Economic Value of Nuclear Power in Future Energy Systems

Required subsidy in various scenarios regarding future renewable generation, electricity demand and fossil fuel generation

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Outline

Introduction

Background

To reduce carbon emissions, we can

1. reduce the use of energy
2. increase use of electricity
3. replace fossil generated electricity by non-carbon energy such as renewables and nuclear

Governments are promoting renewable power but are increasingly considering nuclear as mitigation measure.
The Dutch government has asked market parties to build two nuclear power plants

Research questions

In an electricity system with high shares of renewable generation

1. To what extent does nuclear power require subsidy in comparison to other non-carbon sources?
2. How effective is nuclear power in providing flexibility to zero carbon electricity systems in comparison to hydrogen production, storage and usage?

Method

Power market model

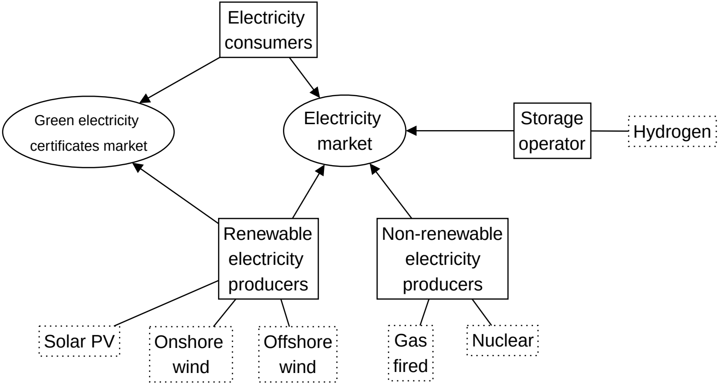
Short-term partial equilibrium model

Electricity:

- Supply: produce electricity when price is higher than marginal cost
  - Gas-fired power plants
  - Nuclear power plants
  - Solar PV, onshore wind, offshore wind
  - International trader
  - Storage operator (in scenario with zero-carbon system)
- Demand: aggregated
- Result: electricity prices, production

Green certificates

Model overview



Schematic model overview

Mathematical model: nuclear power plant (formula)

Optimization problem:

$$\max \sum_{h=1}^{8760} (p_h^E - c^N) \cdot q_h^{E,N},$$

subject to (ramping constraints)

$$K^N \cdot O^{N,\min} \leq q_1^{E,N} \leq K^N \cdot O^{N,\max},$$

$$\max\left\{O^{N,\min}, q_{h-1}^{E,N}/K^N - R^N\right\} \cdot K^N \leq q_h^{E,N}, \ \ h = 2, \ldots, 8760,$$

$$\min\left\{O^{N,\max}, q_{h-1}^{E,N}/K^N + R^N\right\} \cdot K^N \geq q_h^{E,N}, \ \ h = 2, \ldots, 8760,$$

$$q_h^{E,N} \leq K^N \cdot A_h^N \ \ h = 1, \ldots, 8760,$$

Hourly generation $q_h^{E,N}$, installed capacity K^N, utilisation rate O, ramp rate R^N, availability factor A_h^N

Mathematical model: nuclear power plant (parameter values)

Optimization problem:

$$\max \sum_{h=1}^{8760} (p_h^E - 12.24) \cdot q_h^{E,N},$$

subject to

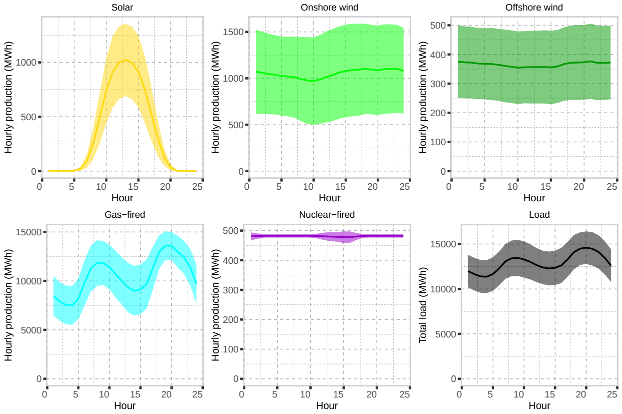
$$K^N \cdot 0.25 \leq q_1^{E,N} \leq K^N \cdot 1,$$

$$\max\left\{0.25, q_{h-1}^{E,N}/K^N - 0.31\right\} \cdot K^N \leq q_h^{E,N}, \ \ h = 2, \ldots, 8760,$$

$$\min\left\{1, q_{h-1}^{E,N}/K^N + 0.31\right\} \cdot K^N \geq q_h^{E,N}, \ \ h = 2, \ldots, 8760,$$

$$q_h^{E,N} \leq K^N \cdot 0/1 \ \ h = 1, \ldots, 8760,$$

Model output, hourly



Hourly variability of production and load within a year (model results for calibrated Dutch market in 2019)

Required subsidy

Required subsidy is amount needed to make Net Present Value (NPV) zero

- Revenues (sales of electricity and green certificates)
- Costs, (operational costs, capital costs)
- Operational revenues and costs are calculated through the model, capital costs are exenously determined

Assumptions, costs

Cost	Unit	Nuclear	Technology Solar	Wind (on-shore)	Wind (off-shore)
Construction cost	€/kW installed	4230	750*	1125*	2160*
Fixed O&M cost	€/kW installed	90	32.4	55.8	157.5
Variable O&M cost	€/MWh produced	1.35	-	-	-
Fuel cost	€/MWh produced	9.00	-	-	-
Cost of waste	€/MWh produced	2.07	-	-	-
Decommissioning cost	% of construction cost	15*	5*	5*	5*

Notes:
All values come from OECD-NEA (2019), page 94, except the values indicated with an *, which come from IEA-NEA (2020). We assume an exchange rate of 0.90 Euro/USD.
The assumed values for the renewable energy technologies are relatively low compared to what is stated by Frauenhofer ISE (2021). That report states that the fixed costs per MW installed capacity are between 530 and 1600 for solar PV, between 1400 and 2000 for onshore wind and between 3000 and 4000 for offshore wind. The costs of Solar PV very much depend on the type of installation: large utility scale PV installations are about 50 percent less expensive than small rooftop installations.

Assumed values regarding costs of various electricity generation technologies

Assumptions, other

Parameter	Unit	Technology		
		Nuclear	Solar	Wind (on- and offshore)
WACC	%	7	7	7
Lifetime	Years	60	25	25
Construction duration	Years	7	1	1

Note: All values come from OECD-NEA (2019). In Section Section 6 we analyse the sensitivity of our results for alternative values for these parameters.

Assumptions regarding lifetime, construction duration and discount factor (WACC) of various electricity generation technologies

Assumptions, storage

Cost	Unit	Technology Electrolyzer	Hydrogen storage	Fuel cell
Construction cost	€/kW installed	1000	0.0	1000

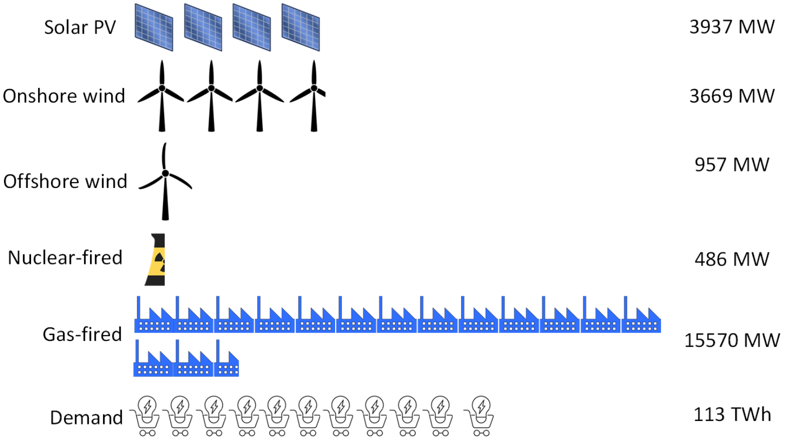
Notes:
All values come from Li and Mulder (2021)

Parameter	Unit	Technology Electrolyzer	Hydrogen storage	Fuel cell
WACC	%	7	7	7
Lifetime	Years	25	25	25
Construction duration	Years	1	1	1

Notes:
All values come from Li and Mulder (2021).

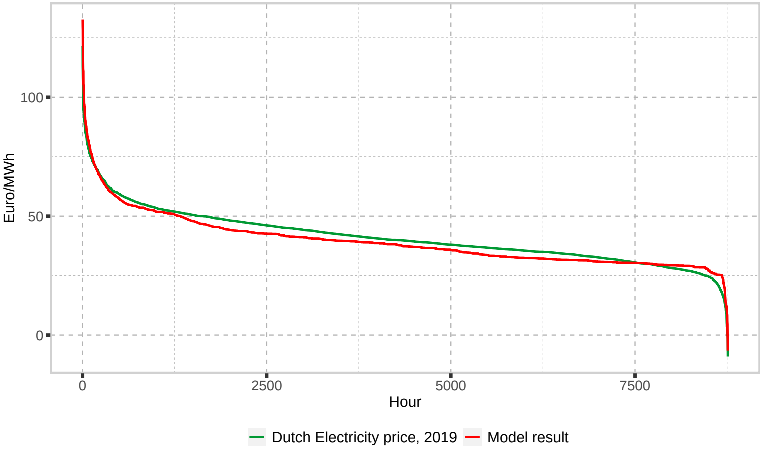
Assumptions regarding lifetime, construction duration and discount factor (WACC) of FES

Current situation



Installed capacities Dutch electricity market, 2019

Calibration of model on Dutch electricity market



Electricity price duration curves in the model and the Dutch electricity market in 2019

Scenarios: regarding renewable capacities and electricity demand

Renewable capacities

- High Renewables: renewable target in 2050

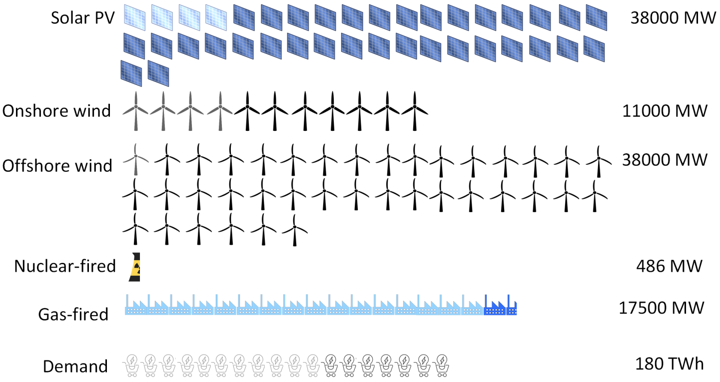
Electricity demand

- Medium Increase, High Increase: electrification

Gas-fired power plants:

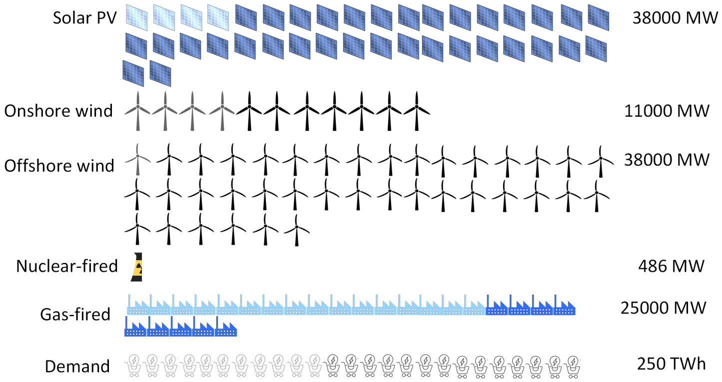
- capacity is adjusted accordingly to remain the same return rate per unit of installed capacity.
- sensitivity: scenario without gas-fired power plants

High Renewables, Medium Increase Demand



Installed capacities *High Renewables- Medium Increase Demand*-scenario

High Renewables, High Increase Demand



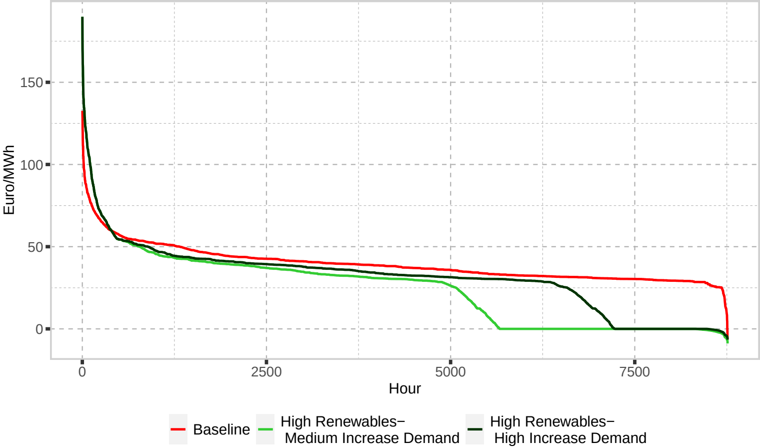
Installed capacities *High Renewables- High Increase Demand*-scenario

Definition of policy variants

- Base
- More nuclear: +1000 MW
- More solar
- More onshore wind
- More offshore wind

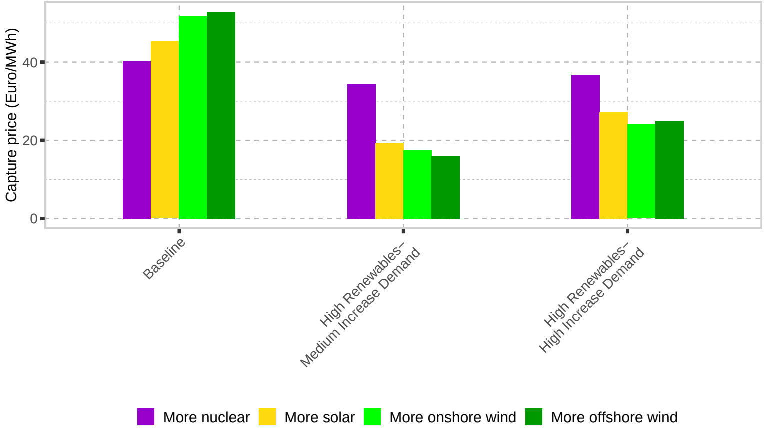
Results

Scenarios, electricity prices



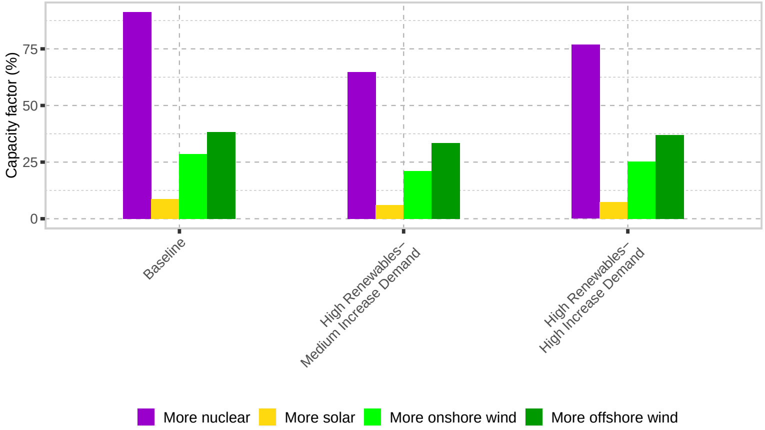
Duration curves of electricity price in considered scenarios

Capture price



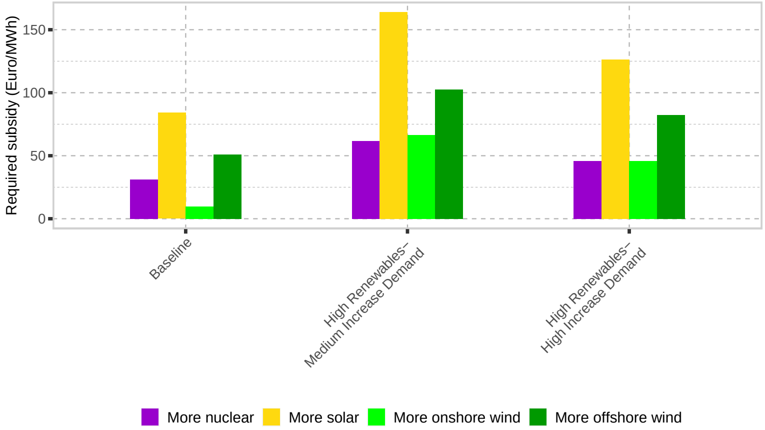
Capture price per technology for different scenarios/policy variants (Euro/MWh)

Capacity factor



Capacity factor per technology for different scenarios/policy variants (Euro/MWh)

Required subsidy



Required subsidy per technology for different scenarios/policy variants (Euro/MWh)

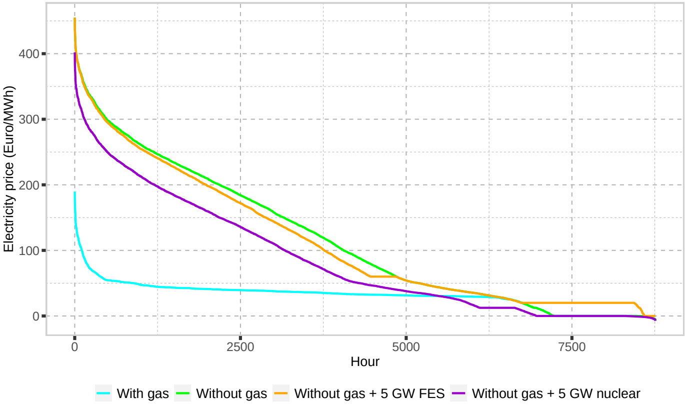
Electricity system with zero carbon emissions

Future: no gas-fired power plants

Two options to deal with need of flexibility

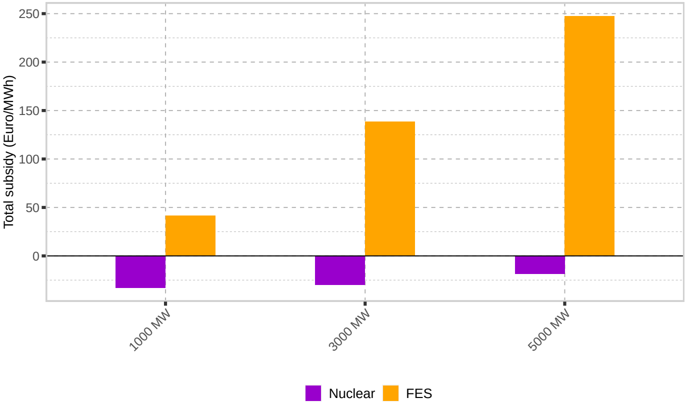
- More nuclear
- Storage
  - Arbitrager: buy when $p^e < \underline{p}$, sell when $p^e > \bar{p}$.
  - Hydrogen: Fuel cell, Electrolyzer, Storage (FES)

Price duration curves



Duration curves of electricity prices, *High Renewables- High Increase Demand*-scenario, different policy variants

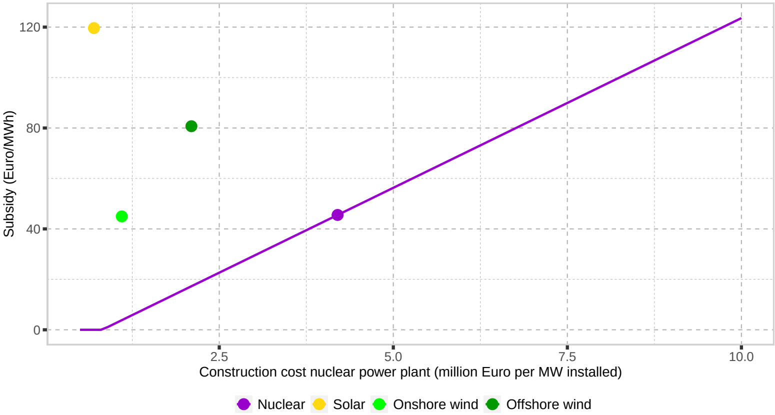
Required subsidy



Required subsidy of nuclear energy and FES, *High Renewables- High Increase Demand*-scenario, different policy variants

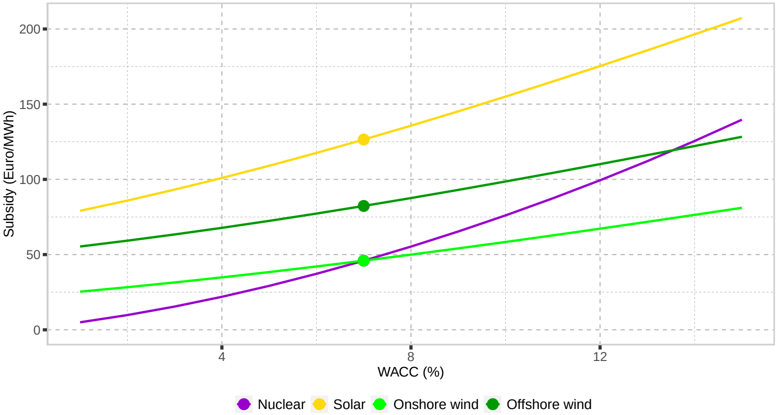
Sensitivity analysis

Construction costs



Sensitivity of required subsidy per MWh produced w.r.t. construction cost of nuclear power plant, *High Renewables- High Increase Demand*

Discount factor (WACC)



Sensitivity of required subsidy per MWh produced w.r.t. discount factor, *High Renewables- High Increase Demand*

Gas prices

Scenario	Setting	Nuclear	Solar	Onshore wind	Offshore wind
Baseline	p^G	31.32	84.10	9.81	50.87
	$p^G \times 5$	0	49.21	0	0
High Renewables- Medium Increase Demand	p^G	61.58	163.93	66.57	102.66
	$p^G \times 5$	18.66	149.94	52.09	90.44
High Renewables- High Increase Demand	p^G	45.93	126.47	45.95	82.33
	$p^G \times 5$	0	98.33	20.40	57.16

Notes:
p^G: gas prices as in 2019.
$p^G \times 5$: gas prices of 2019 multiplied by a factor 5.

Required subsidy per technology w.r.t. various gas prices, for different scenarios (in Euro/MWh)

Baseline: average gas price is about 14 Euro/MWh

Carbon prices

Scenario	Setting	Nuclear	Solar	Onshore wind	Offshore wind
Baseline	c^C	31.32	84.10	9.81	50.87
	$c^C \times 5$	0	62.99	0	20.18
	$c^C \times 10$	0	52.32	0	0
High Renewables-Medium Increase Demand	c^C	61.58	163.93	66.57	102.66
	$c^C \times 5$	43.36	156.04	59.28	96.34
	$c^C \times 10$	25.92	151.4	53.73	91.9
High Renewables-High Increase Demand	c^C	45.93	126.47	45.95	82.33
	$c^C \times 5$	0	112.24	34.31	70.55
	$c^C \times 10$	0	100.79	23.92	60.66

Notes:
c^C: carbon prices as in 2019.
$c^C \times 5$: carbon prices of 2019 multiplied by a factor 5.
$c^C \times 10$: carbon prices of 2019 multiplied by a factor 10.

Required subsidy per technology w.r.t. various carbon prices, for different scenarios (in Euro/MWh)

Baseline: average carbon price is about 25 euro/ton

Conclusions

Conclusions

1. In current power system, building an nuclear power plant requires subsidies
2. In a scenario with already high amounts of renewables, building an nuclear power plant requires less subsidies than building even more renewables (because of impact on capture prices)
3. Nuclear power plants benefit more from high gas and carbon prices than renewables
4. It is more efficient to build a nuclear power plant to provide flexibility than to use hydrogen for that purpose in zero-carbon electricity system

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