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Economic Efficiency of Nuclear Power in Decarbonized Energy Systems

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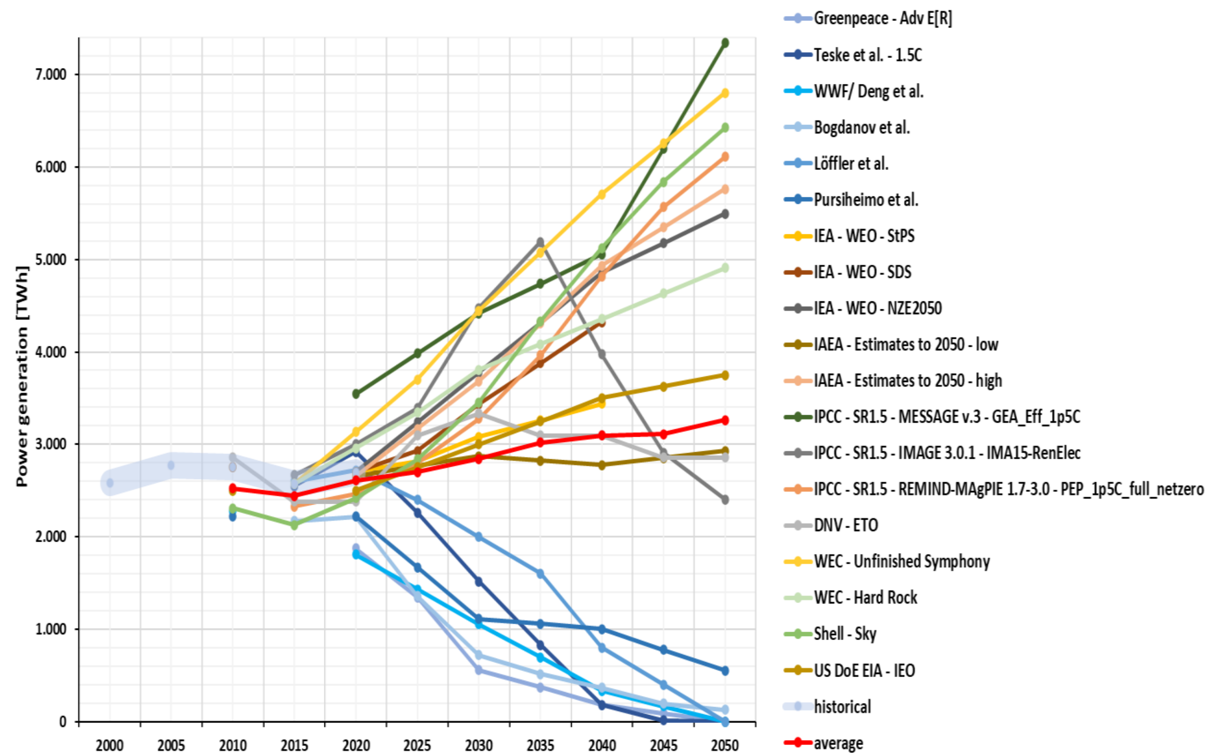
Motivation
Nuclear Power plays an important role in many energy scenarios

Nuclear Power Generation in IPCC scenarios



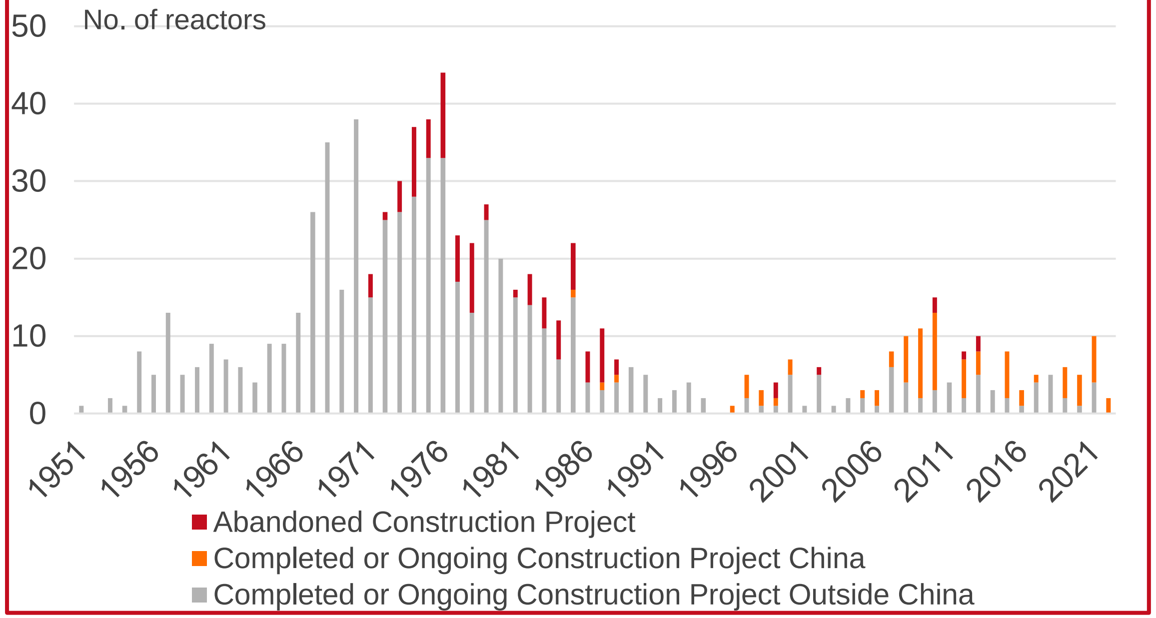
Comments

- Steigerwald et al (2022) identified two distinct groups of scenarios in current IPCC report
- One group of scenarios reaches cost-efficient solutions without nuclear (i.e. 100% renewables), while another group computes a steady increase of nuclear power generation
- The highest nuclear projection is documented in the recent NZE 2050 scenario of the IEA

Source: Steigerwald et al (2022)

Motivation
Nuclear reactor new build projects are slow and few outside of China

Number of Reactor Construction Projects Starting in a Certain Year[1]



Comments

- China has become the major contributor to newly build reactors and is extending its nuclear fleet[1]
- Outside of China, especially in Western countries, reactor new build projects are slow and often well over budget[1,2,3]
- Examples are Flamanville-3, France, Vogtle Station, USA, and Olkiluoto-3, Finland[2,3]
- Nevertheless, governments are extending reactor lifetimes (e.g., USA) and are announcing major new build plans (e.g., France & Japan) with the goal to use nuclear power to decarbonize energy systems and provide low-carbon energy to various sectors[3,4,5]

Given current cost escalations, how cheap must new nuclear reactors become to be a viable option for low-carbon electricity provision in Europe's future decarbonized energy system?

Source: 1: Schneider et al. (2022); 2: Rothwell (2022); 3: Lovins (2022), 4: New York Times (2022), 5: Financial Times (2022)

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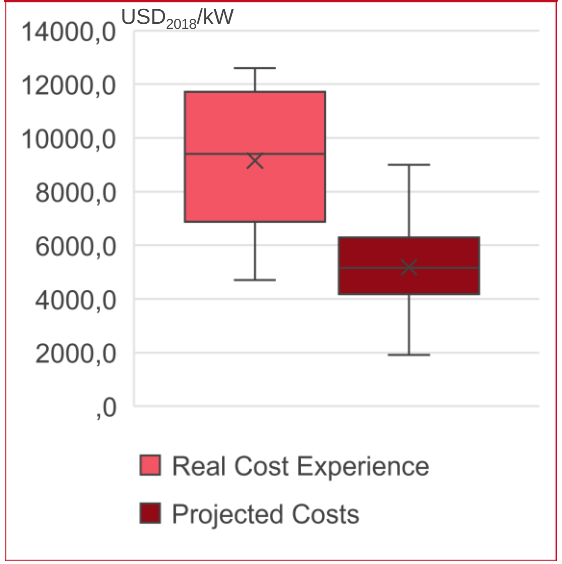
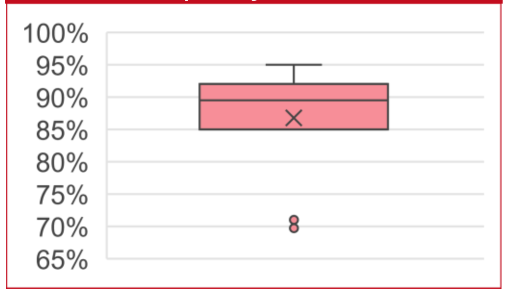
Method | Cost Analysis
Nuclear Cost Parameters in Literature

- Analysis of 32 publications on nuclear power reactor cost – we limit the analysis to OECD countries and GW-sized light-water reactors (LWR)
- Identification of relevant cost parameters to compute future nuclear cost: capital cost (given as overnight construction cost), capacity factor, construction time, fuel cost, operational lifetime, plant efficiency, operation & maintenance (O&M) cost (fixed + variable)
- A large discrepancy amongst projected or assumed and real cost values could be observed

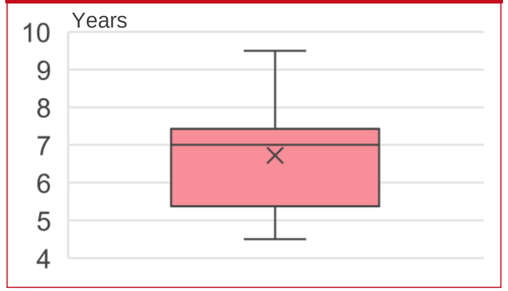
Reported OCC values for LWRs in OECD countries



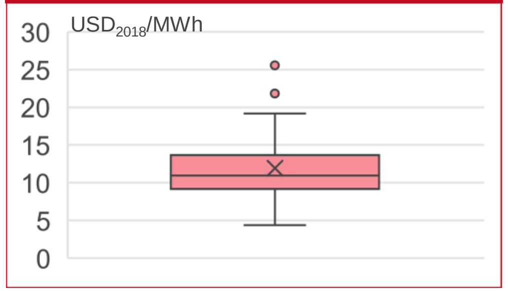
Capacity Factor



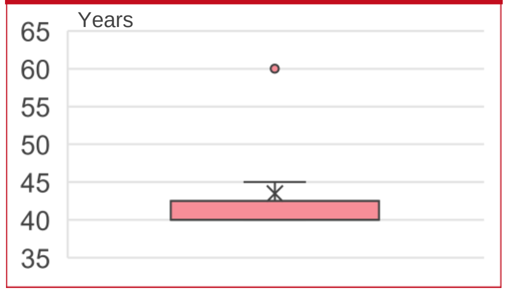
Construction Time



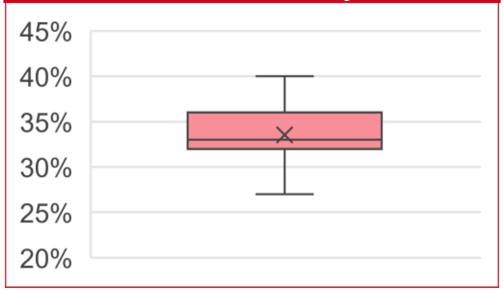
Fuel Cost



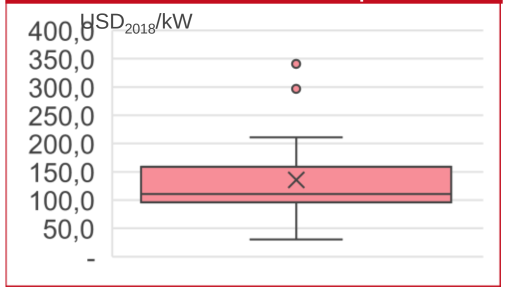
Lifetime



Plant efficiency



Combined O&M Cost per kW



Sources: See References.

Method | Cost Analysis
Nuclear capital cost and Input Parameters

Nuclear Capital Cost

For nuclear, capital costs account for up to 80 % of total project cost[1,2]

Literature mostly provides *overnight construction costs* (OCC), that neglect construction time and interest.[3,4]

Therefore, to calculate total capital cost (TCC) for nuclear new build, both construction time and interest during construction must be taken into account.[4]

This gives the formula

$$TCC = OCC + IDC$$

where IDC is the interest during construction calculated as

$$IDC = \frac{WACC}{2 * t} + \frac{WACC^2}{6 * t^2}$$

where WACC as weighted average cost of capital (we assume 5%) and t is the construction time in years.

Model Input Parameters

Parameter	Unit	Value / Range
Overnight construction cost	US-$ / kW	1,914 – 12,600
Annual fixed O&M cost	US-$ / kW	88.81
Variable O&M cost (incl. fuel)	US-$/MWh	10.96
Capacity Factor	%	95
Construction Time	Years	4-10
Operational Lifetime	Years	60

Note: Non-variable parameters correspond to 25%-percentile of cost analysis and must be interpreted as nuclear-friendly, optimistic assumptions.

Sources: 1: MacKerron (1992); 2: Haas et al. (2019); 3: Lovins (2022); 4: Rothwell (2016)

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Method | Model
Framework and Assumptions

Framework

- This model applies the model framework AnyMod.jl[1]
- The applied version is available at https://github.com/leonardgoeke/AnyMOD.jl/releases/tag/flexibleElectrificationWorkingPaper

Major Assumptions

- Nuclear power plants can only provide electricity and are built without size constraints (capacity, not reactors, is added)
- Full flexibility for nuclear power plants -> no ramp-up
- Integrated European energy system that is fully decarbonized in heat, transport, electricity
- Greenfield approach for 2040
- For nuclear power plants, there are no cycling constraints from, e.g., refueling or safety inspections

Sources: 1: Göke (2021a)

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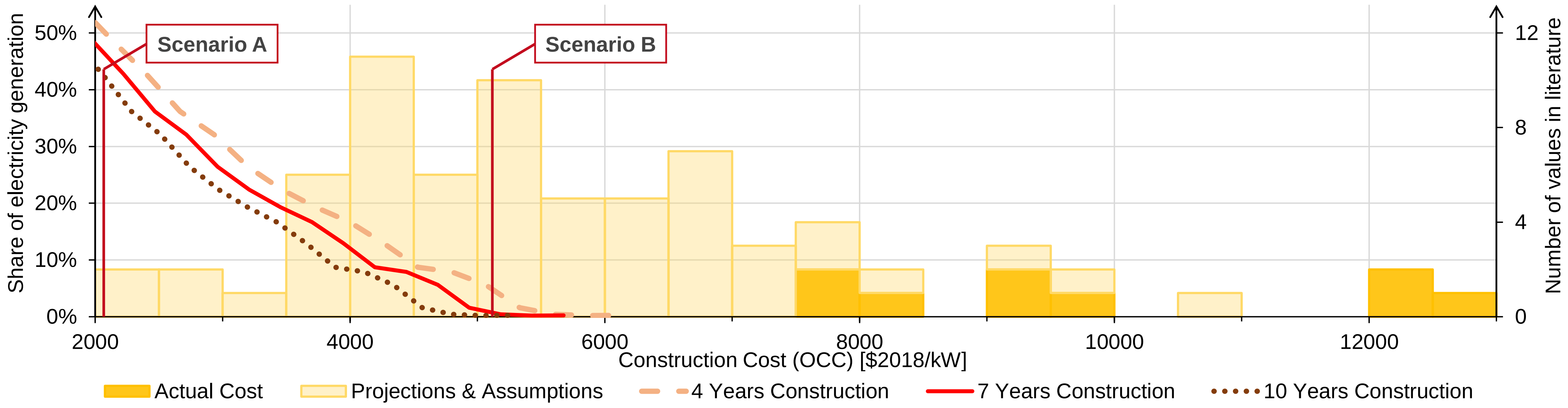
Results | Nuclear Share

Below 5,000 US-$/kW, nuclear electricity production is marginal

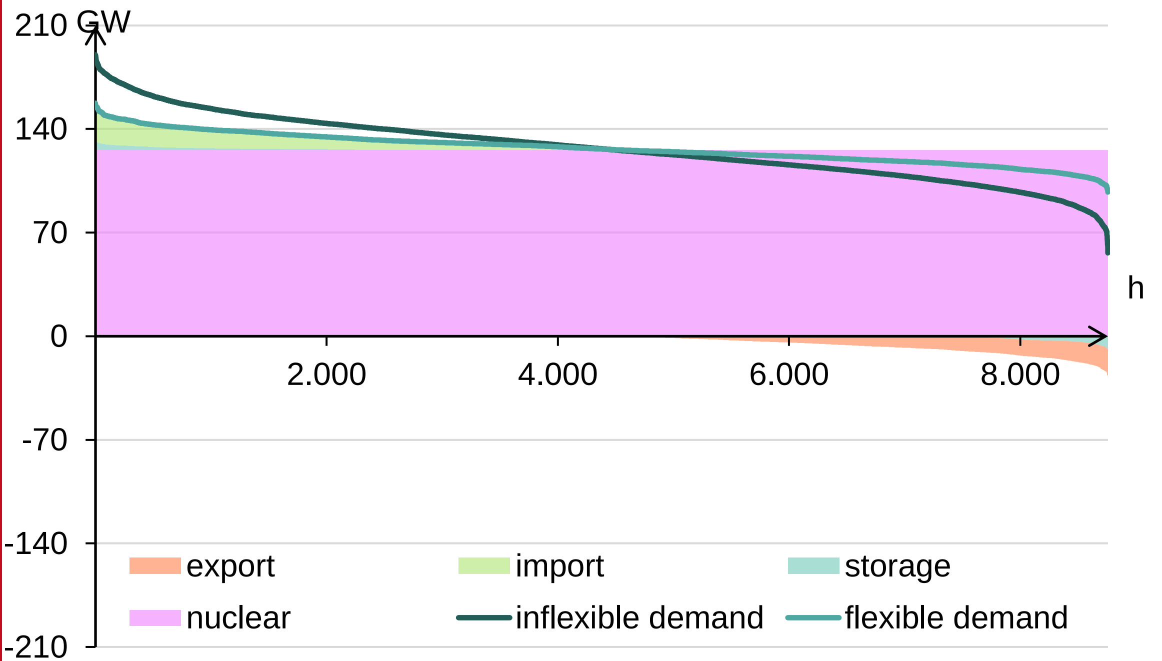
Share of nuclear electricity generation depending on overnight construction cost compared to literature analysis results



Only if total construction costs range in the lowest found values in literature, will nuclear have a noticeable impact on electricity generation. If nuclear projects remain as expensive as current new build projects, nuclear is not cost-efficient and renewable energy sources dominate the energy system.

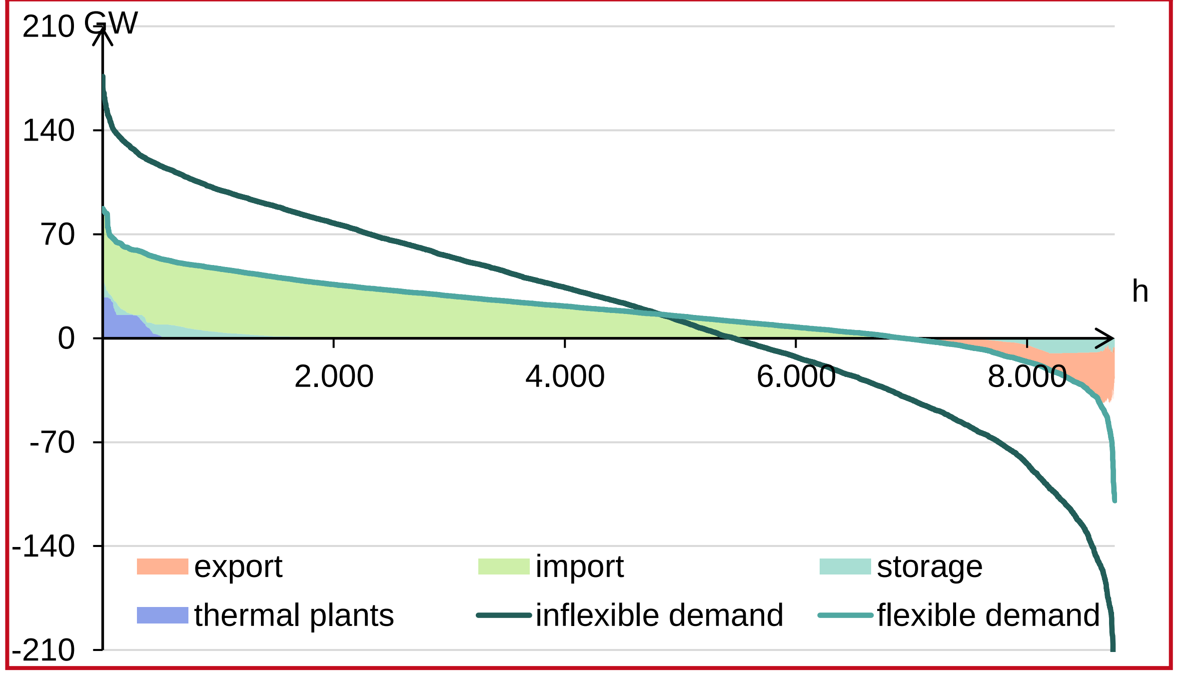
Results | Load Duration Curves in Different Scenarios
Load curves show how varying demands are met in all hours of the year

Scenario A: Highest Nuclear Share



In Scenario A, nuclear power plants run at near full capacity and make no use of implemented flexibility. Residual demand is met through imports and oversupply is exported and stored in small amounts.

Scenario B: No Nuclear



Scenario B reduces residual demand through flexibility measures (e.g., flexible EV charging), gaps are met mostly through import and storage, while peaks are met with thermal plants

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Conclusion & Outlook

Preprint available at https://doi.org/10.48550/arXiv.2302.14515

Conclusion

- In a decarbonized energy system, nuclear power plays a role once OCC fall below 5,000 US-$/kW – a value that has not been observed outside China
- Assuming that all other cost parameters remain low, nuclear power plants can be operated flexibly and operate at near full capacity (95%) – all very optimistic assumptions when taking reality into account
- We neglect decommissioning and waste management costs as well as social costs (external effects) from accident risk
- Nuclear power plants to not operate flexibly – high capital costs result in the need to operate constantly – leading to over-supply
- To help decarbonize Europe's energy system in a cost-efficient manner, nuclear power plants would have to be constructed much faster and must become a lot cheaper than they currently are

Outlook & Future Research

Energy Economics:

- Literature suggests using nuclear power reactors for non-electrical uses, such as desalination of sea water or heat provision. Integrating so-called "new reactor designs" (Gen VI), such as high-temperature reactors, into our model might lead to a more feasible nuclear use-case in Europe
- Refine our nuclear cost data base to provide transparency on nuclear costs

Technical / Engineering:

- In order to succeed in becoming a part of a decarbonized European energy system, nuclear power plants must become a lot cheaper and faster to build
- Even low shares of nuclear in the electricity mix require substantial investments into new plants that, at the current state of the industry, seem rather unlikely

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Questions?

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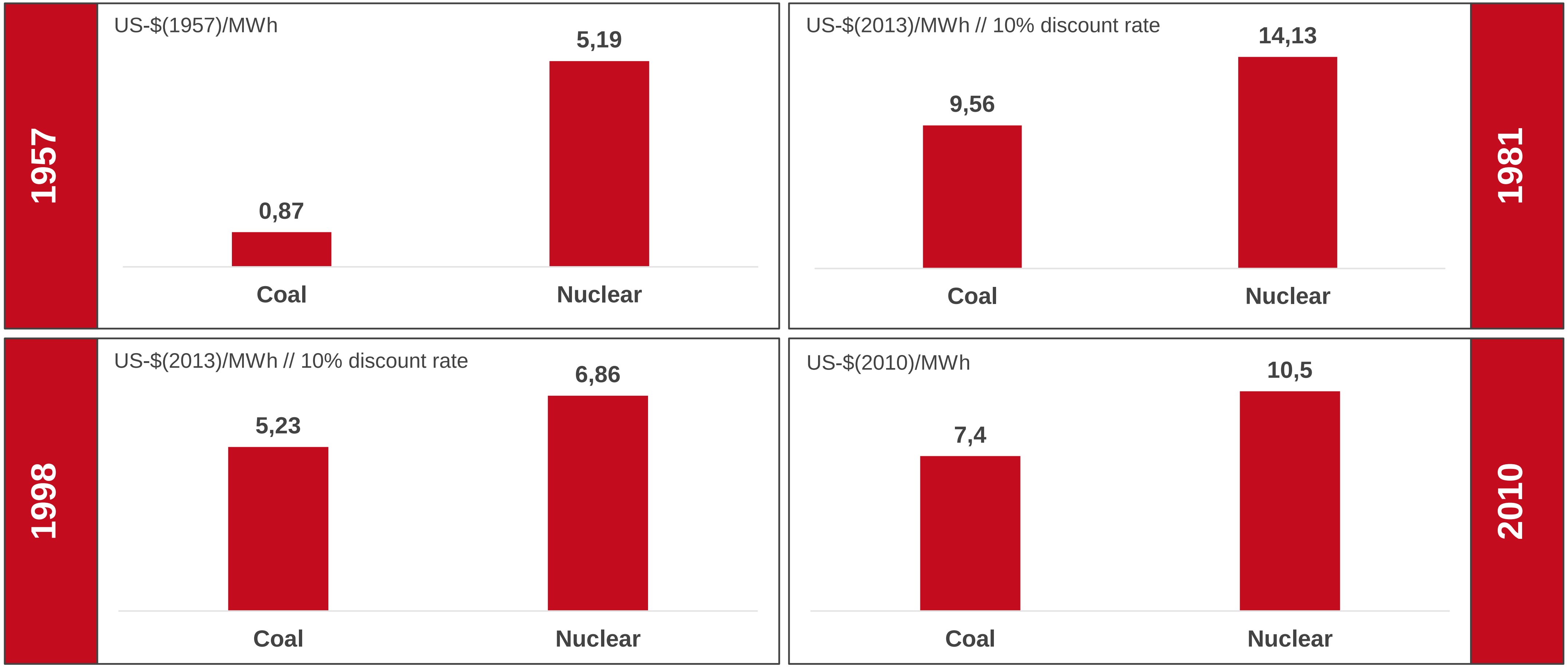
BACKUP | Nuclear Cost

Was nuclear ever competitive?

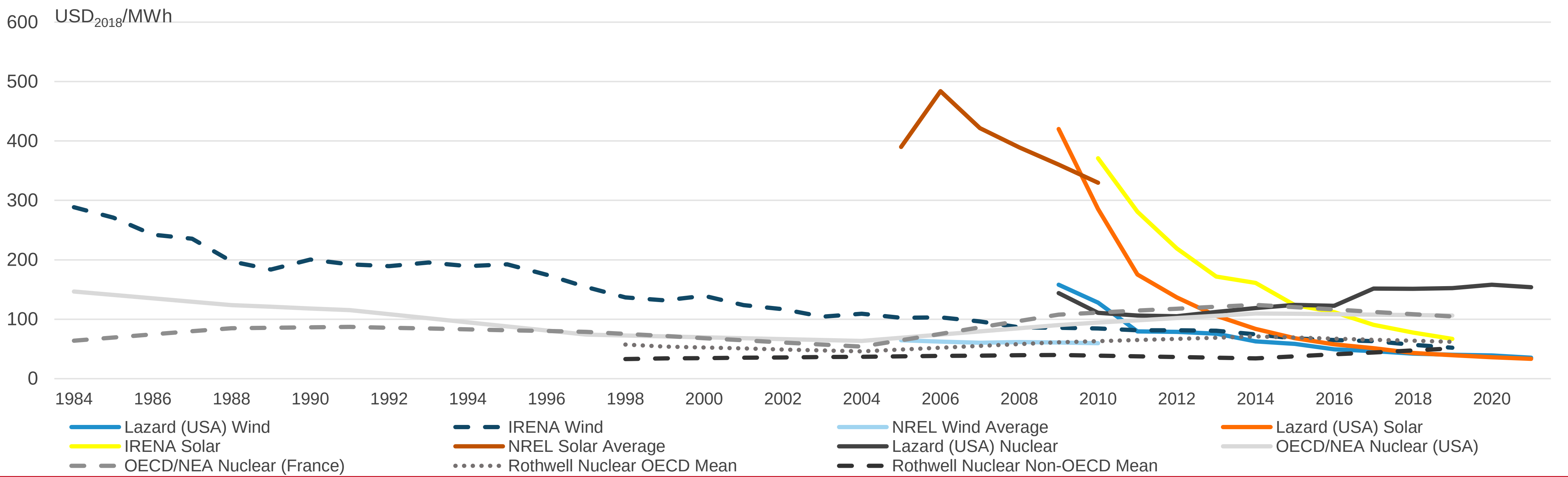


Sources: Baade (1958, 125, exchange rate 1 USD = 4,20 DM), IEA, OECD, NEA (2015), Davis (2012)

BACKUP | Nuclear Cost

Nuclear competitiveness vs. renewables

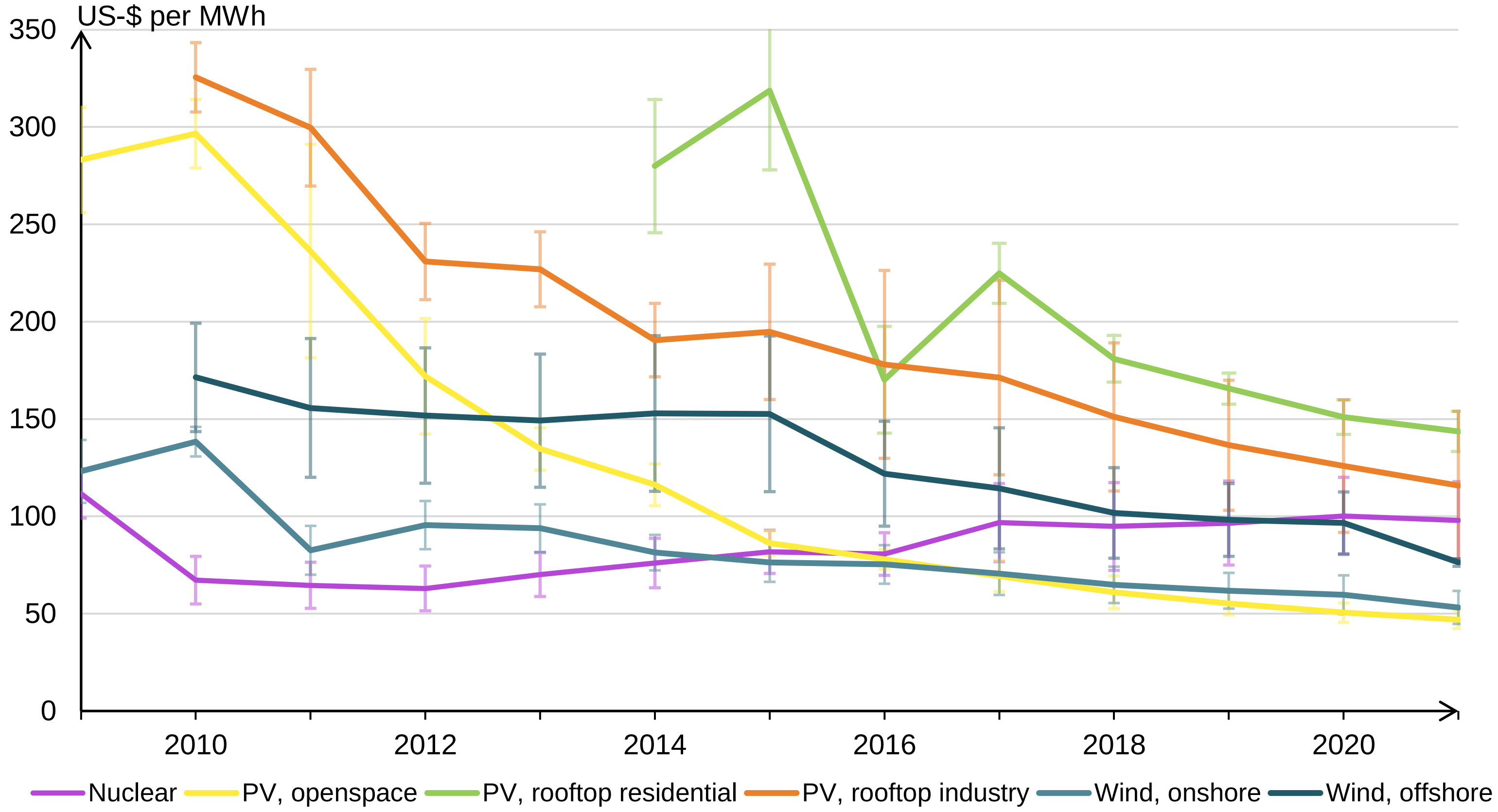
LCOE Values for Wind, Solar and Nuclear over the last decades



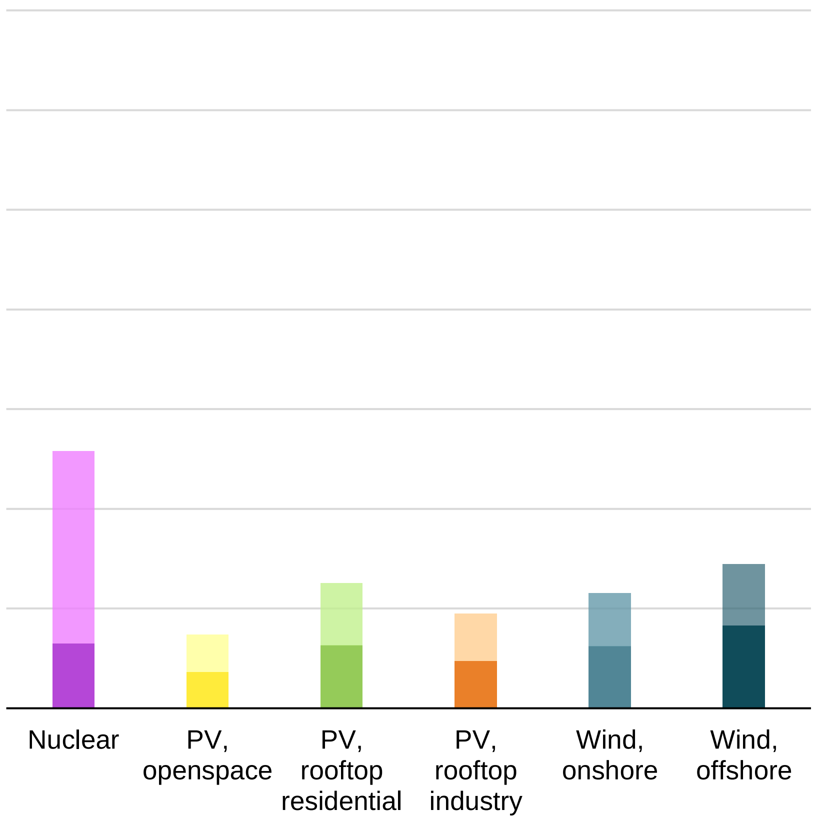
LCOE are a useful way to compare the costs of different technologies. However, they strongly depend on the assumptions, as can be seen in the above graph. Further, LCOE do not include external and other cost factors, such as battery storage, flexibility measures, waste management, decommissioning.

Sources: Haas et al. (2019), Rothwell (2022), IRENA (2020), NREL (2021), Lazard (2010-2022)

BACKUP | Nuclear Cost
Nuclear competitiveness vs. renewables



a) historic development



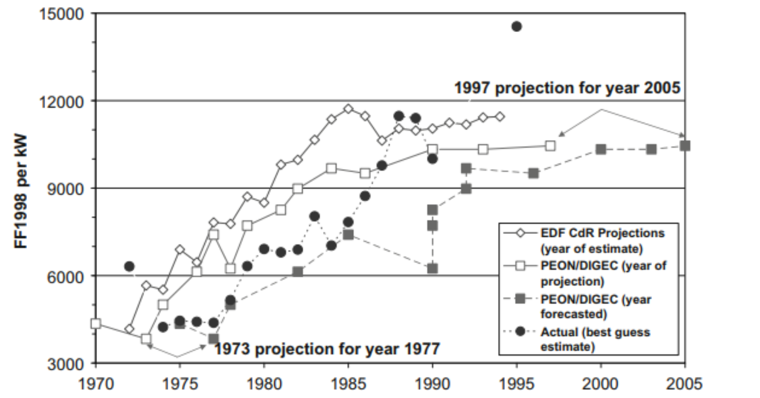
b) range of projections

Sources: Lazard (2010-2022), own calculations

BACKUP | Nuclear construction costs

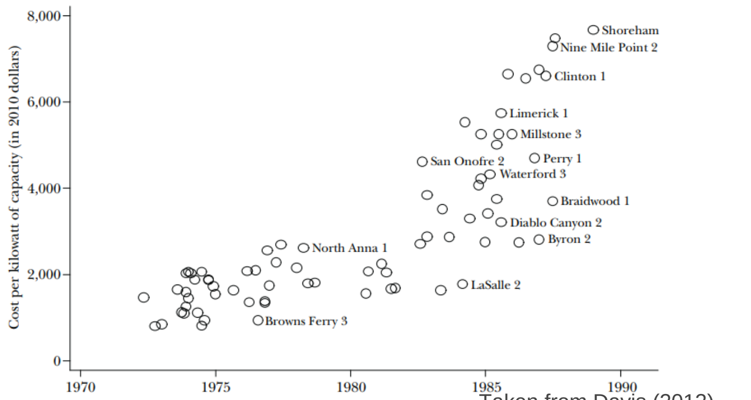
Nuclear construction costs have only grown (in OECD countries)

Cost increase in France



Taken from Grubler (2010).

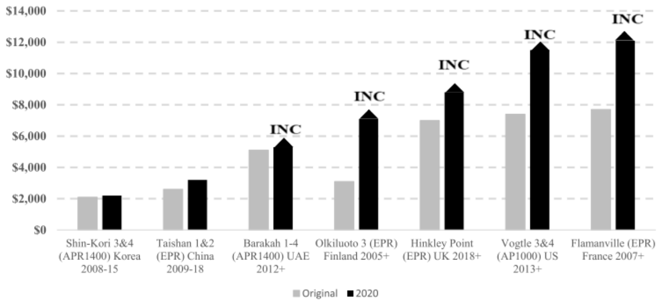
Cost increase in USA



Taken from Davis (2012).

And today's projects…?

- The South Carolina (V.C. Summer) project was canceled in 2017 after more than 9 bn USD had been spent.
- Project costs at Olkiluto-3 increased from 2005 to 2020 from 3,125 to 7,600 USD_{2018}/kW.
- Project costs at Voglte Station have doubled.
- The initial contract price of Flamanville-3 was 3 bn $EUR_{2007.}$ By 2021, costs increased to 12.4 bn EUR_{2020}.
- Chines projects also experienced cost increases, albeit not as drastic (2,600 to 3,200 USD/kW).
- For further reading on costs of current projects refer to Rothwell (2022) and Lovins (2022)



Taken from Rothwell (2022).

Sources: Davis 2012; Grubler 2010; Koomey and Hultman 2007; Koomey, Hultman, and Grubler 2017; Lovins 2022; Rothwell 2022

BACKUP | Supply and Demand | Scenario A

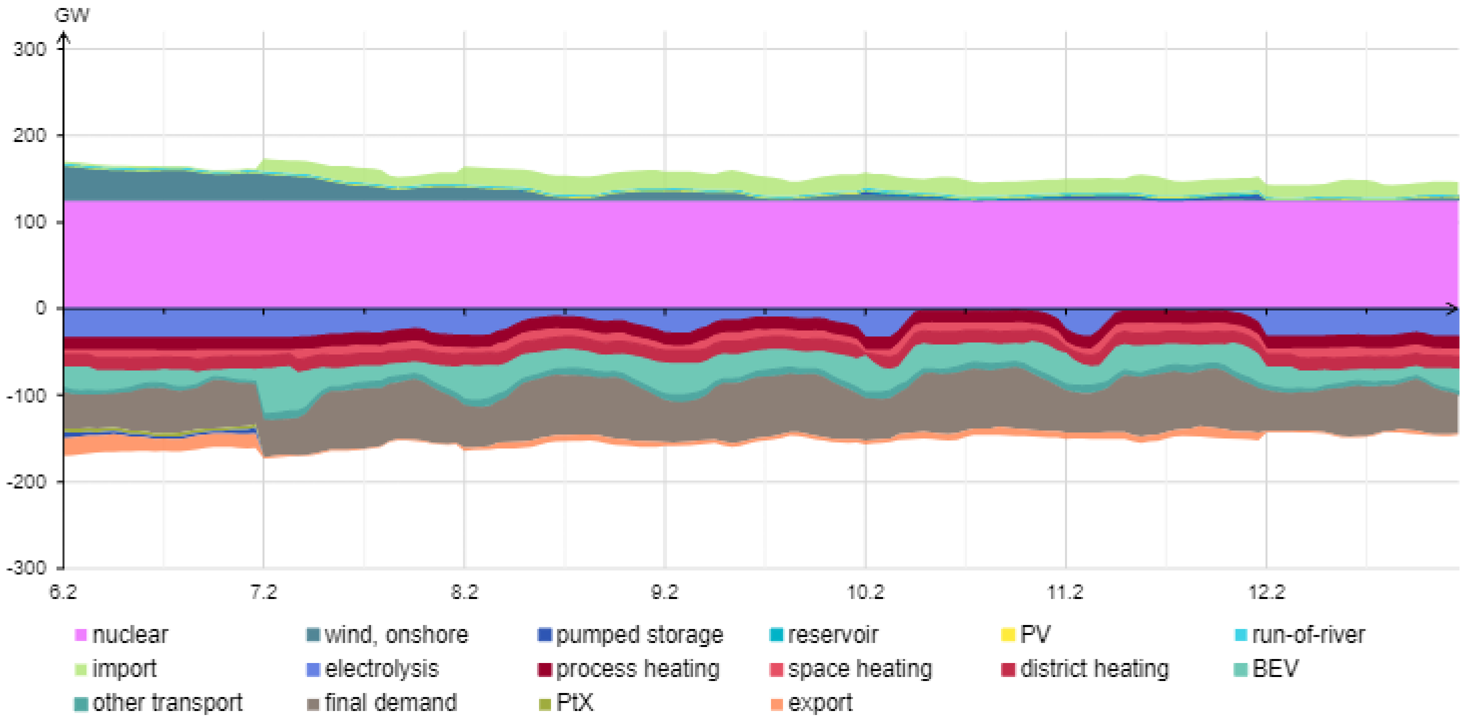


Fig. G11 Supply and demand in Germany for one week and high nuclear scenario

BACKUP | Supply and Demand | Scenario B

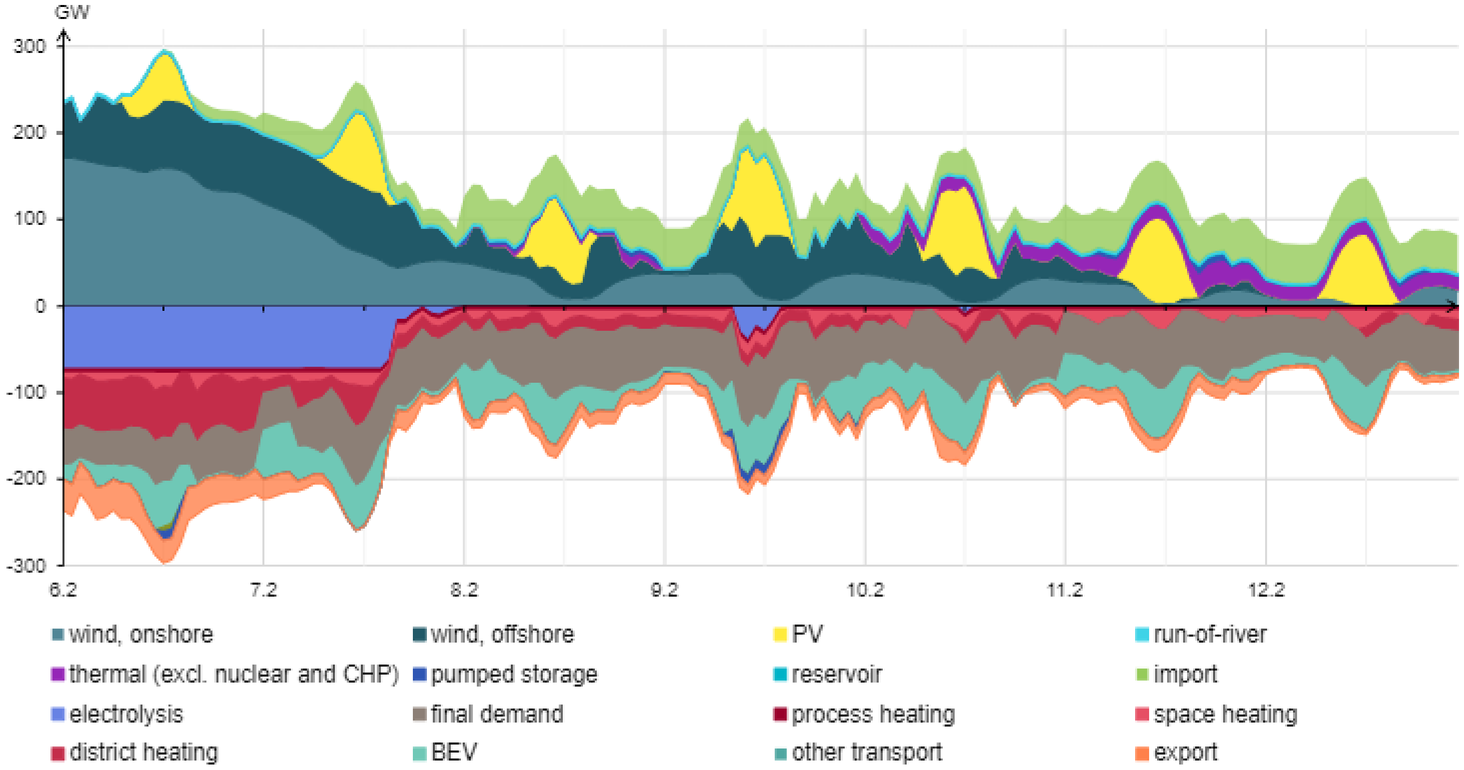
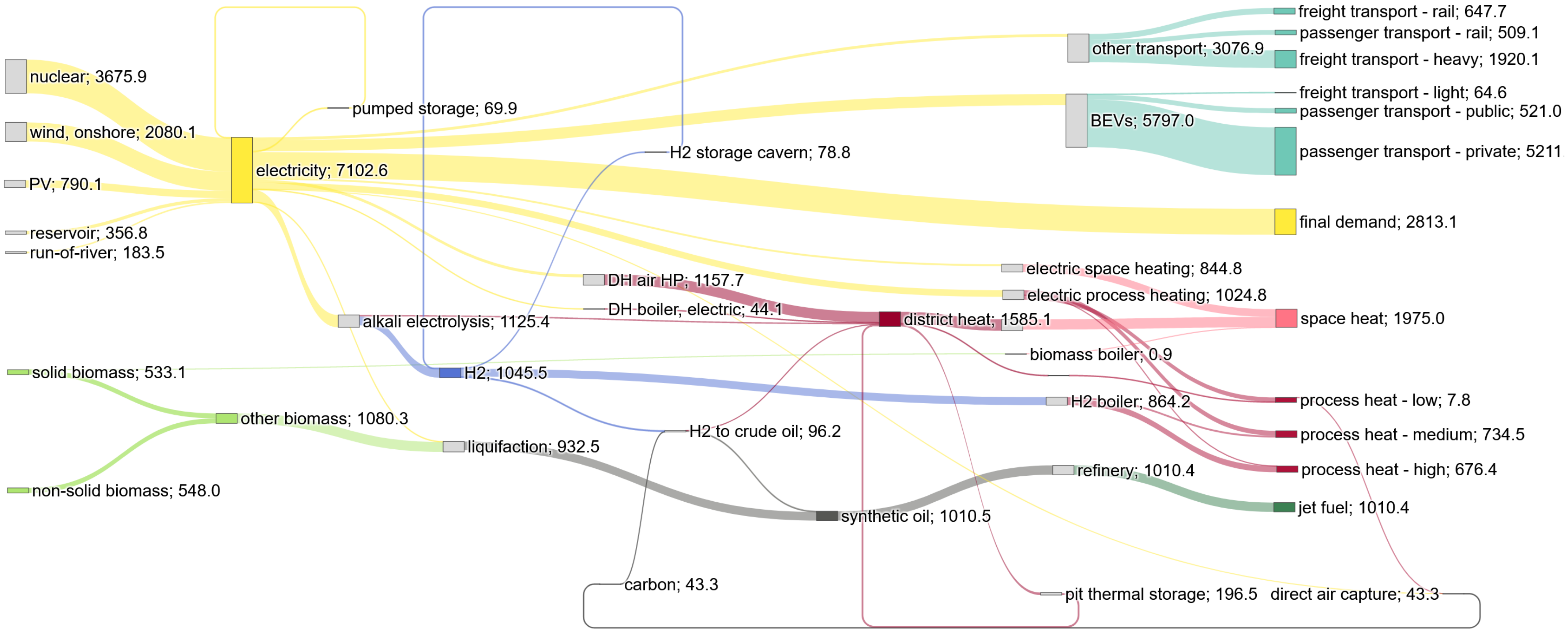


Fig. G12 Supply and demand in Germany for one week and no nuclear scenario

BACKUP | Sankey Scenario A



BACKUP | Sankey Scenario B