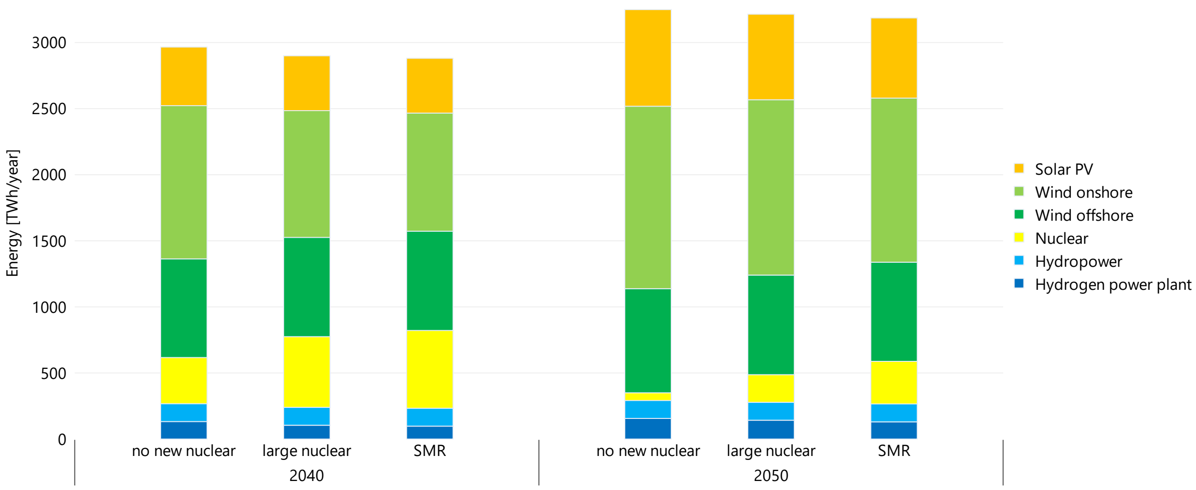
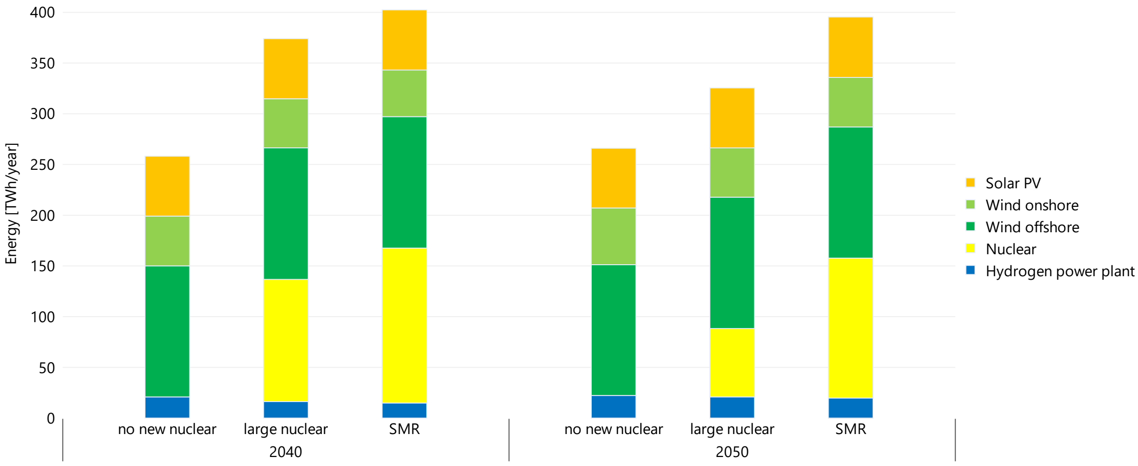


Figure 1.5 Optimised energy production [TWh/year] for the Netherlands in 2040 and 2050 for the 3 scenarios



It should be noted that the optimisation model, despite the option to do so, does not invest in nuclear power plants in the UK. The wind conditions are so good that there is no cost-optimal role for nuclear energy. The UK is investing a lot in wind capacity that is largely used to produce hydrogen and export it via the North Sea pipeline to the Netherlands and partly on to Germany. The Netherlands produces about half of its green hydrogen demand itself and a little more in the scenarios with nuclear power because in these scenarios, the electrolysers operate for more hours.

Whether or not nuclear energy is used as a source in the future energy mix is reflected to a limited extent in the total costs of the Northwest European energy system. The installation of nuclear power plants in regions with limited renewable potential and high energy demand can prevent the need for grid investments. The integral cost of energy averaged over electricity and hydrogen and including transport and storage for 3 scenarios without nuclear energy, large-scale nuclear power and SMR is EUR 38.4, EUR 38.2 and EUR 38.0 per MWh respectively. The sensitivity analyses with nuclear energy thus show lower costs for the Northwest European energy system than the analysis without nuclear energy, although the differences are small. The total annual cost for the scenario without nuclear energy is EUR 106 billion. To arrive at this cost figure, investment costs in generation, network infrastructure and storage were annualised and all annual variable and fixed costs included. Scenarios with large-scale nuclear energy and SMR show cost reductions of EUR 0.6 and 0.9 billion per year respectively, or 0.5 % and 0.8 % relative to the scenario without nuclear energy. The costs of the energy system in the Netherlands are respectively EUR 9, 11 and 13 billion per year. This increase is the direct result of the investments in nuclear energy. Obviously, these expenditures will be offset by revenues such as from exporting electricity and reduced hydrogen imports.

In summary, based on the assumptions made, nuclear energy can fulfil a cost-optimal role in the energy system in the Netherlands. Nuclear energy provides a base load within the Dutch energy mix and thus contributes to the production of more hydrogen using solar and wind energy and rendering the import of electricity unnecessary. The optimal quantity depends partly on the degree to which the Netherlands wants to be self-sufficient. Lastly, the policies of, and coordination with, neighbouring countries are also important.

1.5 Raw material and energy security

The road to climate neutrality will lead to significant geopolitical competition for raw materials and technologies. The Netherlands and the EU are dependent on the import of raw materials, both semi-finished and finished. Of all the raw materials that have been assessed for security of supply and geopolitical risks, many are already on the EU list of critical materials. This list is expected to grow in the coming years, as it has since 2017, as more raw materials are added.

This dependence becomes particularly problematic when the supply risk of a material is high and the impact of a possible disruption would have serious consequences for the European economy and energy transition. These materials are also often used in applications other than climate-neutral technologies. The Netherlands will need to import certain technologies and energy carriers. Although electrolysers are being installed, much of the green hydrogen consumed in the Netherlands will need to be imported. In addition, the permanent magnets needed for wind turbines will probably be imported in their final form rather than being produced on Dutch soil. In this sense, geopolitical risks and the dependence of the Netherlands are to some extent shifted from raw materials to semi-finished products.

Supply shortages for the most critical raw materials and technologies are expected until 2035-2040, as many countries will take steps towards the climate targets at the same time. All technologies need critical raw materials. For nuclear energy, this applies to a lesser extent, partly due to the availability of uranium. Despite trivial differences, the critical metal demand for the Netherlands will be substantial in all 3 electricity mixes presented in the analysed scenarios. This is partly because the amount of nuclear energy in all scenarios is small compared to the amount required by other technologies that partly rely on the same raw materials. The coming years will be characterised by price volatility, creating supply bottlenecks and price peaks for energy technologies. Mitigating factors, such as substitution by other materials or the availability of reserves in partner countries, may increase security of supply.

The concentration of mining and processing of ores and metals in a single country is one of the main indicators of geopolitical risk. Other risk factors are ownership of mines by third countries to control the availability of the metals and minerals, geopolitically motivated export restrictions or the suspension of trade relations. The Chinese dominance of critical mineral supply chains is noticeable, ranging from rare earth elements to silicon, indium, graphite and vanadium. The Chinese government has the ability to influence global supply and cause price spikes by implementing simple changes in domestic policy. Consumers around the world may be affected by a change in the standards for processing vanadium, leading to interruptions in production and therefore supply shortages. The strong increase in demand, the development of more sustainable mining and processing methods and the constant discovery of new reserves will accelerate the exploitation of global resources in the long term. There are also reserves of many materials in Europe; political will and social acceptance will be the determining factors for starting domestic European mine exploration projects.

The geopolitical risks in the area of material procurement are quite limited for nuclear energy. The world’s ample uranium reserves, the diversity of (reliable) suppliers, the relatively small amount of uranium needed to produce electricity and the possibility to store uranium for a long time without degradation of the material, are risk-mitigating factors for Europe's dependence on uranium imports. In the uranium fuel cycle, enrichment, fuel rod production, reprocessing of spent fuel and radioactive material storage are largely carried out by different European companies on European territory.

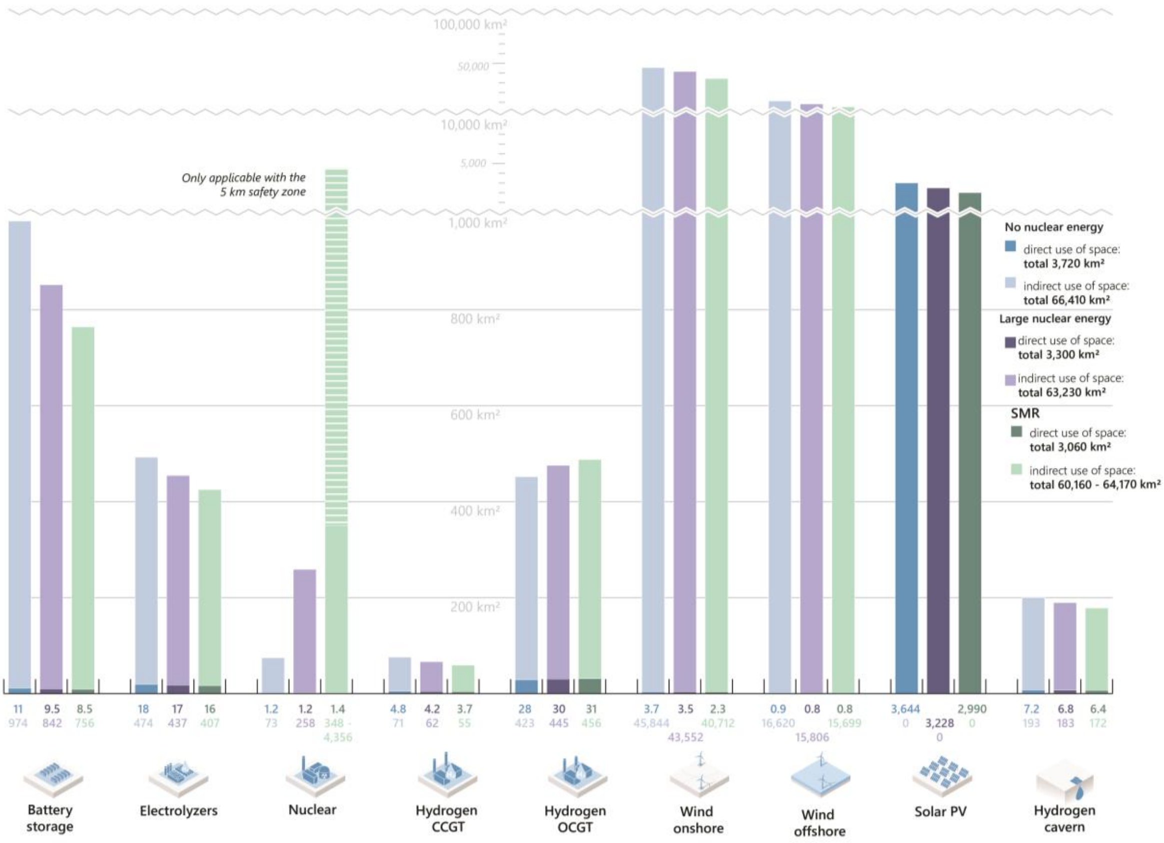
1.6 Spatial integration

For each scenario, the direct use of space (use of space by the energy technology alone) and indirect use of space (obstacles caused by the presence of the energy technology to its surroundings) have been identified. For the scenarios, indirect use of space contributes most to the demand for space. Wind in particular, requires a lot of space, although most of this concerns offshore wind and agriculture and other activities are still possible with onshore wind. Solar PV panels only require direct use of space, albeit a considerable amount. The analysis on a Northwestern European scale shows that nuclear energy (under the assumptions of this scenario study) saves space, as shown in Figure 1.6. Across all energy technologies, nuclear energy saves approximately 180 km^2/GW (22 km^2/GW in direct use of space and 164 km^2/GW in indirect use of space), through a combination of a reduced need for wind, solar PV panels, batteries and electrolysers. In the area of indirect use of space, however, there is the possibility of agriculture, livestock breeding, recreation and nature development or other energy technologies such as solar PV panels, wind, batteries or infrastructure.

For nuclear energy scenarios, large-scale nuclear energy and clustered SMRs mean that the demand for space is manageable within the possible locations (Borssele and Maasvlakte). For individual SMRs, the actual spatial impact depends on the (revised) safety zone around nuclear power plants. If a safety zone of 5 km is maintained around each nuclear power plant which may not include a densely populated area (as currently results from SEV III for larger power plants), the impact will be considerable.

If further research shows that the safety zone around power plants can be less than 5 km, this area will be reduced. This may vary per SMR, depending on the technology and the size of the corresponding SMR.

Figure 1.6 Total use of space (direct+indirect) for Northwest Europe in 2050 for the 3 scenarios



Various reports indicate that a site must meet a number of preconditions in order to be suitable for nuclear energy:

1 A nuclear power plant should be located at a large distance (at least 5 km) from a densely populated area.
2 A location must meet certain safety requirements, including those relating to the proximity of sensitive objects, available infrastructure and escape routes.
3 The storage capacity of radioactive waste must be taken into account.
4 The risk of natural accidents (weather conditions and soil stability) and man-made accidents (including those related to nearby land, river, sea or air, fire, explosions, weapons development and release of dangerous gases from industrial installations, electromagnetic interference) must be taken into account in the site selection process.
5 Depending on the size of the nuclear power plant and the cooling technology used, there must be sufficient cooling water on site.
6 The location must be connected to infrastructure that enables the safe transport of nuclear fuel and radioactive waste.
7 When selecting the location of a nuclear power plant, effects on protected natural areas and soil and water quality must be taken into account, as well as the relevant regulations.
8 The spatial integration of nuclear energy must take account of archaeological and landscape values present at the location.

The regions that the energy system optimisation (see section 2.3 above) designates as optimal for the installation of nuclear energy under the assumptions of the model have not yet been tested against the above preconditions.

1.7 Social considerations of nuclear energy

The social debate surrounding (the expansion of) nuclear energy in the Netherlands has been going on for decades. This is partly due to the events in Chernobyl and Fukushima, as well as the discussion about nuclear waste. In the current geopolitical context, there is scope to explore whether nuclear energy could play a role in contributing to the 3 pillars (affordability, reliability, sustainability) of Dutch energy policy. Relevant aspects analysed in this study include:

- The impact the addition of 2 nuclear power plants in 2035 will have on the Northwest European market.
- The total system costs in 2050 in Northwest Europe with and without nuclear energy.
- The change in dependencies and risks that these dependencies entail on raw materials and rare earth elements in scenarios with and without nuclear energy.
- The impact of nuclear power use on land use versus alternatives.

Social cost and benefit analyses regarding nuclear energy go back to the years 2004 - 2009, with regard to the new building decrees in France, the UK and Finland. A possible follow-up could be to have a new (SCBA) analysis conducted in which all elements of cost and benefit, as evaluated in this study, are translated into a quantifiable social impact. Alternatives have also been developed for social discussion. One of these alternatives is the Participatory Value Assessment. This assessment does not ask citizens to answer yes or no to policy options, but presents them with an overall picture that should be used to assess policy options in context. The lessons from the Participatory Value Assessment climate assessment lead us to the following implications for achieving social integration of nuclear energy:

- A coherent policy is needed that makes clear how the different sectors contribute to CO2 reduction: what will industry do and how? Transparency is emphasised as an important factor here.
- The effect on energy prices and how the effect is distributed among the different energy users will also have to be made explicit.
- If a nuclear power plant is to be co-financed with public funds, it must be clarified how users who have traditionally contributed less to, for example, sustainable subsidies, will now pay their share.

While nuclear energy has not been discussed directly with citizens in the Netherlands in recent years, in light of other discussions about choices in climate policy (biomass, onshore wind energy) much knowledge has been gained about how citizens can be involved. This could include process criteria such as ensuring that the citizens to be involved are treated respectfully and fairly, creating clarity about the process but also about what will happen with the input from a discussion or participation. It is advisable to apply this knowledge in the context of the social integration of nuclear energy.