The Effect of Electricity Generating Park Renewal on Fossil and Nuclear Waste Streams: The Case for the Netherlands

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1. Introduction

Most scenarios for electricity supply development for Western Europe assume a decline for nuclear generation in the coming decades, or a small increase followed by a decline, e.g. the European study "European Energy and Transport, Trends to 2030 – update 2005" [1]. Some scenarios with high economic growth assume an increase in nuclear generation to cover the demand growth associated with the economic growth, e.g. [2].

This study however considers a scenario where nuclear energy is deliberately employed for coupled economic-environmental reasons, for a real country departing from an existing electricity generating park.

The Netherlands currently has a generating park of 21 GWe (2004), running for three quarters on natural gas, see Figure 1. Already for some decades The Netherlands is a main gas producer itself, explaining the large gas share to electricity generation and the low nuclear share, compared to the European mean nuclear share of 35%. However, the main gas source at Slochteren in the north of the country is expected to run out in 2030, and the smaller sources below the Wadden Sea at least before 2050.

So if the Netherlands don’t want to rely heavily on natural gas imports in the future, some form of transition has to take place in the electricity generating sector. The government already set fairly ambitious targets for renewable generation, and forced conservation by legal bans or rationing of electricity is beyond the way of current thinking. Current government plans indicate obligatory CO2 sequestration for new coal plants, making the coal option economically unattractive. So the nuclear option remains the more obvious alternative to generate base-load quantities of electricity with existing technology.

2. The Nuclear/Renewable Transition Scenario for The Netherlands

As electricity generation in the first place should stimulate prosperity and economy, no capital destruction by forced shutdown of power stations is envisaged. We depart from the existing electricity generating park, and the government stimulation plans for renewables are left intact.
During the past 40 years, there has been an increase in the Netherlands of the electricity consumption by a factor of 5.8, which implies an average annual growth of 4.5% [3]. It seems unrealistic to extrapolate this growth rate for the next 50 years, considering the decrease in growth of the Dutch population. Recent studies consider more moderate growth rates. The Dutch study ‘Referentieramingen’ (Reference Estimates), performed for the Government to forecast the Dutch energy consumption and the resulting environmental impact up to 2020, considered annual growth rates of 1.7% for the ‘Strong Europe’ scenario, and 2.7% for the ‘Global Economy’ scenario [4]. On the other hand, the CASCADE MINTS project, funded by the European Union under the support of the 6th RTD Framework Programme, considered annual growth rates ranging from 0.65% in 2010 to about 0.35% in 2030 for the “Baseline” case [5]. The recent Dutch study “Deltaplan Kernenergie” assumed a constant annual growth rate for the electricity production of 1.5% up to 2060 [6].

For the present study, 2 different growth scenarios have been considered (see also Figure 2):

1. The scenario based on the assumptions of the “Deltaplan Kernenergie”, assuming a constant annual growth rate of 1.5%.
2. The scenario based on the assumptions of the CASCADE MINTS project, assuming a constant annual growth rate declining from 0.65% in 2010 to 0.35% in 2030.

In addition, the following boundary conditions have been assumed:

- Phase-out of coal-fired plants: the existing coal-fired plants are serving out their planned lifetimes and no new ones are commissioned except those that already have been planned.
- The contribution of renewable energy (wind, biomass) to the total electricity production is not determined by the market but by government planning. It will increase by 20% in 2020, and by 30% in 2040. These assumptions are in line with the forecast of the “Referentieramingen” [4].
- A gradual deployment of nuclear reactors in the next decades. Presently, only one nuclear power plant is operated in the Netherlands, the Borssele nuclear power plant. Various reactor types are being offered today or will be offered in the coming years. For the present analysis, a fleet consisting of one type of large reactor unit and one type of smaller unit, the latter suitable for heat and power cogeneration, has been assumed for the next decades. For the large unit the European Pressurized Reactor (EPR) was selected, and for the small unit the Pebble Bed Modular Reactor (PBMR).

For the cases with deployment of nuclear reactors, the options of direct disposal of spent fuel (“Once Through” case), and reprocessing of spent fuel (“Reprocessing” case) have been considered.

For comparison reasons, a scenario taking into account the nuclear phase out option has been considered, the nuclear phase-out scenario. For that scenario, an average growth rate for the electricity consumption of 1.5% has been assumed.

An overview of the main design parameters of the fossil-fuel fired plants and the nuclear reactors and fuel cycle is given in Table 1.

3. Computer Tools

Dynamic Energy Economics Analysis (DEEA) is a system dynamics tool which is able to simulate scenarios for the future deployment of fossil-fuel, nuclear and renewable energy systems. Driven by a future energy demand, new energy systems are introduced by means of a decision model that is mainly based on the profit per MWh for each of the different electricity-generating options. DEEA is a macroscopic tool and intended to provide relatively quick results. This brings about that the code models are relatively straightforward, taking into account the overall processes and avoiding too much details. Seven types of nuclear reactors as well as gas-fired and coal-fired fossil fuel plants are characterized by gross data. Renewables are simply modelled by power and energy demand growth rate. The economics model takes into account interest and discount rates and the price of electricity, and compares this with economic factors that are specific for each energy generating system (e.g. levelized cost, fuel cost, carbon tax).

Given a future energy demand, DEEA calculates the relative contributions

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**Fig. 2.** Forecast of the installed electricity generating capacity in the Netherlands for 2 different growth scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>Gas Fired Plant</th>
<th>Coal Fired Plant</th>
<th>Borssele NPP</th>
<th>EPR</th>
<th>PBMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>400</td>
<td>520</td>
<td>484</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>2010</td>
<td>35</td>
<td>30</td>
<td>26</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>2020</td>
<td>0.85</td>
<td>0.85</td>
<td>0.93</td>
<td>0.91</td>
<td>0.95</td>
</tr>
<tr>
<td>2030</td>
<td>0.45</td>
<td>0.39</td>
<td>0.35</td>
<td>0.37</td>
<td>0.41</td>
</tr>
<tr>
<td>2040</td>
<td>2</td>
<td>3</td>
<td>(existing plant)</td>
<td>1.3</td>
<td>0.19</td>
</tr>
<tr>
<td>2050</td>
<td>0.65</td>
<td>0.45</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>2060</td>
<td>14.2</td>
<td>6.0</td>
<td>4.6</td>
<td>3.9</td>
<td>4.4</td>
</tr>
<tr>
<td>2070</td>
<td>3.1</td>
<td>4.2</td>
<td>3.1</td>
<td>4.2</td>
<td>8.1</td>
</tr>
<tr>
<td>2080</td>
<td>33</td>
<td>50</td>
<td>33</td>
<td>50</td>
<td>90</td>
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</tbody>
</table>

1 Including lifetime extension
2 inclusive price of CO2

**Tab. 1.** Average design parameters of the different facilities.
of nuclear, fossil fuel, and renewable energy systems to the total energy production. The development of the nuclear energy production in time then serves as the boundary condition of a detailed analysis of the nuclear fuel cycle. This analysis is performed with the DANESS computer tool.

For the assessment of the nuclear fuel cycle strategies, the DANESS code ("Dynamic Analysis of Nuclear Energy System Strategies" [7]), Version 3.2.03, was used to simulate the flows of fissile material, fresh fuel, spent fuel, high level waste as well as all intermediate stocks and fuel cycle facility throughput. DANESS is an integrated dynamic nuclear process model for the analysis of today’s and future nuclear energy systems on a fuel batch, reactor, and country, regional or worldwide level. Starting from today’s nuclear reactor park and fuel cycle situation DANESS analyzes energy-demand driven nuclear energy system scenarios over time and allows the simulation of changing nuclear reactor parks and fuel cycle options. New reactors are introduced based on the energy demand and the economic and technological ability to build new reactors. The technological development of reactors and fuel cycle facilities is modelled to simulate delays in availability of technology. Levelized fuel cycle costs are calculated for each nuclear fuel batch for each type of reactor over time and are combined with capital cost models to arrive at energy generation costs per reactor and, by aggregation, into a cost of energy for the whole nuclear energy system. A utility sector and government-policy model are implemented to simulate the decision-making process for new generating assets and new fuel cycle options. The different functionalities of DANESS may be switched on or off by the user according to the intended use. The architecture of the DANESS code is depicted schematically in Figure 3.

For the calculation of the amount of nuclear waste, a fuel cycle model is used, as shown in Figure 4. Properties of all fuel cycle facilities are input, including capacity and transition time. For each reactor, a fuel type and back-end route (direct storage or reprocessing) is set. The amounts of waste are given in tonnes heavy metal (tHM), and converted to volumes in m³ for the results in chapter 8.

4. Electricity Supply

The electricity supply distribution over the available sources is determined for the 3 selected scenarios:

![Fig. 3. Schematics of the architecture of the DANESS code.](image1)

![Fig. 4. Fuel cycle model in DANESS code.](image2)
Nuclear/renewable transition with high demand rise: Figure 5.
Nuclear/renewable transition with low demand rise: Figure 6.
Nuclear phase-out with high demand rise: Figure 7.

The initial rise in electricity production is caused by the deployment of newly-built fossil-fuel power plants (e.g. 800 MW Sloe generating plant, 800 MW gas plant Eemshaven, and several others), whereas existing plants are not yet shut down. Around 2040 a ‘bend’ in the integrated curves can be observed: after the phase-out of coal-fired plants, the demand growth is fully covered by nuclear+renewables, so no additional growth of electricity from gas-fired plants is needed.

It can be seen that, with the prescribed growth rate of the renewables, in the high demand scenario nuclear energy will become the largest electricity source with 54% in 2060, whereas in the low demand scenario the renewables take the largest share with 52% in that year. In the nuclear phase-out scenario the electricity need that is not covered by the renewables is almost equally shared between gas and coal.

5. Fossil Waste Generation

The amounts of the gaseous waste emissions from the fossil-fired stations for the next decades have been depicted in Figure 8, 9 and 10. Figure 8 gives the carbon dioxide (CO₂) emissions, Figure 9 the nitrogen oxide (NOₓ) emissions, and Figure 10 the sulphur dioxide (SO₂) emissions. The SO₂ emissions result for the largest part from the combustion of coal. Although in the Netherlands it is required to implement measures to reduce the SO₂ emissions from coal-fired plants, approximately 10% of the total generated SO₂ still is released to the atmosphere. Through better SO₂ reduction methods this percentage is likely to decrease in the future so that the estimated values shown in Figure 10 represent upper limit values.

The difference between the nuclear and non-nuclear scenarios is obvious: for 1.5% demand rise the accumulated CO₂ emission of the nuclear scenario in 2060 is only 12% of that of the nuclear phase-out scenario. In other words, by introducing nuclear energy on the proposed scale, 88% of the total generated SO₂ still is released to the atmosphere. Through better SO₂ reduction methods this percentage is likely to decrease in the future so that the estimated values shown in Figure 10 represent upper limit values.

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generation is a serious option to reduce significantly the emission of hazardous exhaust gases.

6. Deployment of Nuclear Energy

The deployment of nuclear reactors (EPR, PBMR) as calculated by DANESS, is depicted in Figure 11 and Figure 12. DANESS calculates a relatively larger deployment of the small-scale PBMRs in the “CASCADE” case as compared to the “Deltaplan” case, because of the slower growth rate of the energy demand in the “CASCADE” case, which makes it less attractive to deploy the larger-capacity reactor types (1,600 MW EPRs). In case of slower energy demand growth rates, the deployment of large reactors would result in a significant over-capacity of produced electricity. The more gradual deployment of the smaller PBMRs leads to a better match of the demand of electricity. From about 2040 there is less growth in the demand curve for nuclear energy, so the deployment of the smaller-capacity PBMR reactors is preferred above the large-capacity EPR reactors for the reason of demand matching. Therefore no additional EPRs are foreseen.

7. Effect of nuclear cogeneration on CO₂ mitigation

Originally the development of the high-temperature gas-cooled reactor was started to be able to supply not only electricity, but also process heat and cogeneration to various sectors of industry. From previous studies (e.g. [8]), it was demonstrated that high-temperature gas-cooled reactors are capable to deliver, apart from electricity, a significant amount of heat, i.e. up to about 30% of the total thermal power.

In Figure 13 the CO₂ release is depicted for the three considered scenarios, now for the nuclear scenarios also depicting the additional avoided CO₂ emission when using the PBMR in cogeneration mode. It can be seen that the CO₂ emission of the Dutch electricity sector even falls below 0 when the avoided emission of industrial heating is subtracted from the CO₂ emission of fossil-fired power plants.

8. Spent Nuclear Fuel and Nuclear Waste

The amounts of nuclear wastes that have to be taken care of, have been calculated as a function of time for 2
options: direct disposal (‘Once Through’) and recycling (‘reprocessing’). For the 2 options, the amount of waste in interim storage facilities is shown in fig. 14, and the amount of waste in final disposal in Figure 15. As can be seen in the fuel cycle model scheme of figure 4, spent fuel first moves from the reactor to the ‘At Reactor’ storage, consisting of the spent fuel storage ponds at the nuclear plants. After a certain cooling down period at the reactor storage, in this study set to 5 years, the spent fuel is transferred to the spent fuel interim storage facility, where it is able to cool down further. After this, it can take 2 routes:

– It is sent to the spent fuel conditioning facility where it is treated for final disposal in a final disposal facility;
– It is sent to a reprocessing facility, where uranium and plutonium are recovered after which the remaining high level waste is transferred to a HLW interim storage facility for a cooling down period. In the high level waste conditioning facility the waste is prepared for final (geological) disposal.

In Figure 14, the black curve indicates the total amount of spent fuel stored at the nuclear power plants for the high demand scenario. The blue lines indicate the amount of spent fuel stored in interim storage. It can be seen that after about 2045 the waste arisings decrease as a result of the decreased growth in nuclear demand (cf. Figure 11). The difference between the 2 blue lines is reflected by the thin red line: the amount of high level waste coming from the reprocessing plant.

In Figure 15, the amount of high level waste coming from the reprocessing plant is still very low in 2060. This is primarily caused by long transit and waiting periods for reprocessing. For this case still much high level waste is in the pipeline and will arrive at the final repository after 2060. This illustrates the contradiction of societal demand for an operational final storage facility at the start of a nuclear expansion programme on the one hand, and on the other hand the actual arriving of high level waste from the reprocessing plant only several decades later.

For the low demand “CASCADE MINTS” scenario, the predicted amounts of stored waste in the year 2060 are about 30% to 55% less, depending on the type of waste, in comparison with the high-demand “Deltaplan” scenario.

In Figure 16, the actual container volumes are depicted that are needed to for interim storage of spent fuel, high-level wastes and the PBMR pebbles. For vitrified high level waste, the COGEMA HLW container [9] is considered, and for spent fuel the ONDRAF-NIRAS design [10]. For the
PBMR pebbles, the German design storage canister [11] is adopted. We see the volume of the high level waste containers completely vanishing against the large volume of containers holding non-reprocessed spent fuel. For the most part, the larger SF container volume comes from containers holding PBMR pebbles, that mainly consist of graphite and only 7% of nuclear fuel. For the CASCADE scenario, the spent fuel volume rises only to 8,500 m$^3$ in 2060, that is 71% of the volume in that year for the Deltaplan scenario. This can be seen in the bar chart of Figure 17 as well, where the spent PBMR pebble fuel is indicated separately.

From Figure 17 it is also clear that the used PBMR pebbles require by far the most storage and disposal capacity, because for the PBMRs also the moderator material (matrix graphite) of the fuel pebble is also considered as waste. The volumes that are needed to store and dispose HLW are only a minor fraction of the total required volumes.

The growth of the volume of waste containers in geological disposal over time for the whole Dutch nuclear park is similar to Figure 15, with a volume of 42,000 m$^3$ in 2060 for the case of no reprocessing for the high electricity demand case, and 28,000 m$^3$ for the low demand case. Figure 18 is comparing the volume of waste containers in the final storage facility for the 2 demand cases in the year 2060, distinguishing between EPR and PBMR waste. For PBMR, also the amount of waste emerging when recycling the graphite, storing only the coated particle fuel (still no reprocessing). This measure already would reduce the PBMR spent pebble volume by 92%.

Table 2 lists the calculated effective volumes of the waste canisters that are needed to contain the spent fuels, high-level wastes, and PBMR pebbles.

9. Comparison with Existing Interim Storage Capacity in The Netherlands

The facility for interim storage of spent fuel and high level nuclear waste is called HABOG (‘Hoogradioactief Afval Behandeling- en Opslag Gebouw’, Highly-radioactive Waste Treatment and Storage Building). It is located near the city of Vlissingen and the Borssele nuclear power station in the south of the country [12]. The HABOG-building is a modular building. This means the building can be extended if necessary. At this time there are 3 vaults for the storage of heat generating waste and 3 bunkers for the storage of non-heat
generating waste. The license permits only a full load of 2 of the 3 vaults or bunkers. It should always be possible to unload one vault or bunker for inspection.

The capacity of each vault is 135 canisters with vitrified waste and 35 canisters with spent fuel. This means a total capacity at this moment of 270 canisters with vitrified waste and 70 canisters with spent fuel. The capacity of 2 bunkers is approximately 600 drums with different types of conditioned waste. The total volume of all the waste will be 750 m³.

In the high demand case, this capacity will already be used by 2024, and in the low demand case in 2028. The amount of equivalent HABOG capacities for the 3 cases (no reprocessing, no reprocessing but with graphite recycling for the PBMR waste, and reprocessing) per demand scenario in 2060 can be seen in Figure 19. Most storage capacity is needed in the case of high demand and direct storage of all spent fuel: 72 times the current HABOG capacity. This can be reduced to 28 by recycling the graphite of the PBMR spent fuel, and to 17 by recycling the fuel itself (reprocessing). The figures for the low demand scenario are accordingly lower.

10. Conclusions

Table 3 summarizes the amounts of waste generated for the high demand (‘Deltaplan’) scenario and the low demand (‘CASCADE’) scenario. In the case of the deployment of nuclear reactors, in 2060 the release of CO₂ as a result of electricity generation will be reduced to one-third as compared to the case where nuclear electricity generation is not considered.

Choosing between nuclear and non-nuclear generation parks is a trade-off of waste types. All types of energy mix come with a waste mix. When replacing fossil-generated electricity by nuclear, CO₂ and other gaseous waste is traded for radioactive waste, the CO₂ amount being in the order of a million times the amount of radioactive waste. By signing the Kyoto protocol, The Netherlands obliged itself to reduce CO₂ emissions by 13 Mton/year in 20 years time. By implementing the nuclear/renewable transition scenario, this target could be more than achieved by the electricity generating sector alone (factor 1.8), leaving room for other sectors with less possibilities for CO₂ reduction.

The following conclusions with respect to nuclear waste reduction can be drawn from this study:
- Reprocessing of spent fuel results in a significant reduction of volume that is needed

![Fig. 17. Comparison of the expected waste volume in storage at the nuclear plants and in the interim storage facility in the year 2060.](image)

![Fig. 18. Comparison of the volume of waste containers in the final storage facility for the 2 demand cases in the year 2060, distinguishing between EPR and PBMR waste. The case for recycling the PBMR graphite, storing only the coated fuel particles, is shown as well.](image)

<table>
<thead>
<tr>
<th>Effective Volume</th>
<th>Type of storage</th>
<th>Deltaplan Once-Through</th>
<th>Deltaplan Reprocessing</th>
<th>CASCADE Once-Through</th>
<th>CASCADE Reprocessing</th>
</tr>
</thead>
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<tr>
<td>Spent LWR fuel</td>
<td>Interim</td>
<td>1,468</td>
<td>1517</td>
<td>489</td>
<td>514</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>5,777</td>
<td>1517</td>
<td>2,038</td>
<td>0</td>
</tr>
<tr>
<td>High Level Waste (reprocessed fuel)</td>
<td>Interim</td>
<td>0</td>
<td>61</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>7</td>
<td>27</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>Spent PBMR pebble fuel</td>
<td>Interim</td>
<td>10,475</td>
<td>10,729</td>
<td>7,976</td>
<td>8,375</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>35,899</td>
<td>0</td>
<td>25,675</td>
<td>0</td>
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<tr>
<td></td>
<td>Final, recycled graphite</td>
<td>2,764</td>
<td>0</td>
<td>1,977</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. 2. Comparison of canister volumes needed for the storage and disposal of nuclear wastes for the different scenarios in the year 2060.
to finally dispose used radioactive materials in geological repositories.

- Reprocessing of spent fuel impels the deployment of capacity to separate the recyclable material from the HLW.

- In case of not reprocessing, most of the space in the interim and final storage facilities is occupied by spent PBMR fuel. By recycling the graphite part of the waste, a significant volume reduction can be achieved.

11. References


