Systeemeffecten van nucleaire centrales, in Klimaatneutrale Energiescenario's 2050

Datasheets

Kalavasta
Climate Neutral Strategies

Berenschot

Introduction and Summary

This datasheet summarizes the costs, assumptions, and sources used in the Nuclear addition of the Climate neutral Energy Scenarios 2050 (KE2050) LCOE calculations and in the 2019 OECD-NEA report "The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables". The LCOE for 2050 for must run nuclear calculated for the KE2050 study is in line with the OEDC-NEA LCOE for a generation III plant (with the middle scenario capital costs).

With regards to renewables, LCOE estimates vary dramatically between our estimates and those of OECD-NEA. This is attributed to the fact that the data for the 2019 study is adopted from another OECD-NEA study from the year 2015. The costs of renewables have dropped drastically since, and further reductions are still expected towards 2050.

1. Cost breakdown of the II3050 Nuclear addition

Reports and articles that are used as sources for the LCOE calculation:

- Nuclear:
  - SFEN (2018). *Les coûts du production du nouveau nucléaire français*
  - NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
  - MIT (2018): *The future of Nuclear Energy in a carbon constrained world.*
  - IEA (2001). *Analysis of Uranium Supply to 2050.*
- Solar PV:
  - IRENA (2019): *Future of solar*
  - J. Ondraczek et al. (2014): WACC the dog: the effect of financing costs on the levelised cost of solar pv power. *Renewable Energy* 75, 888-898
  - Agora (2017): *The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model*
  - NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
- Onshore wind:
  - IRENA (2019): *Future of wind*
  - Agora (2017): *The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model*
  - NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
- Offshore wind
  - IRENA (2019): *Future of wind*
  - Agora (2017): *The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model*
  - NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.

The following cost items are included in the calculation of the LCOE:

Cost item	Inclusion	Notes
Construction cost	✓	
Financing cost	✓ Construction ✓ Operation	For operation depreciation is applied
Fixed operations & maintenance cost	✓	
Variable operations & maintenance cost	✓	
Fuel cost (front-end)	✓	
Cost of waste processing and storage (back-end)	✓	
Decommissioning costs	✓	Assuming annual deposits to a decommissioning fund.

Table 1. Cost items included in the LCOE calculation.

Kalavasta Climate Neutral Strategies Berenschot

We arrived at the following LCOE values:

Technology	LCOE
Nuclear must run	92
Solar PV	22
Onshore wind	23
Offshore wind	23

Table 2. LCOE values in II3050. Wind excludes grid connection costs, as these are added in the ETM automatically. Inclusive of grid connection costs the LCOE for wind is 36 €/MWh.

The values for the different cost items as well as the sources and assumptions can be found in the tables below.

Nuclear					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kW	5135	2018 extended to 2050 by applying learning effects	Average of the two EPRs being currently built within the EU. It should be noted that these costs reflect the state of affairs in 2018, with cost estimates having since increased by around 18% for both plants. To reflect the recent cost escalations, we added the remainder of the reported cost and the SFEN cost, multiplied by a factor representing the share that is assumed to be structural, i.e. unavoidable in future installations. This factor is assumed to be 50%. We then applied a 20% learning effect to reflect the fact that the EPRs are not going to be first-of-a-kind within the EU and the fact that with 9 GW of nuclear energy added to the system, multiple reactors would be built in the Netherlands.	SFEN (2018). L*es coûts du production du nouveau nucléaire français.* p. 26
Financing cost	%	7	n.a.	NEA middle scenario. Financing cost is applied throughout the construction and operation period.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*. Similar to the French WACC reported in SFEN (2018.) L*es coûts du production du nouveau nucléaire français.*
Fixed operation and maintenance cost	€/MWe	89000	2015, as data for EPR O&M costs are not yet available		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*. p. 95
Variable operation and maintenance cost	€/MWh	7.4	2018	Assumed 1.12 $/€, taken the variable operations and maintenance costs for France (8.35 $/MWhe)	MIT (2018): The future of Nuclear Energy in a carbon constrained world.
Fuel cost	€/MWh	6.27	2050	Assumed a uranium price of 135 $/kg	World Nuclear Association (2019). *Economics of Nuclear Power*. world-nuclear.org; IEA (2001). *Analysis of Uranium Supply to 2050.*
Cost of waste processing and storage	€/MWh	2.07	2015, as 2050 is not available		NEA (2015). *Projected Cost of Generating Electricity. 2015 Edition*.

Nuclear					
Decommissioning cost	% of the construction cost	15	2015, % assumed to remain stable towards 2050		NEA (2015). *Projected Cost of Generating Electricity. 2015 Edition*.
Size	MWe	1600	n.a.	Assumption from the II3050 European scenario in the ETM	
Full load hours	h/year	7800	n.a.	Assumption from the II3050 European scenario in the ETM	
Technical lifetime	years	60	n.a.	Specific for the design of the reactor	
Duration of construction	years	7	2050	Assumption. Amounts to a 53% decrease from the construction times of the Finnish and French EPR plants.	

Table 3. Nuclear: summary of cost items, costs, years of the costs, assumptions, and sources (II30

Solar PV					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kW	278	2050	Average of range given, assuming 1.16 $/€	IRENA (2019): *Future of solar*.
Financing cost	%	4.3	n.a.		J. Ondraczek et al. (2014): WACC the dog: the effect of financing costs on the levelised cost of solar pv power. *Renewable Energy* 75, 888-898
Fixed operation and maintenance cost	% of construction	1.5	2050		Agora (2017): The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	5	2015, % assumed to remain stable towards 2050		NEA (2015). *Projected Cost of Generating Electricity. 2015 Edition*.
Size	MWe	20	n.a.	Assumption from the II3050 European scenario in the ETM	
Full load hours	h/year	895	n.a.	Assumption from the II3050 European scenario in the ETM	
Technical lifetime	years	25	n.a.		

Solar PV					
Duration of construction	years	0.5	2050	Assumption from the II3050 European scenario in the ETM	

Table 4. Solar PV: summary of cost items, costs, years of the costs, assumptions, and sources (II3050).

Onshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	711	2050	Average of range given, assuming 1.16 $/€	IRENA (2019): *Future of wind*.
Financing cost	%	4.3	n.a.	Assumed to be equal to the WACC of solar given similar level of maturity & risk.	
Fixed operation and maintenance cost	%	2.5	2050		Agora (2017): The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	5	2015, % assumed to remain stable towards 2050		NEA (2015). *Projected Cost of Generating Electricity. 2015 Edition*.
Size	MWe	3	n.a.	Assumption from the II3050 European scenario in the ETM	

Onshore wind					
Full load hours	h/year	3000	n.a.	Assumption from the II3050 European scenario in the ETM	
Technical lifetime	years	25	n.a.	Assumption from the II3050 European scenario in the ETM	
Duration of construction	years	1	2050	Assumption from the II3050 European scenario in the ETM	

Table 5. Onshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (II3050).

Offshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	1000	2050	Average of range given, assuming 1.16 $/€. Assumption 1000 €/kW without grid connection, given 1810 €/kW inclusive grid connection.	IRENA (2019): *Future of wind*.
Financing cost	%	4.3	n.a.	Assumed to be equal to the WACC of solar given similar level of maturity & risk.	
Fixed operation and maintenance cost	%	3.2	2050		Agora (2017): The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			

Offshore wind					
Decommissioning cost	% of the construction cost	5	2015, % assumed to remain stable towards 2050		NEA (2015). *Projected Cost of Generating Electricity. 2015 Edition.*
Size	MWe	3	n.a.	Assumption from the II3050 European scenario in the ETM	
Full load hours	h/year	4500	n.a.	Assumption from the II3050 European scenario in the ETM	
Technical lifetime	years	25	n.a.		Agora (2017): *The Future Cost of Electricity Based Synthetic Fuels. Electronic appendix: Model*
Duration of construction	years	1.5	2050	Assumption from the II3050 European scenario in the ETM	

Table 6. Offshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (II3050).

2. Cost breakdown of OECD-NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*

The source of the costs used in the report is NEA (2015). *Projected Costs of Generating Electricity. 2015 Edition*. The data is based on survey results from OECD countries and China. The costs provided by Belgium and Hungary (and perhaps others) are hypothetical. The costs countries outside of Western Europe have likely very different costs with regards to labor costs etc. Therefore, a cost that is an average of the different countries is likely not directly applicable to the Netherlands. Moreover, it is unclear whether cost reductions are featured in for renewables. OECD works with survey results of LCOEs from member states that appear to be historical, or, as mentioned before, hypothetical. These numbers cannot be checked and should as such be treated with caution.

From the revoew session with OECD-NEA we know that OECD-NEA internally uses IEA numbers for its calculations.

The following cost items are included in the calculation of the LCOE:

Cost item	Inclusion	Notes
Construction cost	✓	
Financing cost	✓ Construction ✓ Operation	"Investment costs include the overnight and contingency costs as well as interest accrued during construction. They represent the cash outlays that have been committed until plant completion and before any revenue can be expected from the investment." NEA (2019), p. 125.
Fixed operations & maintenance cost	✓	
Variable operations & maintenance cost	✓	
Fuel cost (front-end)	✓	
Cost of waste processing and storage (back-end)	✓	
Decommissioning costs	✕	Decommissioning costs are practically omitted by the NEA method. The cost is only applied at the end of the lifetime of the plant, and thus for nuclear plants it become practically zero due to discounting, even at lower discount rates.

Table 7. Cost items included in the OECD-NEA LCOE calculation.

Technology	LCOE (€/MWe)
Nuclear	**74.91 (Belgium)** 69.10 (Finland) 80.05 (Hungary) 74.72 (The Slovak Republic) **89.67 (The United Kingdom)**
Solar PV – commercial rooftop	105.6 (Austria) 168.90 (Belgium) 126.15 (Denmark) 143.41 (Germany) 159.35 (Hungary) 159.61 (Italy) **121.81 (The Netherlands)** **88.44 (Portugal)** 117.48 (Spain) 144.71 (Switzerland) **246.06 (The United Kingdom)**
Solar PV – large, ground-mounted	113.15 (Germany) 127.85 (Italy) **90.30 (Portugal)** 97.83 (Spain) **149.31 (The United Kingdom)**
Onshore wind	100.81 (Austria) **111.54 (Belgium)** **63.03 (Denmark)** 83.24 (Germany) 82.22 (Italy) **75.60 (The Netherlands)** 72.84 (Portugal) 90.95 (Spain) 110.33 (The United Kingdom)
Offshore wind	**169.87 (Belgium)** **120.91 (Denmark)** 163.48 (Germany) **149.54 (The Netherlands)** 198.59 (Portugal) 140.86-155.06 (The United Kingdom)

Table 8. LCOE values in OECD-NEA (2015), at a 1.12 $/€ rate. The lowest value is marked in green, the highest in red. These are **actuals cost figures prior to 2015** reported by the member countries. For nucleair this means the data are based on second generation nuclear plants, with the exception of

Belgium who reported costs for third generation nuclear plants.

Nuclear					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kW	4183	2015-2030	Includes contingency of 15%. The overnight construction cost (OCC) of nuclear does not take into account the rise of construction costs post-2015.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Financing cost	%	7	n.a.	NEA middle scenario. Low scenario is 3, high is 10.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Fixed operation and maintenance cost	€/MWe	89000	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Variable operation and maintenance cost	€/MWh	1.34	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Fuel cost	€/MWh	8.9	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Cost of waste processing and storage	€/MWh	2.07	2015	Included in the fuel cost.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Decommissioning cost	% of the construction cost	15	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Size	MWe	1000	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Full load hours	h/year	8760	n.a.	Assumes a load factor of 100%.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Technical lifetime	years	60	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.

Nuclear					
Duration of construction	years	7	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.

Table 9. Nuclear: summary of cost items, costs, years of the costs, assumptions, and sources (OECD-NEA) at 1.12 $/€.

Solar PV					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	1424	2015	The overnight construction cost (OCC) of solar PV does not take into account the decrease of construction costs post-2015. Includes contingency of 5%.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Financing cost	%	7	n.a.	NEA middle scenario. Low scenario is 3, high is 10.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Fixed operation and maintenance cost	€/MW/year	32040	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	5	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Size	MWe	1	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Full load hours	h/year	1314	n.a.	Load factor of 15%	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.

Solar PV					
Technical lifetime	years	25	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Duration of construction	years	1	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*

Table 10. Solar PV: summary of cost items, costs, years of the costs, assumptions, and sources (OECD-NEA at 1.12 $/€.

Onshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	2247	2015	The overnight construction cost (OCC) of onshore wind does not take into account the decrease of construction costs post-2015. Includes contingency of 5%.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables..*
Financing cost	%	7	n.a.	NEA middle scenario. Low scenario is 3, high is 10.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Fixed operation and maintenance cost	€/MW/year	255180	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	5	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*

Onshore wind					
Size	MWe	50	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Full load hours	h/year	2628	n.a.	Load factor of 30%.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Technical lifetime	years	25	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Duration of construction	years	1	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*

Table 11. Onshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (OECD-NEA at 1.12 $/€.

Offshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	4450	2015	The overnight construction cost (OCC) of offshore wind does not take into account the decrease of construction costs post-2015. Includes contingency of 5%.	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Financing cost	%	7	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Fixed operation and maintenance cost	€/MW/year	155750	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.*
Variable operation and maintenance cost	€/MWh	n.a.			
Fuel cost	€/MWh	n.a.			

Offshore wind					
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	5	2015		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Size	MWe	250	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Full load hours	h/year	3504	n.a.	Load factor 40%	NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Technical lifetime	years	25	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.
Duration of construction	years	1	n.a.		NEA (2019). *The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*.

Table 12. Offshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (OECD-NEA at 1.12 $/€.

Cost Breakdown of IEA (2019): World Energy Outlook

Every year the IEA publishes its World Energy Outlook. This contains several scenarios for the year 2040. For the Stated Policies scenario the IEA also shares the technology cost. We picked the values reported for the European Union inputs from the latest World Energy Outlook from November 2019 (IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.). They are listed in the following tables.

The following cost items are included in the calculation of the LCOE:

Cost item	Inclusion	Notes
Construction cost	✓	
Financing cost	? Construction ✓ Operation	Unclear if/how included
Fixed operations & maintenance cost	✓	
Variable operations & maintenance cost	✓	
Fuel cost (front-end)	✓	
Cost of waste processing and storage (back-end)	✓	
Decommissioning costs	?	Unclear if included

Table 13. Cost items included in the IEA LCOE calculation.

Solar PV					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	545	2040	Stated policies scenario for the year 2040	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Financing cost	%	n.a.	n.a.		
Fixed operation and maintenance cost	€/MW/year	n.a.			

Solar PV					
Variable operation and maintenance cost	€/MWh	8.9	2040	Includes all O&M (fixed and variable) as well as fuel	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	n.a.			
Size	MWe	n.a.	n.a.		
Full load hours	h/year	1226	n.a.	Load factor of 14%.	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Technical lifetime	years	n.a.	n.a.		
Duration of construction	years	n.a.	n.a		

Table 14. Solar PV: summary of cost items, costs, years of the costs, assumptions, and sources (IEA at 1.12 $/€.

Onshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	1571	2040	Stated policies scenario for the year 2040	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Financing cost	%	n.a.	n.a.		
Fixed operation and maintenance cost	€/MW/year	n.a.			
Variable operation and maintenance cost	€/MWh	13.4	2040	Includes all O&M (fixed and variable) as well as fuel	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			

Onshore wind					
Decommissioning cost	% of the construction cost	n.a.			
Size	MWe	n.a.	n.a.		
Full load hours	h/year	2628	n.a.	Load factor of 30%.	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Technical lifetime	years	n.a.	n.a.		
Duration of construction	years	n.a.	n.a		

Table 15. Onshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (IEA at 1.12 $/€).

Offshore wind					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	2304	2040	Stated policies scenario for the year 2040	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Financing cost	%	n.a.	n.a.		
Fixed operation and maintenance cost	€/MW/year	n.a.			
Variable operation and maintenance cost	€/MWh	8.9	2040	Includes all O&M (fixed and variable) as well as fuel	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	n.a.			
Size	MWe	n.a.	n.a.		
Full load hours	h/year	5168	n.a.	Load factor of 59%.	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.

Offshore wind					
Technical lifetime	years	n.a.	n.a.		
Duration of construction	years	n.a.	n.a		

Table 16. Onshore wind: summary of cost items, costs, years of the costs, assumptions, and sources (IEA at 1.12 $/€).

Nuclear					
Cost item	**Unit**	**Cost**	**Year**	**Assumptions**	**Source**
Construction cost	€/kWh	4018	2040	Stated policies scenario for the year 2040	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Financing cost	%	n.a.	n.a.		
Fixed operation and maintenance cost	€/MW/year	n.a.			
Variable operation and maintenance cost	€/MWh	31.3	2040	Includes all O&M (fixed and variable) as well as fuel	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Fuel cost	€/MWh	n.a.			
Cost of waste processing and storage	€/MWh	n.a.			
Decommissioning cost	% of the construction cost	n.a.			
Size	MWe	n.a.	n.a.		
Full load hours	h/year	7900	n.a.	Load factor of 90%.	IEA (2019): World Energy Outlook. World Energy Model. Techno-economic inputs.
Technical lifetime	years	n.a.	n.a.		
Duration of construction	years	n.a.	n.a		

Table 17. Nuclear: summary of cost items, costs, years of the costs, assumptions, and sources (IEA at 1.12 $/€).

Actual LCOEs for Renewables

To provide some context to the cost assumptions, we offer a brief overview of current LCOEs for solar PV, onshore and offshore wind in the context of the Netherlands. We cannot give such an overview for nuclear because no third generation plant has been built in Europe yet. We created this overview using winning bids for onshore, offshore and solar PV installations. Since in the Netherlands only offshore wind projects are allocated by tenders, we used German tenders for onshore wind and solar PV to determine the current cost of projects. Due to the location of the Netherlands location on the coast, the wind conditions can be assumed to be more favorable than in Germany, whereas the efficiency of solar PV can be assumed to be higher in Southern Germany than in the Netherlands, due to its lower latitudes. Around 40% of the solar PV capacity of Germany is situated in the two southern most states, while they cover 30% of the German area[1].

For offshore wind the record tender in the Netherlands is still Borssele 3+4. This tender was held in 2016 and resulted in a strike price (LCOE) of 54 €/MWh[2]. The park is currently under construction and will come online in 2021.

For onshore wind and solar PV, we look at the German situation as there is no tender system for these technologies in the Netherlands. The German system for auctioning rights to develop renewable projects are set out in the German Renewable Energy Sources Act (EEG). The system functions in a similar manner to the Dutch one. In Germany developers bid competitively for the rights to develop a project, with the bid being ranked based on price. The price reported by the Bundesnetzagentur is a weighted average of the bids. Therefore, some of the bids were made at a lower price than the one reported. The reported price thus does not report the realized cost reductions but the average prices. The bid determines the price that the developers receive for the electricity generated, even when the market price is lower. The remainder is compensated from a fund that is collected from a surcharge that mostly households pay on their electricity price[3].

In Germany, the most recent bids for onshore wind projects have been heavily undersubscribed since 2018, with prices around 62 €/MWh. This has been attributed to issues with granting permissions for wind parks on a state level and has resulted in increasing risk for developers. In order to avoid including the bias, the mean of the tenders in early 2018 were chosen as representative. This results in a price of 52.23 €/MWh. The lowest weighted average of the bids was achieved in February 2018 with a price of 47.3 €/MWh.

For solar we used the median price for auctions in 2018 and 2019, resulting in a price of 48.5 €/MWh[4]. This was done to avoid the bias of an outlier price in the March 2019 auction that saw a high number of bids being rejected due to formal errors[5]. This value is equal to the LCOE for solar reported by IEA for Germany with commissioning in 2019[6]. The lowest weighted average of bids was achieved in February 2018 with a price of 43.3 €/MWh.

Globally even lower prices have been achieved in tenders. In Mexico, a tender for onshore wind achieved the price of 17.7 USD/MWh[7], and in record for solar PV was made in the Arab Emirates with a price of 16.9 USD/MWh[8]. This comes down to 15.8 €/MWh and 15.1 €/MWh, respectively. These values are already lower than our estimates for

[1] Agentur für Erneuerbare Energien (2019). Bundesländer-Übersicht zu Erneuerbaren Energien.
[2] Eneco (2018): Blauwwind Consortium reaches Financial Close on Borssele III/IV
[3] Bundesministerium der Justiz und für Verbraucherschutz (2014). Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2017).
[4] Bundesnetzagentur (2020). Ausschreibungen für EE- und KWK-Anlagen.
[5] Enkhardt, S. (2019). Average price in Germany's first special PV tender reaches €0.065/kWh. PV Magazine.
[6] IEA (2020): Global average LCOEs and Auction results for Utility Scale PV by commissioning date.
[7] Deign, J. (2017). The World's Cheapest Solar Bid Is Actually for Wind. GTM.
[8] DEWA (2019). DEWA receives world's lowest bid of USD 1.69 cents per kW/h for 900MW 5th phase of the Mohammed bin Rashid Al Maktoum Solar Park.

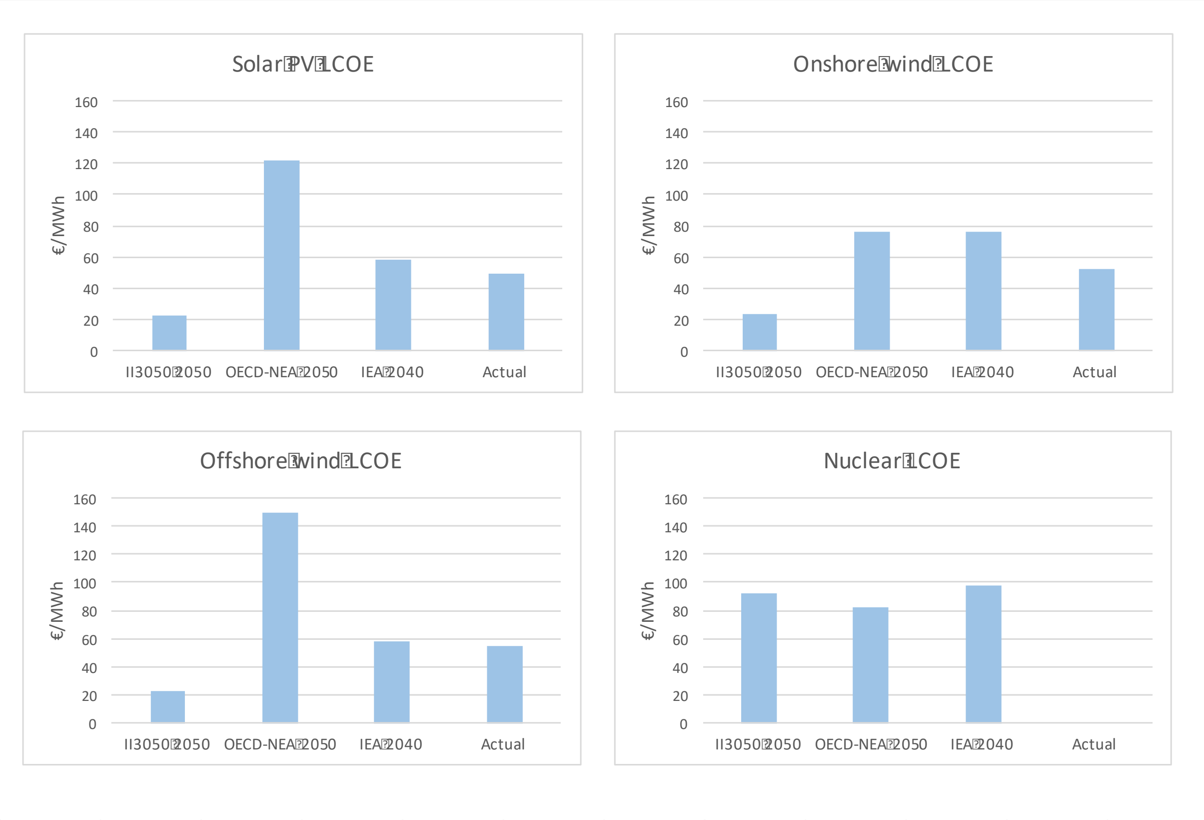
2050 in the Netherlands, but given the differing full load hours and labor costs, they are not directly comparable to a Dutch situation.

We can however linearly correct for the full load hour difference: the windiest areas onshore around the world have about 50% more full load hours than in the Netherlands (so 4500 full load hours), while the sunniest areas have over 120% more full load hours than in the Netherlands (1900 full load hours[9]). If we correct for the full load hours, these record tenders would translate to LCOEs of 15.8*150% = 24 €/MWh and 15.1*220% = 33 €/MWh equivalent for the Dutch situation for onshore wind and solar PV. This is still inclusive of lower labor costs of course, so it is still a bit too optimistic, but it shows that the 2050 estimates are not actually that far off from what we can achieve today.

[9] Full load hours for solar are inclusive of the panels' performance ratio; they are not to be confused with the global horizontal irradiation.

Comparison LCOEs

In this chapter we summarise the LCOEs of the previous sources (II3050, OECD NEA, IEA, actual results) for all technologies in the following table and graphs:



Over-view	Solar PV				Onshore Wind				Offshore Wind				Nuclear			
	This study	OECD NEA	IEA	Actu-al	This study	OECD NEA	IEA	Actu-al	This study	OECD NEA	IEA	Actu-al	This study	OECD NEA	IEA	Actual
Year	'50	'50	'40	Pre '20	'50	'50	'40	Pre '20	'50	'50	'40	Pre '20	'50	'50	'40	Pre '20
LCOE [€/MWh]	**22**	**122**	**58**	**49**	**23**	**76**	**76**	**52**	**23**	**150**	**58**	**54**	**92**	**82**	**98**	**NA**

Table 18 and Figure 1: Comparison of Levelised Cost of Electricity (LCOE) between II3050 and OECD NEA estimates for 2050, IEA estimates for 2040 and actual projects delivered in North Western Europe (Netherlands and Germany). Offshore wind costs in II3050 are excluding grid connection costs, these are however added later with the ETM based on TenneT data. Inclusive of grid connection costs the LCOE for offshore wind would be 36 €/MWh.

From the comparison of the results in this table and figure we can identify the following main points.

1. The OECD NEA and IEA renewables' LCOEs are all significantly higher than the actual LCOEs for these technologies
    - The LCOEs for solar PV, onshore wind and offshore wind which OECD NEA calculates for 2050 and IEA for 2040 are all significantly higher than the LCOEs which have been achieved in the Netherlands and Germany already. They are between 10% and 200% higher. In this way, they appear to forecast a technology cost increase (as these are all first order calculations), while many trends and potential improvements point towards a cost reduction. For IEA this is particularly striking since it reported an LCOE of 49 €/MWh achieved for solar in Germany for 2019, while later forecasting an LCOE of 58 €/MWh for solar in Europe in 2040. It is likely OECD NEA and IEA have not taken into cost reductions which have been achieved in recent years nor have included potential reductions towards the future. It appears fair to conclude they therefore significantly overestimate future LCOEs for these technologies.
2. The II3050 renewables' LCOEs are all significantly lower than actual LCOEs
    - The LCOEs for solar PV, onshore wind and offshore wind we calculate for 2050 are all significantly lower than the LCOEs which have been achieved in the Netherlands. We base our calculations on the average[10] IRENA investment cost estimates for 2050. These numbers include further cost reductions through economies of scale, economies of numbers, automatization and technological improvements (e.g. panel efficiency). The LCOEs we calculate are therefore significantly lower than average actual LCOEs, but not that much lower than records observed in North Western Europe or records globally translated to Dutch conditions (full load hours).
3. The nuclear LCOEs are similar and all assume significant cost reductions relative to plants being built now
    - The LCOEs for nuclear are all found in the range of 80 to 100 €/MWh. The II3050 value is in the middle of this range. Because no third generation nuclear plant has been built in Europe yet, we cannot compare these costs to representative actual costs. We do know based on the cost escalations which have occurred during the (still ongoing) construction of plants in England, France and Finland, that all of these LCOEs for 2050 and 2040 do assume significant cost reductions relative to the plants which are being built now.

To summarise, we see cost reductions and similar LCOEs for nuclear in all calculations. But for renewables we see a cost reduction in the II3050 calculation and a cost increase in OECD NEA and IEA relative to current projects in The Netherlands and Germany. The latter appear to come from a neglect of recent cost reductions and future potential cost reductions and most likely constitute serious overestimations. It is not very surprising that this occurs in both OECD NEA and IEA, as OECD NEA also uses IEA data.

[10] IRENA reports ranges for 2050, of which we have taken average values.

3. Conclusion

The differences in the LCOE calculations of nuclear and renewables are prominent only in the case of renewables. The II3050, OECD NEA and IEA LCOEs are all similar for nuclear, with the II3050 value in the middle of this range. The LCOEs for renewables vary wildly. The II3050 LCOE assumes further cost reductions from today, while the OECD NEA and IEA LCOEs exceed those which have already been achieved. The OECD NEA and IEA LCOEs for 2050 and 2040 are 10%-200% higher than recent auctions and projects in the Netherlands and Germany. This appears to be the result of a neglect of recent cost reductions and future potential cost reductions. As a consequence, the LCOEs for renewables in the OECD NEA and IEA studies are likely large overestimations.

With regards to the LCOE of nuclear there seems to be more of a consensus if one assumes a must run situation. TNO also recently did a literature study on the LCOE for nuclear and found similar results to what we have found.

APPENDIX B: LEVELIZED COST OF ELECTRICITY (LCOE) FOR NUCLEAR ENERGY FROM DIFFERENT LITERATURE SOURCES €$_{2017}$

Source	Lifetime [years]	Capacity factor [%]	Discount rate [%]	LCOE [€$_{2017}$/MWh]
MIT, 2018	30	85	10	73
EIA, 2018[10]	30	90	6.2	82 (79-86)
IEA/NEA, 2015[11]	60	85	7-10	65-120
D'haeseleer, W. D., 2013[12]	60	85	10	93

Notes:
10. LCOE values are calculated based on a 30-year cost recovery period and the nominal WACC used to calculate LCOE was 6.2% for plants entering service in 2020.
11. Minimum and maximum LCOE values (with 7% and 10% discount rate respectively) for nuclear energy in Belgium and UK. The impact of a 50% increase on the lead time has been applied to the maximum LCOE value of $135/MWh (UK), which given the sensitivity analysis in IEA/NEA (2015), this represents an increase of approximately 15% to the LCOE value.
12. LCOE based on FOAK brownfield single.

Figure 2. TNO meta study results for LCOE values. Source: Gamboa Palacios, S. and Jansen, J. (2018). *Nuclear energy economics: An update to Fact Finding Nuclear Energy*. TNO.