COMPARATIVE COST ANALYSIS FOR DUTCH NUCLEAR PLANT ROLLOUT VS WIND & SOLAR ROLLOUT

SUMMARY

Prompted by the 2015 Paris Accord, and the necessity to act on climate change, the Dutch Government is planning to cut domestic emissions by closing coal and gas-fired power plants. To achieve this, they envision the massive and almost exclusive rollout of wind- and solar energy. We question whether this is the most affordable option.

We provide an alternate outlook based on building 10 nuclear reactors—in the Netherlands— for the production of electricity and other energy modalities—at reasonable cost. In this paper, we examine and compare the possible cost-range for building and operating nuclear power plants, solar power plants, and wind farms in the Netherlands, and find that nuclear power is a better option if certain prerequisites are met. We show that nuclear power can be built within a reasonable timeframe, at reasonable cost, and with a large cost benefit ratio. In fact, we find that nuclear energy—in the Netherlands—is more cost-effective than wind and solar.

By deploying 10 reactors, the Netherlands could cut as much as 100 Megatons of annual carbon emissions (~45%). There would still be a need for significant extra low-carbon power plants.

This article foregoes the need for backup generation and storage for a vast renewable rollout. This will add cost on the renewable side, but these costs are not modeled in this article.

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INTRODUCTION

The Netherlands is a small but industrious country in Europe with a growing population of 17 million people. According to the Bureau of Statistics, in 2017, carbon emissions per capita per year were 15.4 metric tons of CO_2eq. In total the Dutch emit between 260 and 270 megatons of CO_2eq per year.

However, the same bureau also states that Dutch carbon emissions were 193 megatons of CO_2eq (CO_2 163 megatons; N_2O, CH_4 & F-gases 29 megatons) In 2017.

There are proposals to reduce Dutch carbon emissions by as much as 49%—relative to Dutch emissions in 1990—by 2030 (41 megatons CO_2eq). It is important to note that this is a political choice, and the proposed 41 megaton reduction does not constitute 49% of total 1990 emissions (222 megatons CO_2eq). They propose ending the use of natural gas for heating purposes; electrifying transportation; **and replacing existing fossil fueled electricity production with wind and solar energy.** The Dutch Central Planning Bureau estimates that achieving the stated goals would require investments around 80 to 90 billion Euros and increases in annual government expenditures of 3 to 4 billion Euros per year by 2030.

We propose an alternative route that still depends on significant future solar and wind deployments in the Netherlands but will mitigate land and material use by introducing firm baseload / multi-purpose nuclear reactors to a potential future Dutch energy mix. The Dutch government is also planning to shut coal-fired power plants down by 2030.

There are three operational reactors in the Netherlands as of May 2019. Two reactors**—the High Flux reactor at Petten and a reactor in Delft—**are used for training or medical and research purposes; one is used for electricity production **(Borssele 1)**.

The Dutch Government selected 12 locations for new nuclear reactors in the 1970s. Five locations are still available (Borssele 2, Maasvlakte 1&2, Eemshaven 1&2).

In 2017 Dutch energy infrastructure generated 116.4 Terawatt hours (TWh). Forecasts show that the demand for electricity by 2030 may end up between 115.6 and 138.4 TWh/year.

We propose an alternative to remediate the need for a massive buildout of wind and solar: Adding 10 nuclear reactors to the Dutch energy mix (X Model).

TECHNOLOGICAL READINESS ASSESSMENT

To assess the technological readiness of reactor technologies, we create five criteria:

- The Dutch government has determined that the minimal requirement for new nuclear deployments should fall within Generation III specifications;
- The reactors must have been licensed and have been built elsewhere. This means reactors that have a status of "In Operation", "Construction" or "Licensed" in the Advanced Reactors Information System (IAEA ARIS);
- To make the most out of the limited space ready for nuclear reactor installation we pick high-capacity reactors (1100+ MWe);
- Must have passed the FOAK (first of a kind) stage;
- Reactor vendors cannot reside in countries under sanctions by the Netherlands (which excludes Russian VVER designs).

These reactors will be sorted by number of units operational, under construction, and planned. Initially, we determine that the following reactors fit within the criteria: APR1400 (13 units), AP1000 (12 units), EPR (10 units), ABWR (9 units). See appendix

PRODUCTIVITY FIGURES & AVOIDED CO2 EMISSIONS

The aim is to show the volume of carbon emissions that can be offset by closing coal and gas and replacing them with nuclear power plants. We modelled 10 large reactors (X Model) and assume a 0.9 Capacity Factor (CF). We also assume a high carbon footprint of 15 gCO_2eq/KWh for both renewable and nuclear energy and this means that the emissions for wind and solar will be equivalent to those stated underneath each reactor technology. Note: the fuel for these reactors can be fabricated in the Netherlands at URENCO.

X MODEL	EPR	ESBWR	APR1400	ABWR	AP1000
Single unit capacity (MW)	1770	1600	1455	1420	1200
Total capacity of 10 units (MW)	17700	16000	14550	14200	12000
Assumed minimal Lifetime (years)	60	60	60	60	60
Annual Production of 10 units (TWh)	140	126	115	112	95
Annual emissions (Megatons CO_2eq)	2.09	1.89	1.72	1.68	1.42

During operation, nuclear power stations incur no carbon emissions. Only during the fabrication of all the materials, the construction of the plant, and fuel production for a nuclear power station will carbon emissions occur. Construction, fueling and maintenance emissions for nuclear power plants are equivalent to those of wind and solar power generators on a productivity-based level playing field.

Dutch Coal Plants run at Capacity Factors ranging from 0.59 to 0.66, with an installed capacity of 4,660 MW. These plants can produce between 24 and 27 TWh per year. The life cycle emissions from coal are between 740 and 910 gCO_2eq/KWh resulting in a range from 17.8 to 24.6 Megatons CO_2eq per year.

Dutch Gas Plants run at Capacity Factors ranging from 0.38 to 0.79, with an installed capacity of 15,347 MW. These plants can produce between 51 and 106 TWh per year. The life cycle emissions from gas are between 410 and 650 gCO_2eq/KWh resulting in a range from 20.9 to 68.9 Megatons CO_2eq per year.

Annual demand in the Netherlands is several TWh higher than is delivered by domestic installed capacity. Therefore, the balance of electricity is consistently imported from Belgium, Germany, Great Britain and Denmark.

In our X Model, all technologies (EPR, ESBWR, APR1400, ABWR, AP1000) displace all coal and all gas-fired electricity generation on the low end of the range offsetting 95 to 98% (36.58 and 91.38 megatons CO_2eq) of all emissions from coal and gas. Smaller units are less effective offsetting 71 to 95% (36.58 and 66.46 megatons CO_2eq) of all emissions from coal and gas. 10 EPR reactors would generate more electricity than projected demand.

Adding 10 nuclear reactors to the Dutch electricity mix would result in a 36.58 to 91.38 Megatons reduction of annual carbon emissions, almost matching or completely overshooting the Dutch Government's ambition to cut 41 megatons per year by 2030 but simultaneously bridging a more significant gap towards a fully carbon neutral economy, decades ahead of schedule.

INVESTMENT, ANNUAL COSTS, BENEFITS

A recent MIT Study has outlined that it is cheaper to deploy an all-of-the-above electricity mix. Instead of only deploying variable renewables like the Dutch government is planning, the Dutch should include firm baseload power sources, storage, demand response, and CCS. The study offers a new taxonomy for electricity sources:

“fuel saving / variable renewables”, “Low Carbon Firm Baseload / Nuclear, natural gas with CCS”, “Fast-Burst / storage, demand response”.

There’s more to nuclear reactors than cost, they also generate large volumes of heat and/or electricity that can be used to add value to the Dutch Economy. Additionally, nuclear reactor facilities pay taxes over the commodity produced; they pay property taxes; and they employ hundreds to thousands of highly skilled, well-paid individuals who each contribute to the economy. According to a report by Deloitte *“Every Euro of the nuclear industry’s direct contribution to EU GDP generates an indirect contribution of 4 Euro, totaling an impact of 5 Euro in the EU GDP”*; according to the same article, *“Every job created directly in the nuclear sector sustains another 2.2 jobs, totaling an impact of 3.2 jobs on the EU labor force market”*; and *“Every Euro of disposable household income generated due to the nuclear industry translates into a total impact of 3.6 Euro household income throughout the EU”*. It is therefore reasonable to assert that civilian nuclear power plants offer great economic benefit and should be considered seriously.

In our X model we calculate levelized cost of electricity based on a discount rate range from 3 to 10% with increments of 1%. We assume a maximum reasonable cost-to-produce-electricity of 60 Euro/MWh which is in line with current cost-to-produce-electricity and would maintain a reasonable cost of electricity for end-users (~220 Euro/MWh). We use historical data to set wind and solar capacity factors; Solar has reached its highest CF so far in 2018 at ~10%; Average weighted Wind CF is ~25% (onshore & offshore; 2010-2017); Nuclear capacity factors have been arbitrarily set to 90% which is lower than the norm in the United States.

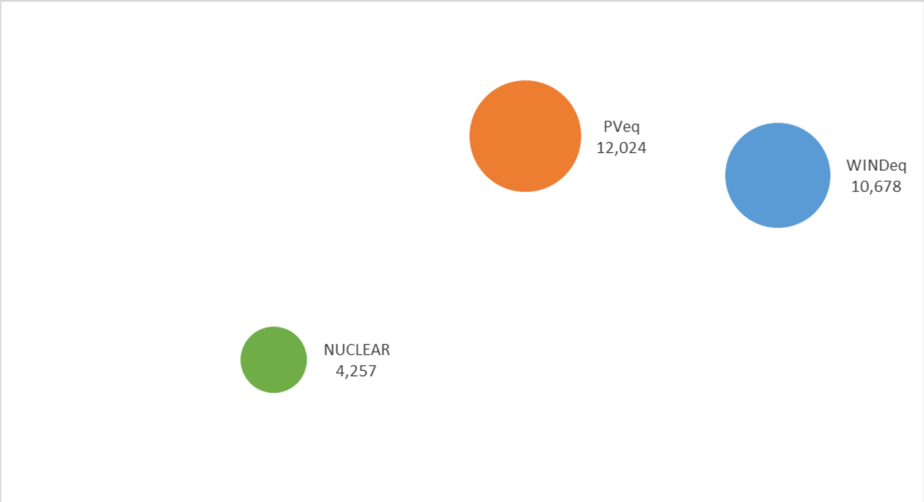
Dutch ratepayers pay about 150 Euro/MWh in taxes (VAT & Energy Tax) which means that any form of energy production is a sizeable source of income for the Dutch government. Note: electricity taxes vary from year to year.

We find that capital expenditures for the EPR ranges from 2,000 to 7,000 Euro/kW; the APR1400 ranges from 1,600 to 4,000 Euro/kW; the AP1000 ranges from 2,400 to 10,000 Euro/kW; PV ranges from 770 to 3,900 Euro/kW; Wind ranges from 1,200 to 6,600 Euro/kW.

Our Fixed and Variable cost assumptions are averaged values derived from the February 2019 EIA Electricity Market Module.

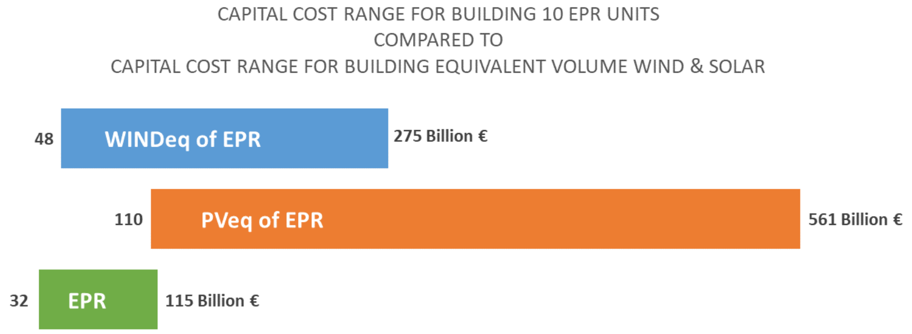
Note: the cost of decomissioning a nuclear power plant is an integral element of the Fixed O&M (it is included in all subsequent LCOE results).

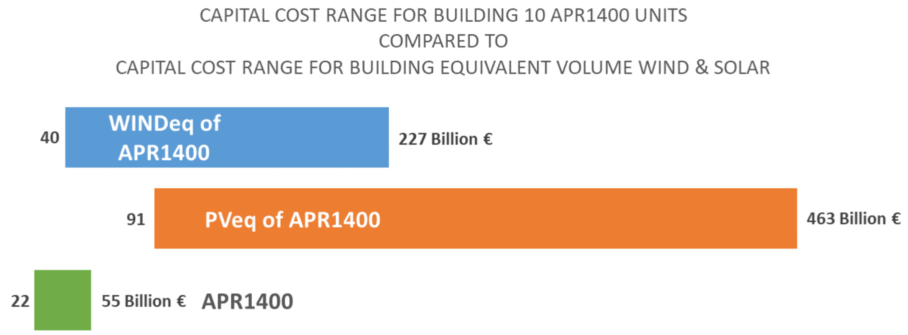
Based on actual Dutch capacity factors, to get a commensurate volume of energy production for each nuclear capacity unit, you have to build 9 units of solar or 3.75 units of wind. On average—in terms of capital expenditure—for every 4,257 Euro spent per kW on nuclear you have to spend 12,024 Euro for 9 kW of PV capacity and 10,678 Euro for 3.75 kW of wind capacity to get a similar volume in annual energy output (with a different and less-dependable delivery pattern).

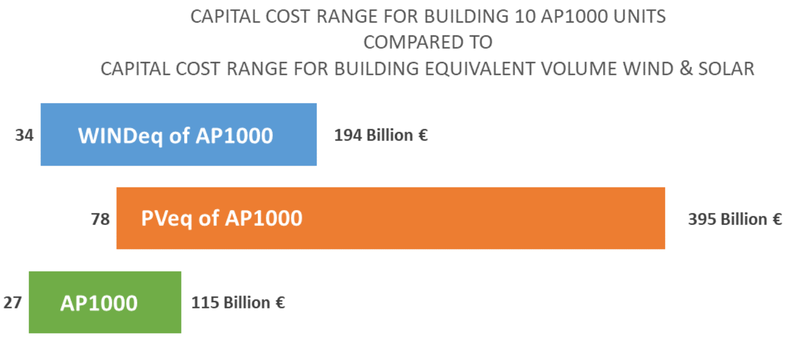


While analysing the potential cost ranges for the X models and equivalents for the separate technologies we note that all reactor technologies are competitive. The highest level of uncertainty in CAPEX cost can be seen with the AP1000, which is a result of the cost overruns at Vogtle 3 & 4. However, we see higher degrees of uncertainty at the wind and solar power equivalents. This is a function of the lower and unpredictable capacity factor as we are comparing capacities with equivalent volume of annual generation.

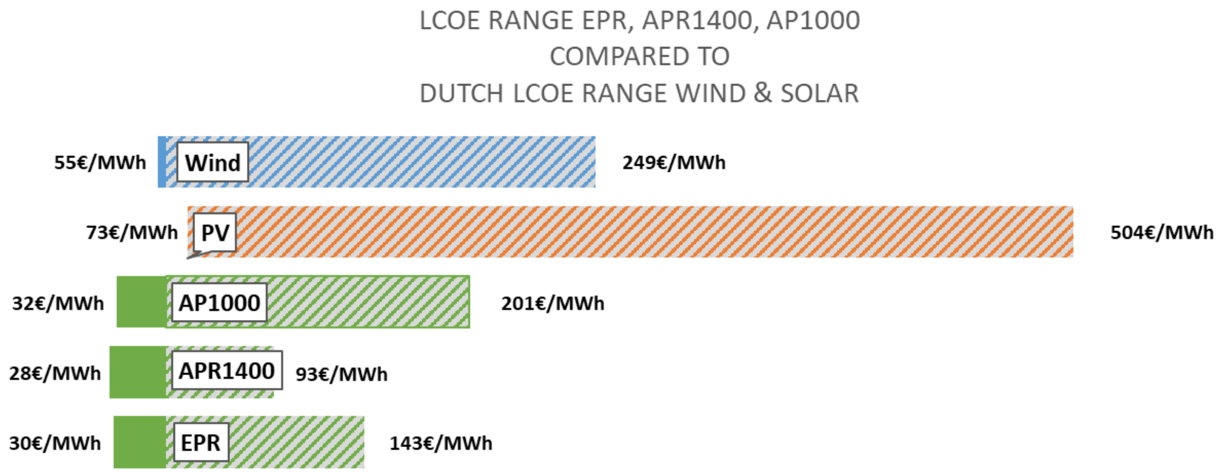
The potential investment range of all models for 10 reactors sits between 22 and 115 billion Euro; the equivalent of solar sits between 78 and 561 billion Euro; the equivalent of wind sits between 34 and 275 billion Euro.







We find that the Levelized Cost of Electricity (LCOE) for the EPR ranges from 30.2 to 142.6 Euro/MWh; for the APR1400 ranges from 28.2 to 93.2 Euro/MWh; the AP1000 ranges from 32.0 to 200.8 Euro/MWh; PV ranges from 72.5 to 504.3 Euro/MWh; Wind ranges from 55.4 to 249.2 Euro/MWh.



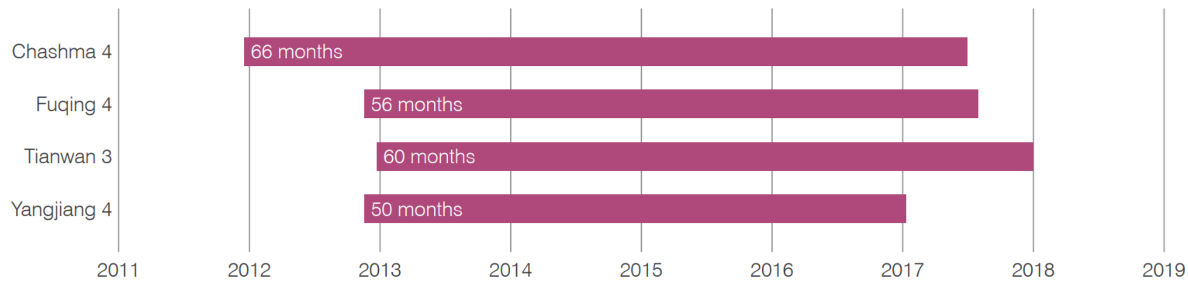
We find that within this range Nuclear produces a favorable LCOE* in 59.7% of all the possible outcomes; Solar produces no favorable results; and Wind produces favorable results in 2.4% of all possible outcomes, which is near zero and offers negligible benefits, if any. (Consult Appendix favorability chart)

*** favorable means <60 Euro/MWh**

BUILD TIME

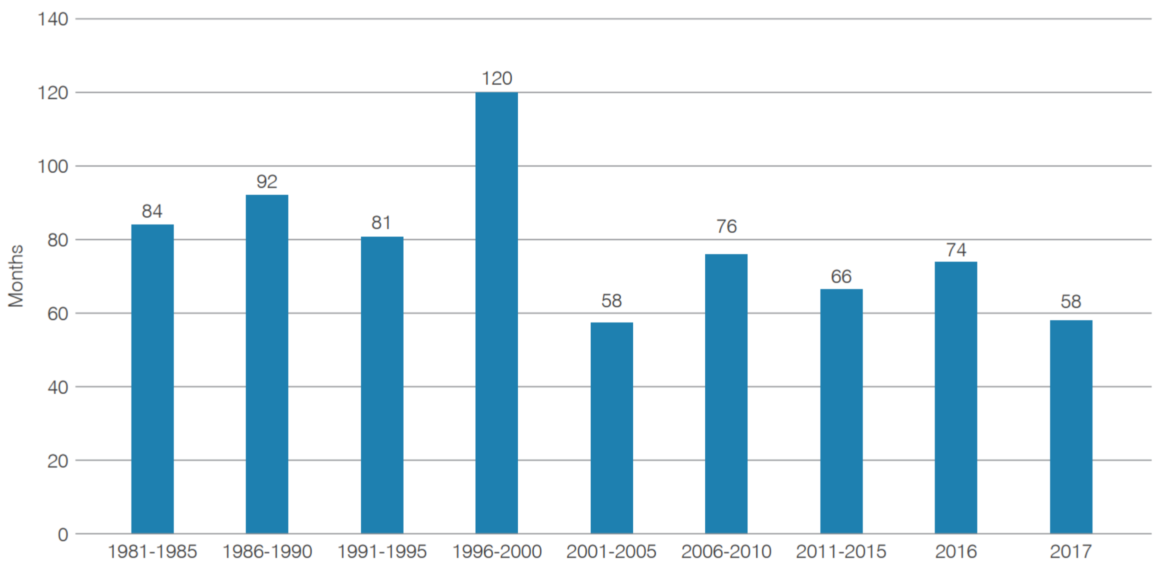
It is often said that nuclear takes a long time to build. The question is whether these claims are based on real-world outcomes. When we consider the IAEA PRIS Database, we find that the all-time average build time (date commissioned <> date operational) for nuclear reactors is 8.2 years; 67 reactors (16%) have been constructed within 5 years; 266 reactors (62%) have been constructed within 10 years; 94 reactors (22%) took over 10 years to complete. The following graphs copied from the 2018 World Nuclear Performance Report offer more insight.

Figure 12. Construction times of new units connected to the grid in 2017



Source: World Nuclear Association, IAEA PRIS

Figure 13. Median construction times for reactors since 1981



(figures extracted from report)

With a median build time of 58 months in 2017, down from 74 in the year before, nuclear deployment speeds are sufficiently high to expect that the Netherlands can decarbonize a large portion of their electricity network before or around 2030 by deploying 10 nuclear reactors—thus making significant carbon reductions, mandated by the Paris Agreement, possible.

AVOIDING PITFALLS

Before considering a new nuclear buildout, it is important to note that nearly failed FOAK projects are not the norm. A study published in 2018 determined several key aspects that can be used to differentiate between low-cost and high-cost power plants.

Low Cost Plants	High Cost Plants
• Design at or near complete prior to construction • High degree of design reuse • Experienced construction management • Low cost and highly productive labour • Experienced EPC consortium • Experienced supply chain • Detailed construction planning prior to starting construction • Intentional new build programme focused on cost reduction and performance improvement • Multiple units at a single site • NOAK design	• Lack of completed design before construction started • Major regulatory interventions during construction • FOAK design • Litigation between project participants • Significant delays and rework required due to supply chain • Long construction schedule • Relatively higher labour rates and low productivity • Relatively higher labour rates and low productivity • Insufficient oversight by owner

(figure extracted from report)

For additional insights we refer to *The ETI Nuclear Cost Drivers Project: Summary Report.*

ELECTRICITY COST DIFFERENCES BETWEEN COUNTRIES

The price consumers pay for electricity in Germany, is significantly higher than in the Netherlands (300 Euro/MWh over 240 Euro/MWh). One of the reasons why their electricity prices are higher is the renewable surcharge which accounts for one fifth of their electricity bill (64 Euro/MWh); grid charges are one fourth (71 Euro/MWh); supplier's costs is one fourth (69 Euro/MWh). It seems that with the advent of a massive renewable rollout in the Netherlands Dutch ratepayers will see similar surcharges and a commensurate increase in grid charges. In fact, for offshore wind it is estimated that the average offshore grid charge (on top of regular grid pricing) will be 19 Euro/MWh which is an order of magnitude more expensive than contemporary onshore resources.

Electricity prices in France, on the other hand, are much lower. In fact, they have among the lowest prices in all of Europe—having decarbonized a significant portion of their electricity grid—and this mainly due to a high penetration of Nuclear, built with optimal financing costs. The French pay around 179 Euro/MWh (somewhat more than half of what the Germans pay for their electricity). In France the makeup in electricity costs is almost evenly divided between Supplier's costs, Grid charges and taxes (~60 Euro/MWh each).

RECOMMENDATIONS

CHOOSE A STANDARDIZED DESIGN

If the Dutch Government or a company goes forward with the commissioning of one or more reactors, it would be beneficial to buy a proven design that does not require any significant alterations. This is possible, because there are operational reactors of the types that we've used to model the outcome of this article, following the criteria laid out previously. We suggest choosing one of these existing standardized reactors and replicate it 10 times.

WORK WITH EXPERIENCED PARTNERS

To expedite the deployment of nuclear reactors we suggest cooperation between Dutch and international partners that are experienced in managing the construction of nuclear power plants. Consider for instance the four APR1400 units (Barakah 1,2,3,4) that are under construction in the United Arab Emirates and are being built by national and international contractors and reactor vendor KEPCO. Out of the 12 APR1400 reactors, one is operational, 7 more are being built in South Korea and 4 are being built in the United Arab Emirates.

For building EPR power plants, a similar network of partners can be found across many different countries: The Chinese have constructed and completed one EPR unit (Taishan1) and are in the process of finishing the second unit (Taishan 2); Finland is in the process of finishing their EPR (Olkiluoto 3); France is in the process of finishing their first EPR (Flamanville 3) and are planning to build another 2 (sites to be determined); The United Kingdom is building their first two EPR units (Hinkley Point C1 &2) and planning another two (Sizewell C1 & 2); India has plans to build six units (Jaitapur).

Five countries are considering building or have built AP1000 reactor power plants: China, The United States of America, Bulgaria, India, and The United Kingdom.

- So far, four reactors have been completed (Sanmen 1 & 2, Haiyang 1 & 2);
- 4 reactors are under construction in the United States (Vogtle 3 & 4), of which two are now halted for economic reasons (VC Summer 2 & 3) but may return to construction once a new owner is found;
- The Bulgarian government has signed a shareholder agreement for the construction of one AP1000 (Kozlyduy 7);
- In the United Kingdom the construction of the three planned AP1000 units (Moorside) is unsure;
- In March 2019, The United States and India have agreed to build 6 AP1000 units.

There are four operational ABWR units operational (Kashiwazaki-Kariwa 6 & 7, Hamaoka 5, Shika 2).

The APR1400 (KEPCO), AP1000 (Westinghouse), and EPR (AREVA) seem to be the most suitable candidates for blueprinting and deployment in the Netherlands; provided that the Netherlands is willing and able to facilitate higher education domestically to provide the necessary expertise; hire international expertise; work with international construction firms to expedite deployment and introduce new learning opportunities.

DUTCH R&D

The Netherlands has strong nuclear R&D potential. There is ongoing research in nuclear materials-science; production of medical isotopes; reactor design (SAMOFAR project amongst others). By investing in and expanding existing infrastructure at the Technical University in Delft and the reactor complex in Petten the Netherlands can maintain a prominent role in nuclear operation and R&D. Also, URENCO, a world leading company in nuclear fuel production has a plant in Almelo, The Netherlands.

BEYOND GENERATION III

NON-ELECTRIC ENERGY USES / COGENERATION

The Netherlands is home to several energy intense industries: steel production; fertilizer production; chemical production; and oil refining. These industries are notoriously difficult to decarbonize, as they mostly require heat-based energy input instead of electricity. Most of the heat in these industries is generated by burning natural gas and coal. We can use high-temperature reactors (HTR — which do not include the EPR, APR1400, or AP1000) to generate this heat, this offers an alternate avenue to wean the Dutch economy off natural gas without having to eliminate its world-class gas-distribution network. In fact, HTR reactors can be used to create hydrogen that the Dutch consumer can use instead of natural gas. It is also possible to synthesize other lower carbon (or even carbon neutral) liquid fuels to offset natural gas usage.

These high temperature reactors, generally, are small modular reactors that offer more versatility. These technologies will become commercially available before 2030, but likely too late to help the Dutch to get rid of their coal- and gas fired power plants in time. However, we could deploy HTRs in addition to 10 large generation III reactors to create district heat, potable water, H_2, NH_3, and other commodities.

The Generation III reactors selected in this study are also capable of providing district heat.

Below you can see the outcome of our Cost-Benefit ratio analysis and it shows that nuclear in general, but specifically small modular reactors will likely offer the highest benefit per unit of cost. The high-end of the Cost-Benefit ratio for SMRs is based on the IMSR600 (Integral Molten Salt Reactor) that is being developed by Terrestrial Energy. There are other startups working on similar designs.

NUCLEAR WASTE

Currently, the Dutch are seeking ways to dispose of nuclear waste. The Dutch have an intermediate storage facility called COVRA (Central Organization for Radioactive Waste). A lot of the waste stored at COVRA comes from radio-medicine.

Spent nuclear fuel is regarded as nuclear waste. And this is true if you consider it from a conventional reactor technology point of view. Less than 5% of the energy has been extracted from the fuel. The rest is sequestered as waste. However, Generation IV reactors (like the Molten Salt Reactor) can recycle this spent nuclear fuel and extract the remaining energy from it, greatly reducing the longevity of said “nuclear waste”. In the future, waste-converting reactors will be commercially available. We suggest rebranding nuclear waste into nuclear products and store them in a repository from which they can be retrieved.

PREREQUISITES FOR A SUCCESSFUL NUCLEAR ROLL-OUT

We advise the Dutch government to consider the following:

- Building 10 new nuclear reactors (APR1400, EPR, AP1000) in order to meet the goals, set in accordance with the Paris Accord;
- Continue stimulating the construction of wind and solar projects in conjunction with new nuclear deployments;
- Investigating newer and evaluate which of them would fit within the goal of replacing natural gas with another liquid/gaseous fuel to burn instead, thus keeping a world-class gas-distribution network intact;
- Investigating newer designs in the context of which of them would fit within the goal of recycling spent nuclear fuel;
- Re-evaluate their stance on spent nuclear fuel, i.e. nuclear waste, and consider it a resource for future reactors;
- Invest in new qualified personnel required to operate this fleet of reactors.

Any nuclear roll-out should be based upon the following prerequisites:

- Finance new energy infrastructure with low-cost (government) loans to keep CAPEX low;
- Buy a blueprinted product, not a project, and do not allow any unnecessary blueprint alterations after construction has begun;
- Create a strictly enforced timeline (from the start of the build until commercial operation);
- Concentrate on increasing build-speed & efficiency from the first until the last unit build;
- Willingness to work with international experts and construction firms;
- Willingness to educate a future nuclear workforce.

CONCLUSION

We find that nuclear is the cheapest option to decarbonize the Dutch electricity network and competes very well with solar and wind. Additionally, nuclear offers more system stability, and offers co-production opportunities, maximizing utility. In terms of cost, given the low capacity factors, solar and wind have higher outcomes than nuclear and seem more expensive considering levelized cost in a levelized playing field, for example, when compared using equalized discount rates. We determine that it is feasible to close all coal-fired power plants in the Netherlands as early as 2030 by putting into operation 10 new high capacity nuclear reactors at reasonable capital expenditure (under 100 Billion Euro for 10 reactors); likely to be much lower than the investment required for wind and solar and commensurate backup systems and grid increases. The lower end based on low discount/low CAPEX Chinese reactors; the higher end based on high discount/high capex European and American reactors (Vogtle, Flamanville, Hinkley C, Olkiluoto) which will be the more likely scenario for the Netherlands if nothing changes policy-wise. This serves as a stark reminder that nuclear can be done cheaply under the right circumstances and shows us that the Dutch government must enact new legislation to help make nuclear a viable option. Deploying 10 new nuclear reactors will result in a carbon emissions reduction of up to 100 megatons per year.

APPENDIX

ARIS / PRIS CHECK

In operation

ABWR	GE-Hitachi	
Advanced Boiling Water Reactor	1420 MWe	
https://aris.iaea.org/PDF/ABWR.pdf		
Planned	Under Construction	Operational (or testing)
5	1	3
APR1000	KEPCO	
Advanced Power Reactor	1050 MWe	
https://aris.iaea.org/PDF/APR1000.pdf		
Planned	Under Construction	Operational (or testing)

Under Construction

EPR	AREVA	
The Evolutionary Power Reactor	1770 MWe	
https://aris.iaea.org/PDF/EPR.pdf		
Planned	Under Construction	Operational (or testing)
4	5	1
APR1400	KEPCO	
Advanced Power Reactor 1400	1455 MWe	
https://aris.iaea.org/PDF/APR1400.pdf		
Planned	Under Construction	Operational (or testing)
	9	4
AP1000	Westinghouse	
Advanced Passive PWR	1200 MWe	
https://aris.iaea.org/PDF/AP1000.pdf		
Planned	Under Construction	Operational (or testing)
6	2	4

Licensed

ESBWR	GE-Hitachi	
The Evolutionary Power Reactor	1600 MWe	
https://aris.iaea.org/PDF/ESBWR.pdf		
Planned	Under Construction	Operational (or testing)
2		

END NOTES