The economic efficiency of non-light water reactors and their non-electrical applications in decarbonized energy systems

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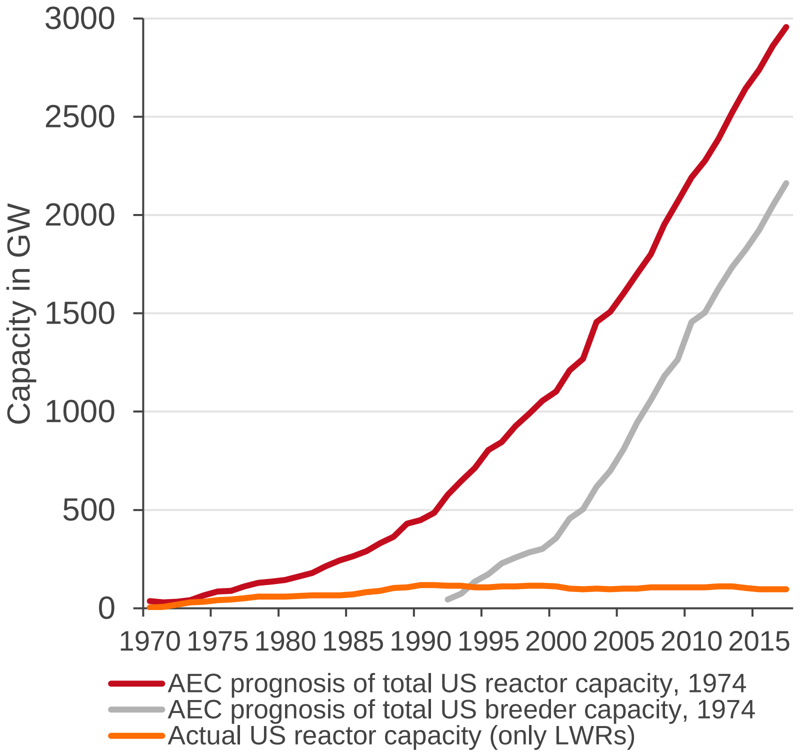
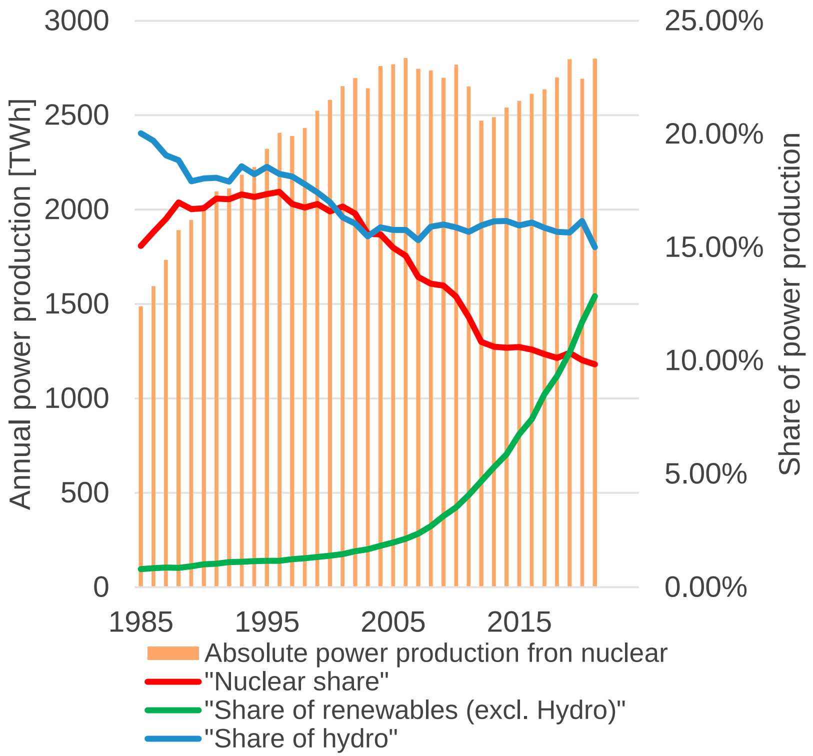
Introduction | Nuclear power has often been expected to „take over“, but it has never delivered

AEC prognosis of future reactor development in the US made in the 1970s



*AEC= Atomic Energy Commission

Global development of power production from nuclear power and renewables



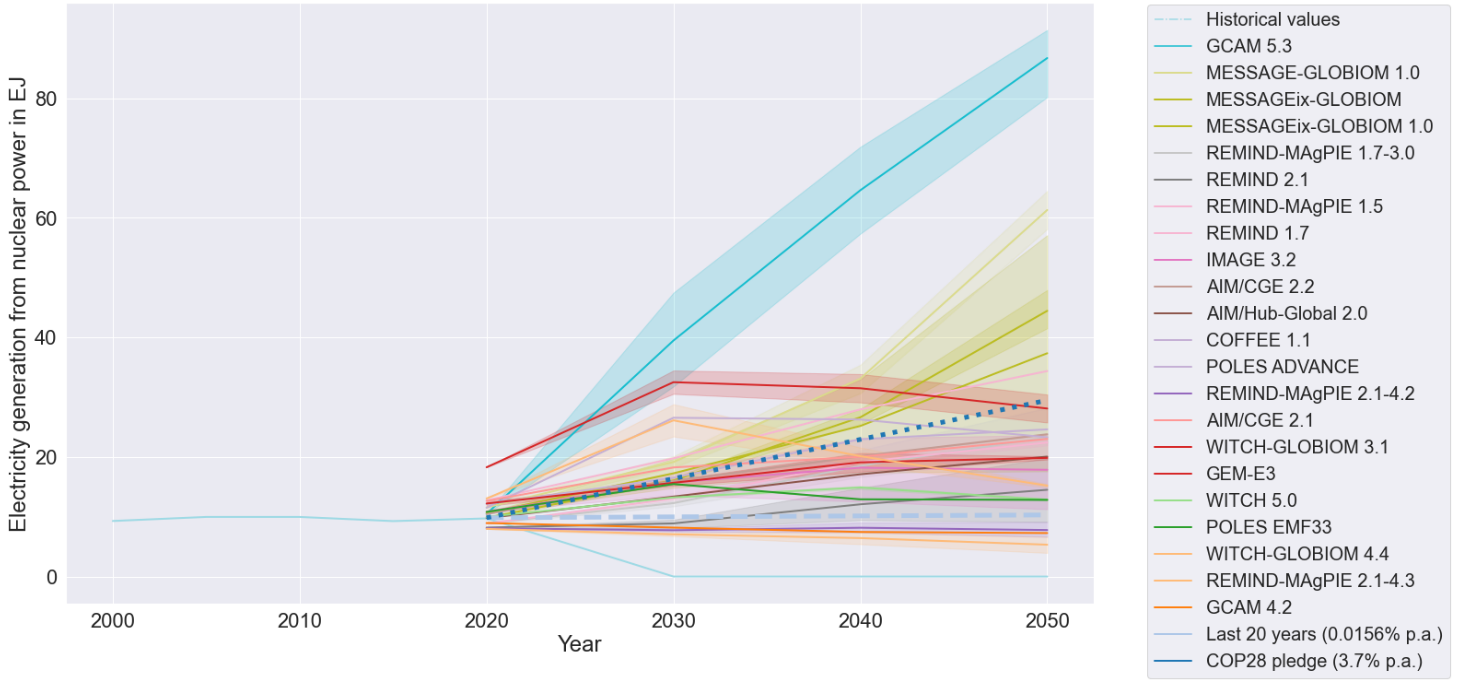
Comment

- Globally, the share of nuclear power generation is in decline (and has been for decades)
- New build outside of China is stagnating, half of all ongoing projects are delayed and are experiencing substantial cost increases
- Ageing reactor fleets require lifetime extensions and new build as up to 200 GW are scheduled to come offline until 2050

References: von Hirschhausen et al. (2023), Wimmers, Böse et al. (2023), Böse et al. (2024)

Introduction | The expectations of nuclear expansions remain the same as forty years ago – will the industry be able to deliver?

Expected power production from nuclear power until 2050 in 94 IAM-Scnearios with a 1.5°C-emission target in 2100



Comment

- Some climate protection scenarios (from integrated assessment models) expect a rapid increase in electricity generation from nuclear energy
- The assumptions on which the models are based must be reviewed and critically scrutinised due to technological and actor-related non-availability of technologies
- Hundreds of reactor projects would have to be started today to build up the necessary capacities; ageing fleets would first have to be replaced also
- Statements and announcements, e.g. regarding a "tripling of existing capacities"* by 2050, are questionable from today's perspective

We thus ask: could **so-called “new” or “advanced” reactor technologies** overcome the current challenges of today’s light water reactor fleets and if so, how would they **perform economically** in a future decarbonized energy system?

References: Böse et al. (2024); *e.g.: WNN (2023)

Agenda

1 Introduction

2 Non-electrical applications for nuclear reactors

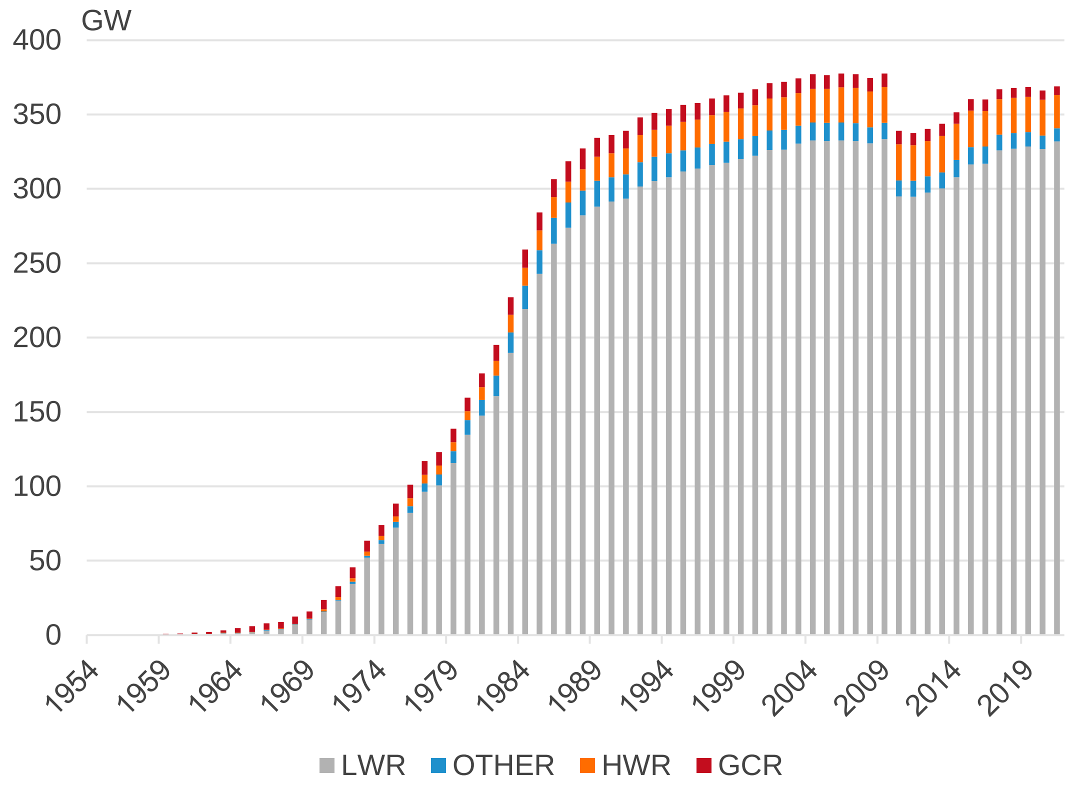
3 Method: Cost analysis and model

4 Results

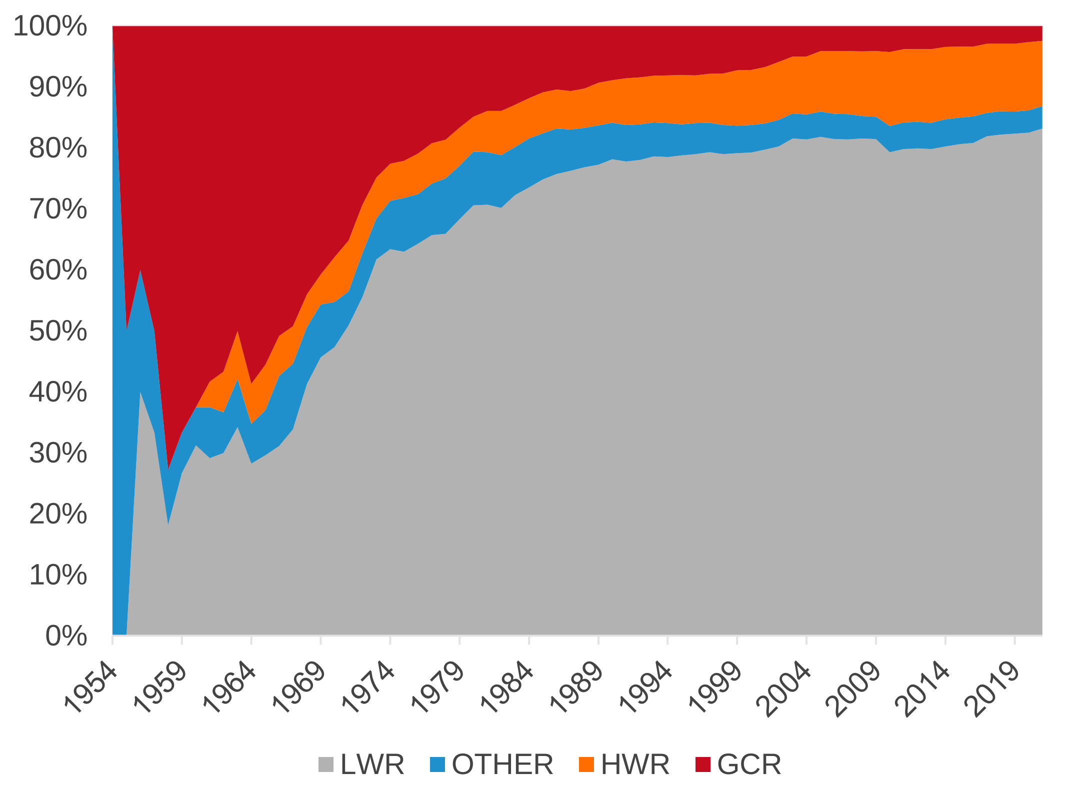
5 Conclusion and Outlook

Reactor technologies | Today‘s global fleet is dominated by high-capacity light-water reactors

Cumulated installed global reactor capacity



Reactor technology shares (global)



Note: OTHERS includes HTGR, LWGR and FBR technologies. LWR includes PWR and BWR reactors.

Reference: Own depictions with data taken from Schneider et al. (2022).

Reactor technologies | In theory, multiple reactor concepts and designs exist; some have been historically tested, others not

Light water reactors (LWR)

High-capacity LWRs
- Most common reactor concept today
- More than 300 MW capacity
- “lumpy” technology
- Limited non-electrical applications
- High capital cost

“Small Modular Reactors” (SMR)
- Potential for reduced (specific) cost due to “economies of learning”
- Potential inherent passive safety systems
- Certain off-grid applications possible
- No such reactor exists today

Fast neutron spectrum reactors (FBR)

Sodium-cooled fast reactors (SFR)
- use U-238 and depleted fuel rods to generate Pu
- Increased thermal efficiency and higher outlet temp. than LWRs
- Historically researched but many failures and accidents

Lead-cooled fast reactors (LFR)
- Lead is less reactive than sodium, potentially less dangerous
- LFRs used exclusively in Russia for submarine propulsion
- One ADS-driven system under construction in Belgium (MYRRHA)
- No real operational experience

High temperature reactors (HTR)

- Several prototypes (e.g. Pebble Bed Design) operated in 1960s & 1970s, all shut down after too large technological challenges, thus very limited operational experience
- Potential outlet temperatures of ~950°C could be used for process heat
- Two prototypes operational in China, one design in pre-licensing stage in US

Molten salt reactors (MSR)

- Using molten salt as coolant could allow for high operational temperatures from 600 to 700°C
- Multiple concepts under development, but no single reactor/prototype has operated so far

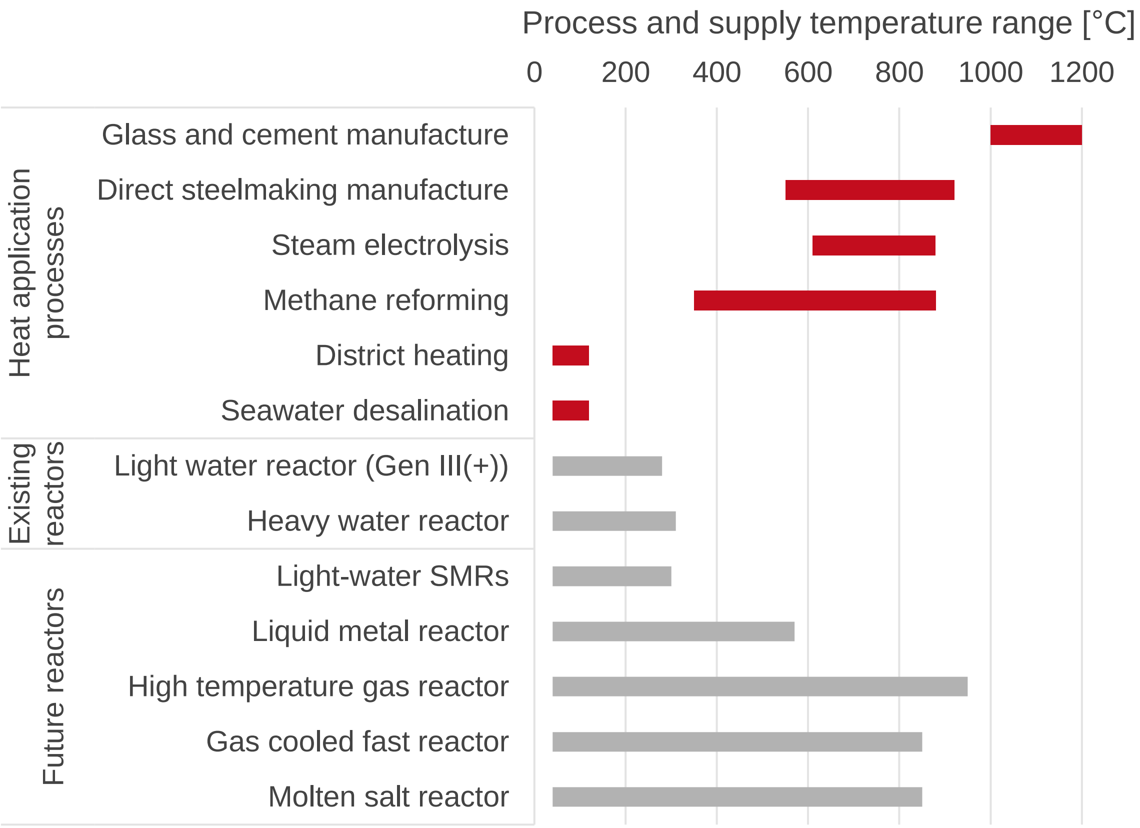
In order to succeed in a decarbonized energy system, such reactor concepts must be 1) **affordable**, 2) **economically competitive**, 3) socially acceptable, and 4) commercially available***** (Committee on New and Advanced Reactors (2023)).

References: Pistner et al. (2023), Steigerwald et al. (2023), Black et al. (2023), Böse et al. (2024).

*4) was discussed in detail by Böse et al. (2024).

Reactor technologies | Non-electrical applications are limited to individual plants, but theoretically, reactor concepts could supply services

Potential heat application processes



Own depiction following IAEA (2017).

Historical non-electrical uses

Load following and flexibility services

- Nuclear often portrayed as dispatchable energy source (e.g. Lynch et al. (2022), Jenkins et al. (2018)), but potential safety risks due to increased material stress (Ramana (2021))
- Despite theoretical potential, actual implementation is limited to France and individual reactors in U.S. (Schneider et al. (2023))

District heat

- Provision of low temperature heat to neighboring municipalities has been practice in several countries (refer to Appendix A)
- Transportation of heat over long distances challenging (Safa (2012))

Process heat for industry

- Individual applications at low-capacity projects at medium temperature ranges (<300°C), e.g. Gösgen plant in Switzerland for cardboard production (IAEA (2019)); Bruce HWR (Canada) for greenhouse, ethanol production, plastic film production, and others (IAEA (2017), Kupitz (2001))

Seawater Desalination

- Applicability demonstrated at several locations; mostly in Japan, Kazakhstan and Russia (refer to Appendix A)

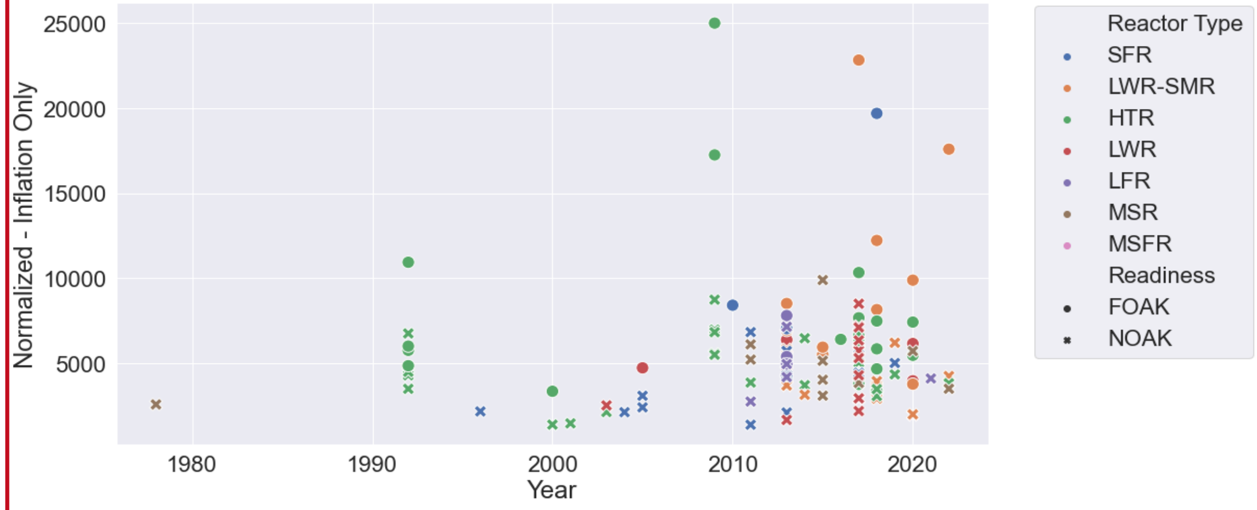
Other

- Water vessel propulsion (mainly in Russia), Data mining and crypto (IAEA (2002), Schneider et al. (2023))

Method | Several publications that make assumptions on future costs of non-light water reactors exist

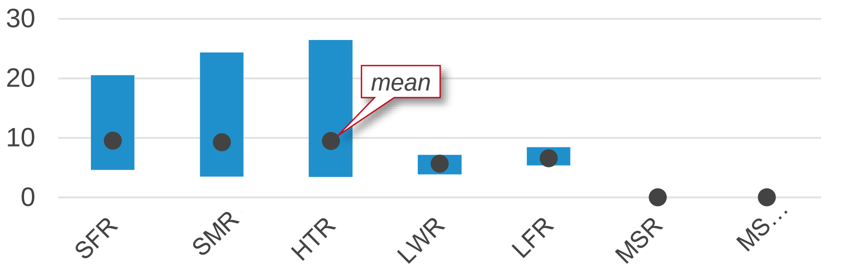
A total of 124 cost assumptions for "overnight construction costs" were gathered. The earliest estimation is from 1978. All data was normalized to USD-2019 following Abou-Jaoude et al. (2023). Assumptions are either "first-of-a-kind" assumptions "n-th-of-a-kind" that assume some form of learning. This would likely require the construction of tens to hundreds of identical reactors.
Similar to what was shown by Göke et al. (2023) (see Appendix B), estimations are very optimistic considering soaring costs of today's projects. Steigerwald et al. (2023) showed that estimations and theoretically realizable cost reductions for SMRs are wide apart.

Distribution of OCC assumptions in USD-2019 for different reactor concepts from 1978 to 2023

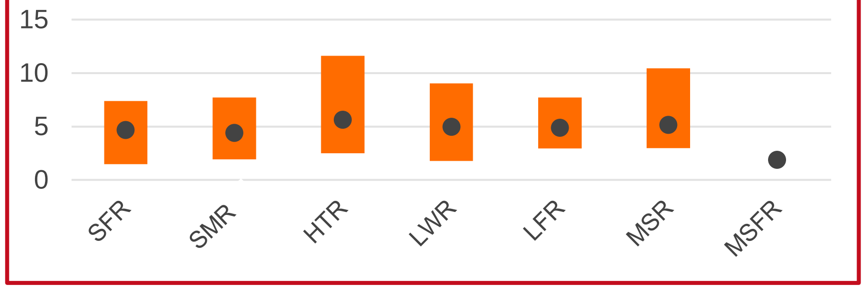


Note: SFR = Sodium-cooled reactor on a fast neutron spectrum; LWR-SMR = light water cooled small modular reactor; HTR = high-temperature reactor; LWR = high-capacity light-water reactor; LFR = lead-cooled reactor on a fast neutron spectrum, MSR = molten-salt reactor (thermal); MSFR = molten salt reactor (fast neutron spectrum)

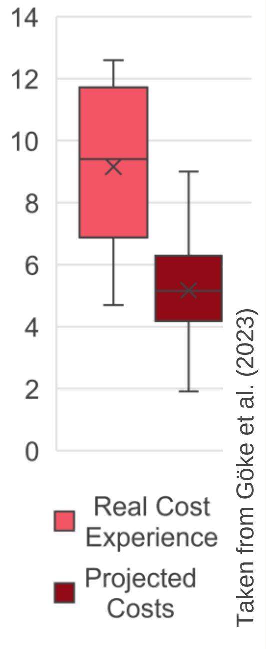
Distribution of FOAK cost assumptions in TUSD-2019 per kWe



Distribution of NOAK cost assumptions in TUSD-2019 per kWe



LWR OCC data



References: Various, see Slide 19.

Method | Introducing nuclear capital cost calculations and chosen reactor technologies

Nuclear Capital Cost

For nuclear, capital costs account for up to 80 % of total project cost (MacKerron (1992), Wealer et al. (2021))

Literature mostly provides *overnight construction costs* (OCC), that neglect construction time and interest (Lovins (2022), Rothwell (2016))

Therefore, to calculate total capital cost (TCC) for nuclear new build, both construction time and interest during construction must be considered (Rothwell (2016)). 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 10%) and t is the construction time in years.

Model Assumptions and Input Parameters

We assume that four reactor technologies can be built. Each reactor technology can generate electricity and some form of heat. Three cost scenarios (FOAK, NOAK_mean, NOAK_min) are applied. Various technology combinations are applied.

Parameter	Unit	Value / Range
Overnight construction cost	US-$ / kW	1476 - 9511
Combined O&M Cost (excl. fuel)	US-$ / MWh	3.22 – 53.45
Fuel cost	US-$/MWh	9.16 – 11.9
Capacity Factor	%	90
Construction Time	Years	7
Operational Lifetime	Years	40

Note: HTRs provide medium and high process heat; LWRs provide district heat; SMRs can provide low process heat; SFR provide medium process heat

Method | The applied model framework and major assumptions

Framework

- This model applies the model framework AnyMod.jl
- The model itself is based on EuSysMod, a greenfield model for the European energy system
- The applied version is available at https://github.com/leonardgoeke/EuSysMod/tree/greenfield_nuclearHeat

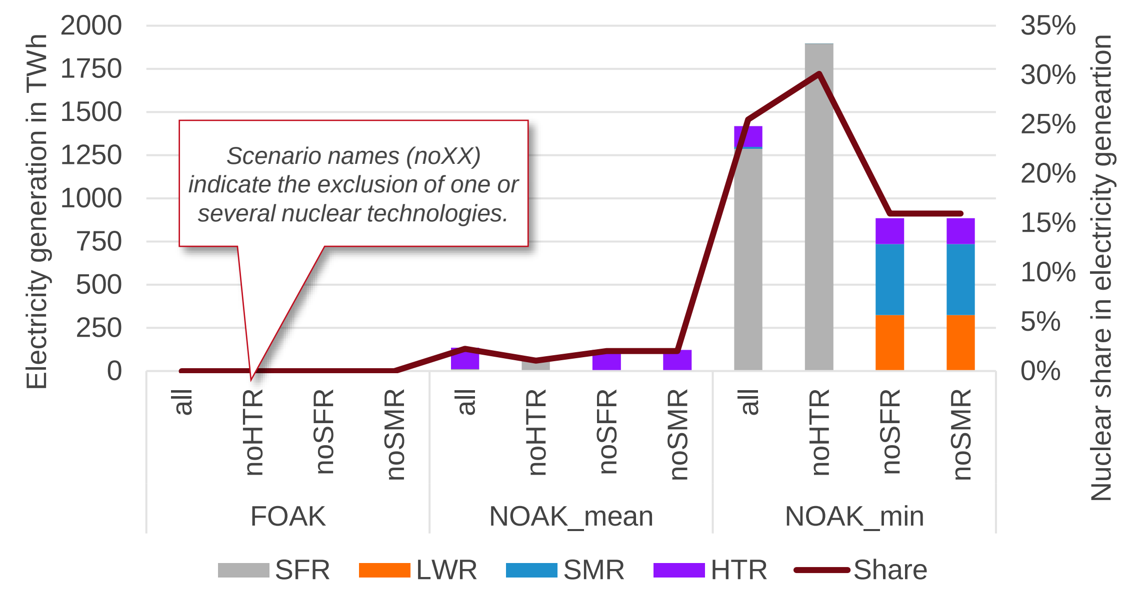
Major Assumptions

- Nuclear power plants can flexibly switch between heat or electricity provision (limit is 90% heat and 10% electricity) and are built without size constraints (capacity, not reactors, is added)
- Full flexibility for nuclear power plants -> no ramp-up
- All operational parameters are “nuclear optimistic”, i.e. they favor the implementation of nuclear power
- Integrated European energy system that is fully decarbonized in heat, transport, electricity
- Greenfield approach for 2040, 4392-hr resolution
- For nuclear power plants, there are no cycling constraints from, e.g., refueling or safety inspections
- Four “nuclear technologies”: high-capacity LWRs (district heat), SMR (low process heat), SFRs (medium process heat), HTRs (medium and high process heat)

References: Göke (2021), Göke et al. (2023)

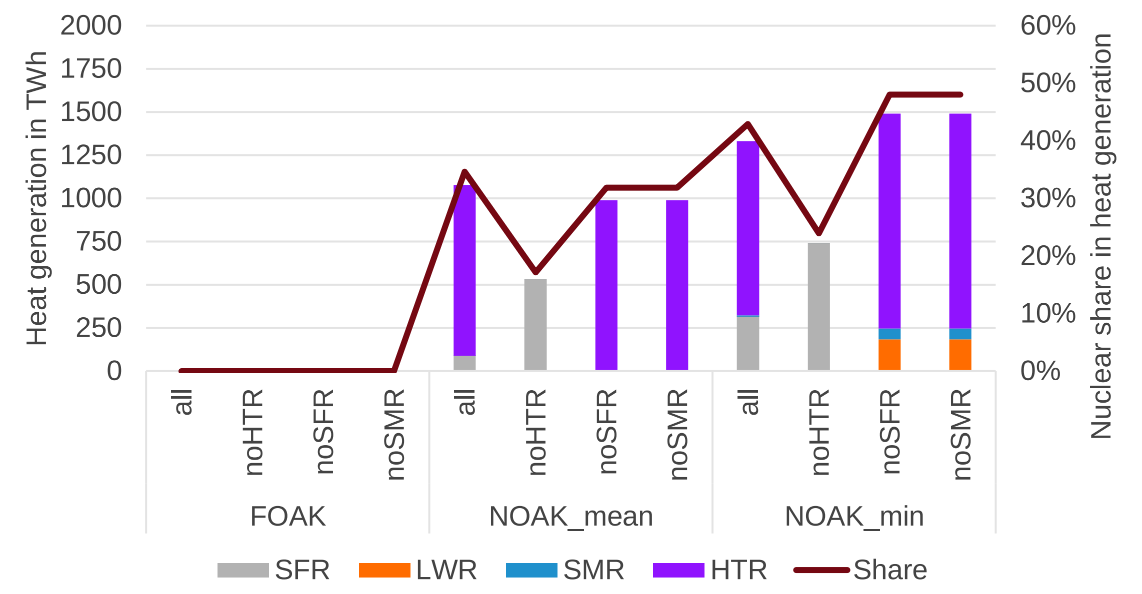
Results | Heat and electricity generation is dominated by (at least from the assumptions) cheap HTRs and SFRs that can provide valuable heat

Electricity generation



Scenario names (noXX) indicate the exclusion of one or several nuclear technologies.

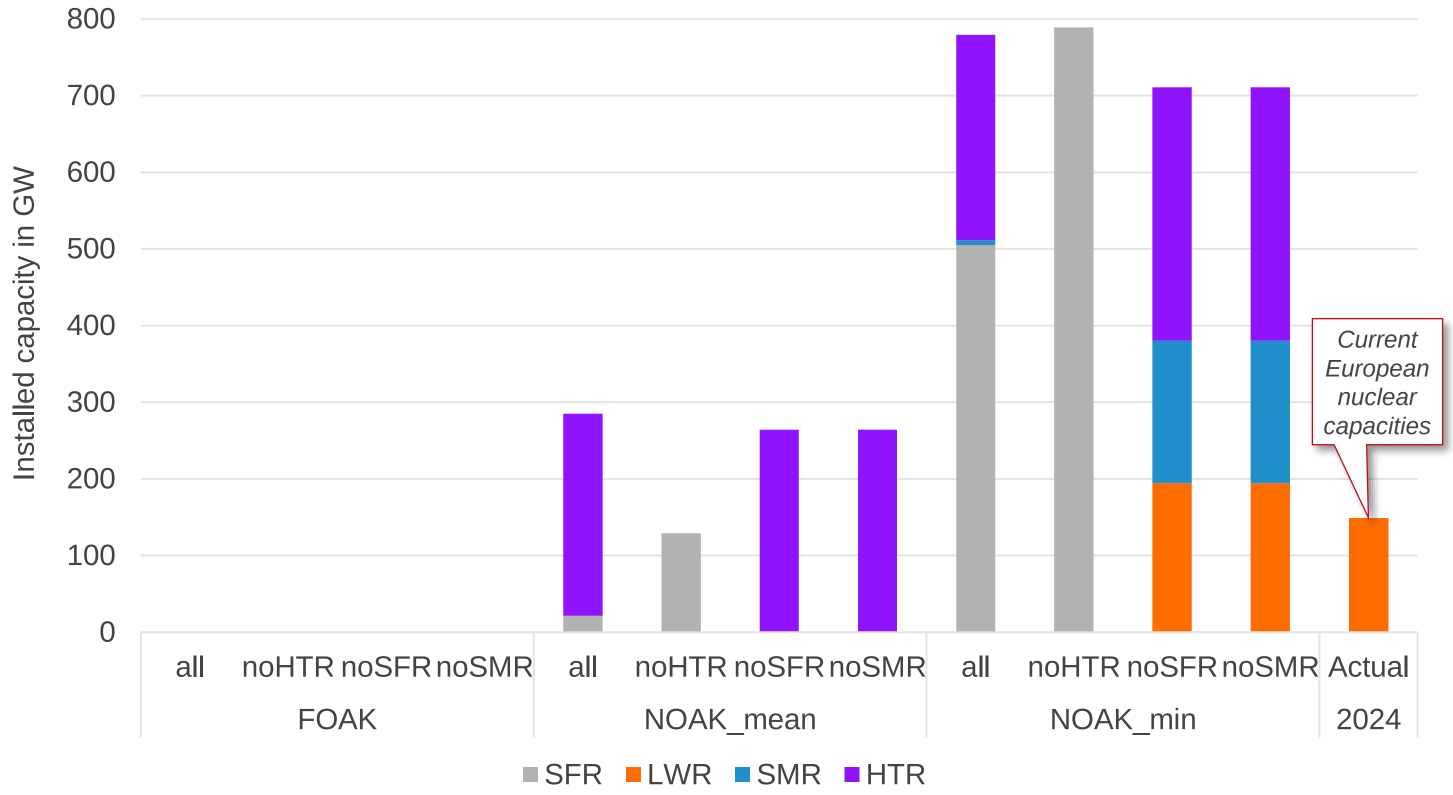
Heat generation



For **FOAK costs**, **no type of reactor** is chosen by the cost-optimizing model. At mean estimates of **NOAK cos**t, **HTRs** begin to provide a **substantial share of heat** (medium heat ≈ high heat), but electricity is still mostly provided by other sources. If HTRs are excluded, they are somewhat substituted by SFRs. Only at the **lowest observed cost estimates** per technology does the **share of electricity generation increase**. When SFRs are excluded, LWRs and SMRs are added. Otherwise, these technologies are obsolete.

Results | The distribution of built capacity mirrors the generation of energy – the nuclear fleet is dominated by HTRs and SFRs

Installed capacity in GW



Current European nuclear capacities

Comment

- In the NOAK_mean scenarios, most capacity is used to supply heat (low and medium)
- In the NOAK_min scenarios, capacities are expanded significantly and then also used to generate electricity alongside heat
- Only when SFRs are excluded, are LWRs and SMRs built – this likely stems from the value of high and medium process heat
- Compared to current European nuclear capacities (168 reactors with 148.7 GW capacity (IAEA 2024), only LWRs!), these expansions are unrealistic

Conclusion and Outlook

Conclusion

- We find that there exist many assumptions and projections for the future costs of non-light water reactors technologies that go back decades
- While these assumptions are all made for hypothetical reactor concepts that do not exist, they will likely be much too low compared to actual projects (if they are ever realized), analogously to high-capacity LWRs (see Göke et al. (2023))
- Our model shows that overnight construction cost for non-light water reactors must be in the range of NOAK estimates (~ 4400 – 5600 USD per kW) for HTRs to be built for heat provision;
- At even lower cost (~ 1450 – 2500 USD per kW), nuclear energy production becomes very high
- These capacity expansions would have to be built, cost reduction achieved, and we question whether the industry can deliver

Outlook

- Future (and ongoing) research on this work will refine the scenarios and include more reactor availability variations
- A sensitivity analysis on the model outcomes will be conducted regarding the WACC, construction times, operational lifetime, and capacity factors, amongst others
- A more detailed comparison with current new build estimates and ongoing (research) projects for non-light water reactors to assess the feasibility of potentially substantial capacity expansions for these reactor types

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Thank you for your attention.
Questions?

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Appendix A | Non-electrical use cases of reactors – Examples (I/II)

Country	Reactor	Type	Gross Power (MWe)	Heat provided (MWth)	Operational Lifetime	Application	Reference	Comment
Bulgaria	Kozloduy-3	PWR	440	230 (total)	1981-2006	District heat	Kupitz 2001	
Bulgaria	Kozloduy-4	PWR	440	230 (total)	1982-2006	District heat	Kupitz 2001	
Bulgaria	Kozloduy-5	PWR	1100	230 (total)	1988 - today	District heat	Kupitz 2001, 3E News	
Bulgaria	Kozloduy-6	PWR	1100	230 (total)	1993 - today	District heat	Kupitz 2001, 3E News	
Canada	Bruce-3	CANDU	868	840 (total	1978 - today	Process heat	Kupitz, 2001	S.O. from 1995 to 2012
Canada	Bruce-4	CANDU	868	840 (total	1979 - today	Process heat	Kupitz, 2001	S.O. from 1998 to 2004
China	Haiyang-1	PWR	1250	n.a.	2018-today	District heat	Kraev (2021)	
China	Haiyang-2	PWR	1250	n.a.	2019-today	District heat	Kraev (2021)	
Germany	Stade	PWR	630	40	1972 - 2003	Process heat	Kupitz, 2001	
Germany	Greifswald-1	PWR	440	180 (total)	1974-1990	District heat	Kupitz, 2001	
Germany	Greifswald-2	PWR	440	180 (total)	1975-1990	District heat	Kupitz, 2001	
Germany	Greifswald-3	PWR	440	180 (total)	1978-1990	District heat	Kupitz, 2001	
Germany	Greifswald-4	PWR	440	180 (total)	1979-1990	District heat	Kupitz, 2001	
Hungary	Paks-1	PWR	509	55 (total)	1983-today	District heat	Kupitz, 2001, OECD/NEA 2022	
Hungary	Paks-2	PWR	509	55 (total)	1984-today	District heat	Kupitz, 2001, OECD/NEA 2022	
Hungary	Paks-3	PWR	509	55 (total)	1986-today	District heat	Kupitz, 2001, OECD/NEA 2022	
Hungary	Paks-4	PWR	509	55 (total)	1987-today	District heat	Kupitz, 2001, OECD/NEA 2022	
India	Madras 1	PHWR	205		1983-	Desalination	WNA (2020)	
India	Madras 2	PHWR	205		1985-today	Desalination	WNA (2020)	
Japan	Ikata-1	PWR	566		1977-2016	Desalination	Faibish et al 2002	
Japan	Ikata-2	PWR	566		1982-2018	Desalination	Faibish et al 2002	
Japan	Ikata 3	PWR	890		1994 - today	Desalination	Faibish et al 2002	
Japan	Ohi-1	PWR	1175		1979-2018	Desalination	Faibish et al 2002	

Appendix A | Non-electrical use cases of reactors – Examples (II/II)

Country	Reactor	Type	Gross Power (MWe)	Heat provided (MWth)	Operational Lifetime	Application	Reference
Japan	Ohi-2	PWR	1175		1979-2018	Desalination	Faibish et al 2002
Japan	Ohi-3	PWR	1180		1991 - today	Desalination	Faibish et al 2002
Japan	Ohi-4	PWR	1180		1993 - today	Desalination	Faibish et al 2002
Russia	Bilibino-1	LWGR	12	19	1974-2019	District heat	Kupitz, 2001
Russia	Bilibino-2	LWGR	12	19	1975-today	District heat	Kupitz, 2001
Russia	Bilibino-3	LWGR	12	19	1976-today	District heat	Kupitz, 2001
Russia	Bilibino-4	LWGR	12	19	1977-today	District heat	Kupitz, 2001
Russia	VK-50	BWR	50	n.a.		District heat	Kupitz, 2001
Slovakia	Bohunice-3	PWR	500	240 (total)	1985-today	District heat	Kupitz, 2001
Slovakia	Bohunice-4	PWR	500	240 (total)	1985-today	District heat	Kupitz, 2001
Sweden	Agesta	PHWR	12	55-68	1964-1974	District heat	Kupitz, 2001, Leppanen 2019
Switzerland	Beznau-1	PWR	380	80	1969 - today	District and process heat	Kupitz, 2001, OECD/NEA 2022
Switzerland	Beznau-2	PWR	380	80	1972 - today	District and process heat	Kupitz, 2001, OECD/NEA 2022
Switzerland	Gösgen	PWR	1060	n.a.	1979-today	Process heat	Kupitz, 2001
U.K.	Calder Hall 1-4	GCR	60	n.a.	1956-2006	Process heat	Kupitz, 2001
U.S.	Diablo Canyon-1	PWR	1197	n.a.	1985-today	Desalination	Kupitz, 2001
U.S.	Diablo Canyon-2	PWR	1197	n.a.	1986-today	Desalination	Kupitz, 2001
Ukraine	Rivne-1	PWR	420	291 (Total)	1981-today	District heat	Kupitz, 2001
Ukraine	Rivne-2	PWR	415	291 (Total)	1982-today	District heat	Kupitz, 2001
Ukraine	Rivne-3	PWR	1000	291 (Total)	1987-today	District heat	Kupitz, 2001

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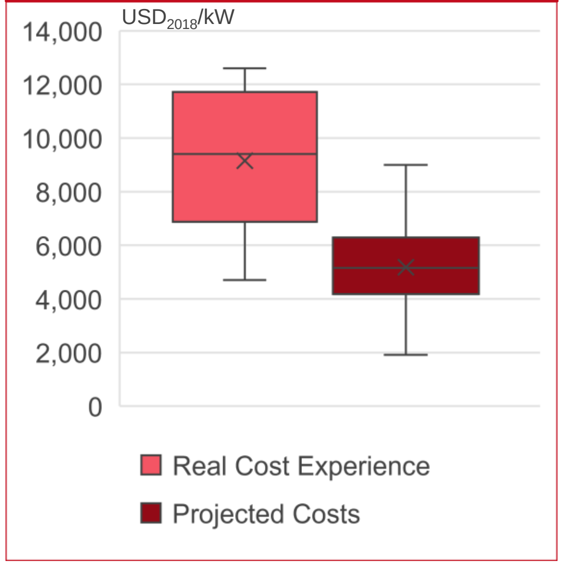
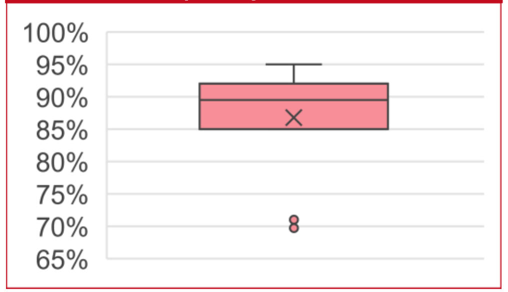
Appendix B | Cost analysis for LWRs from Göke et al. (2023) as presented at Enerday 2023*

- 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

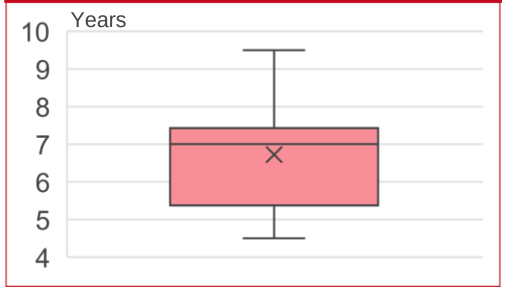
Reported OCC values for LWRs in OECD countries



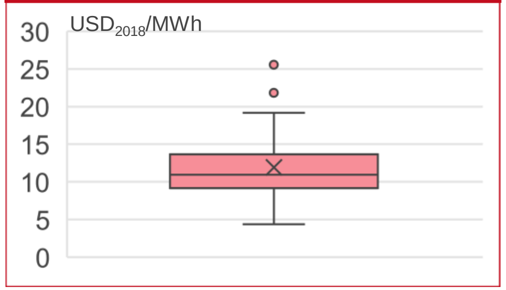
Capacity Factor



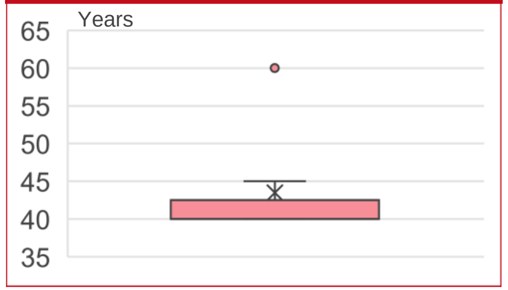
Construction Time



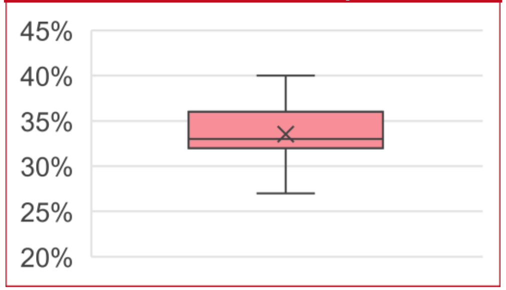
Fuel Cost



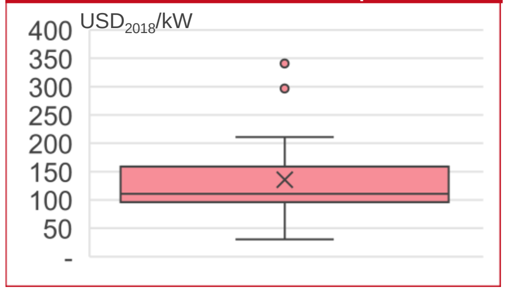
Lifetime



Plant efficiency

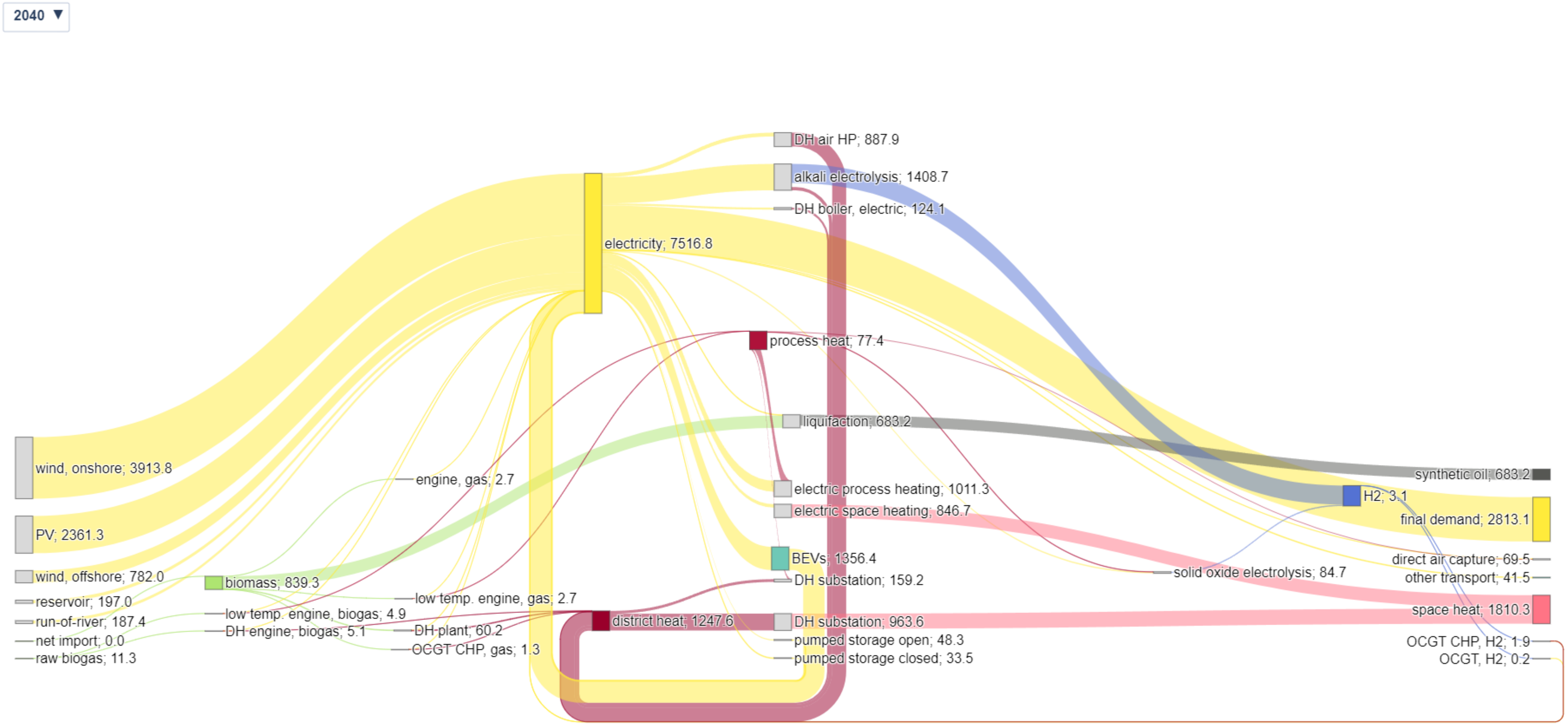


Combined O&M Cost per kW

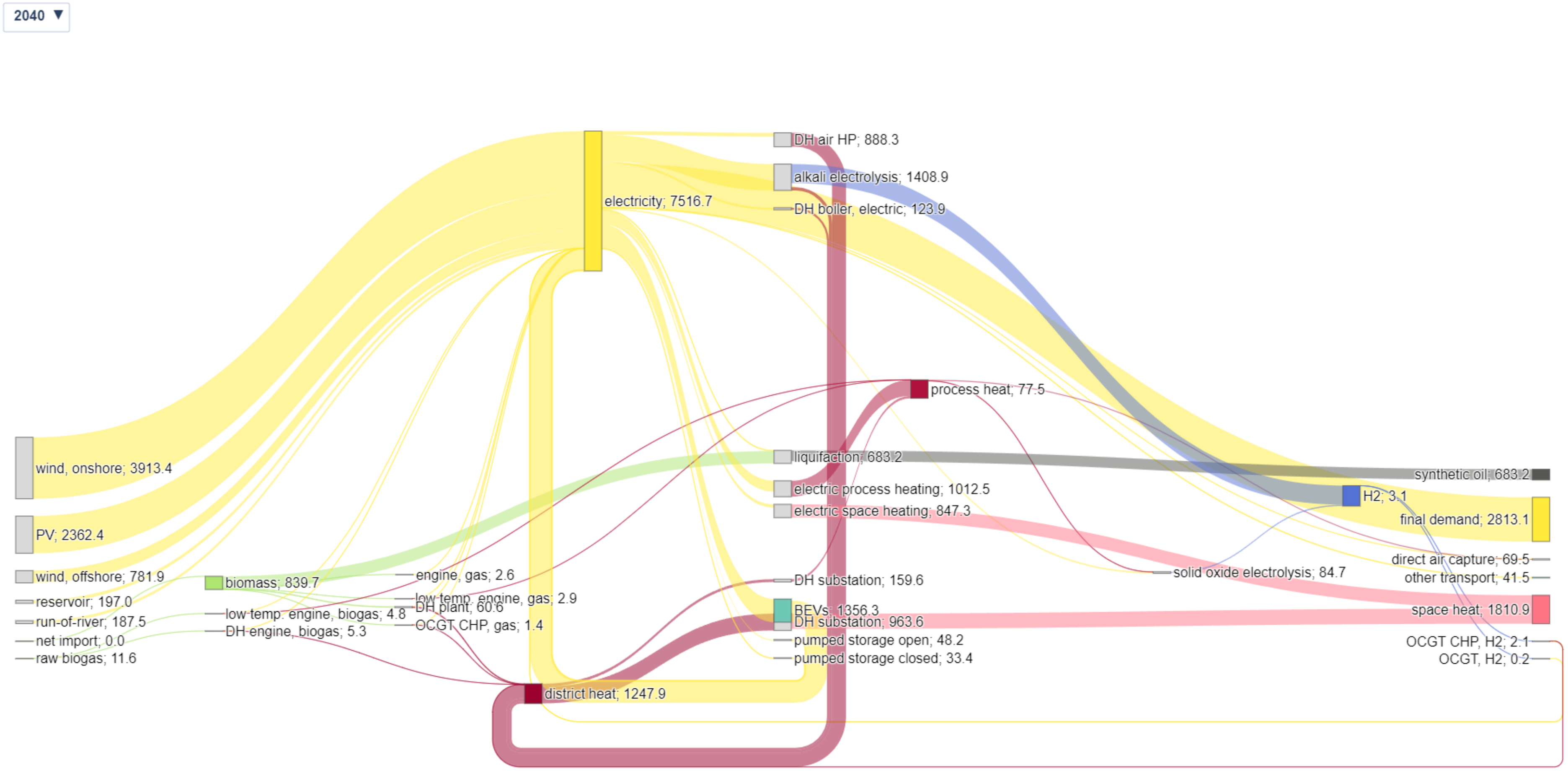


*https://tu-dresden.de/bu/wirtschaft/bwl/ee2/ressourcen/dateien/tagungen/enerday/enerday-2023/technology-assessment/Technology-Assessment-Alexander-Wimmers.pdf?lang=de.

Appendix C | Sankeys | FOAK_all

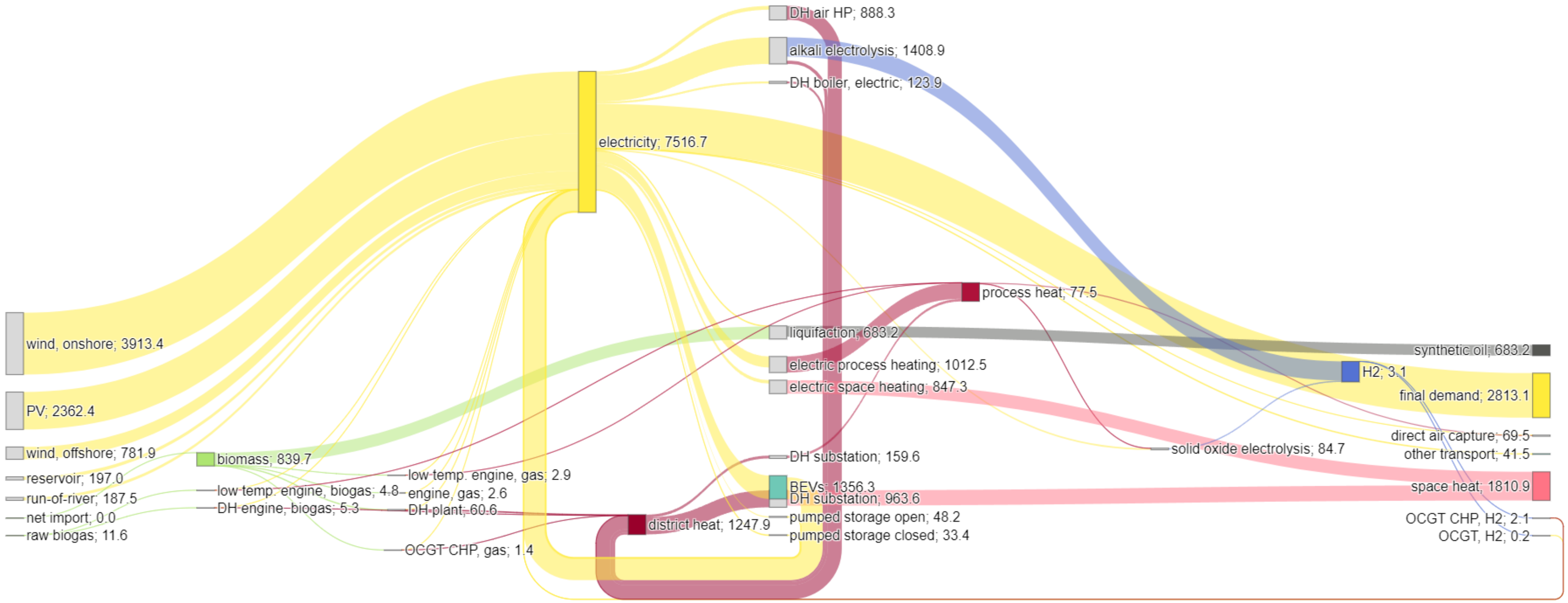


Appendix C | Sankeys | FOAK_noSFR



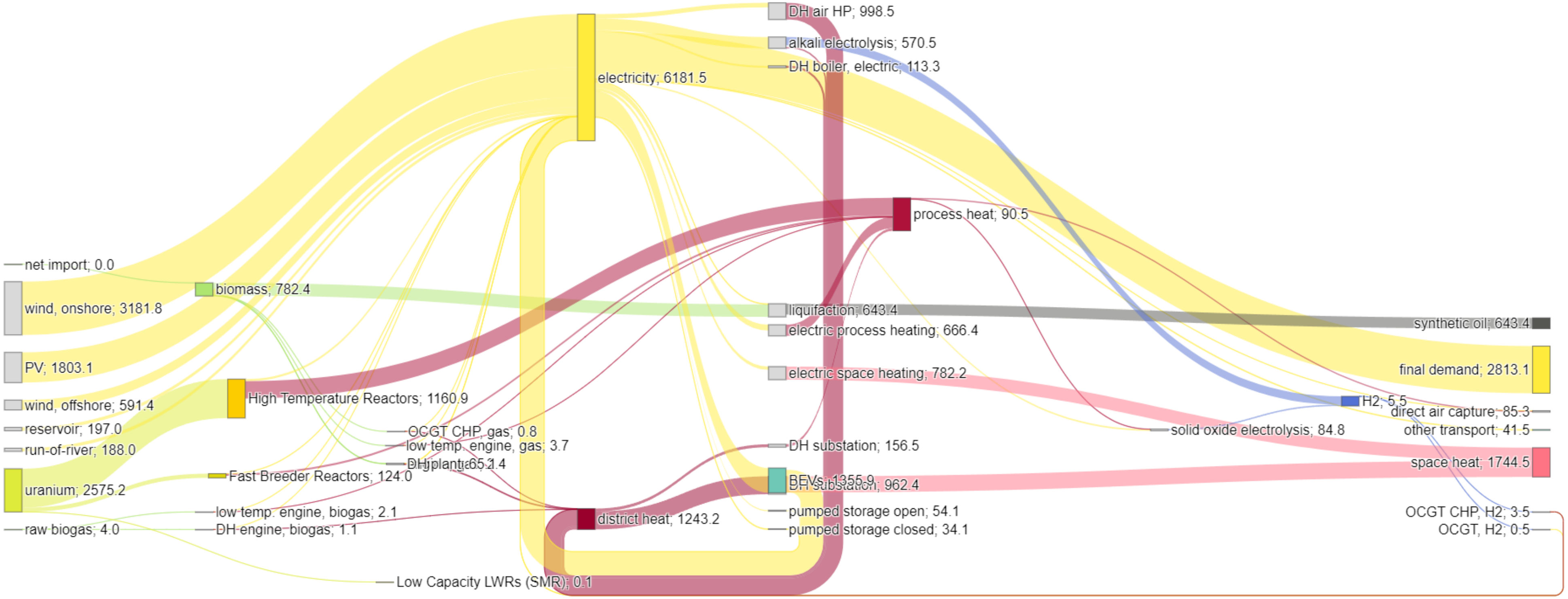
Appendix C | Sankeys | FOAK_noSMR

2040 ▼

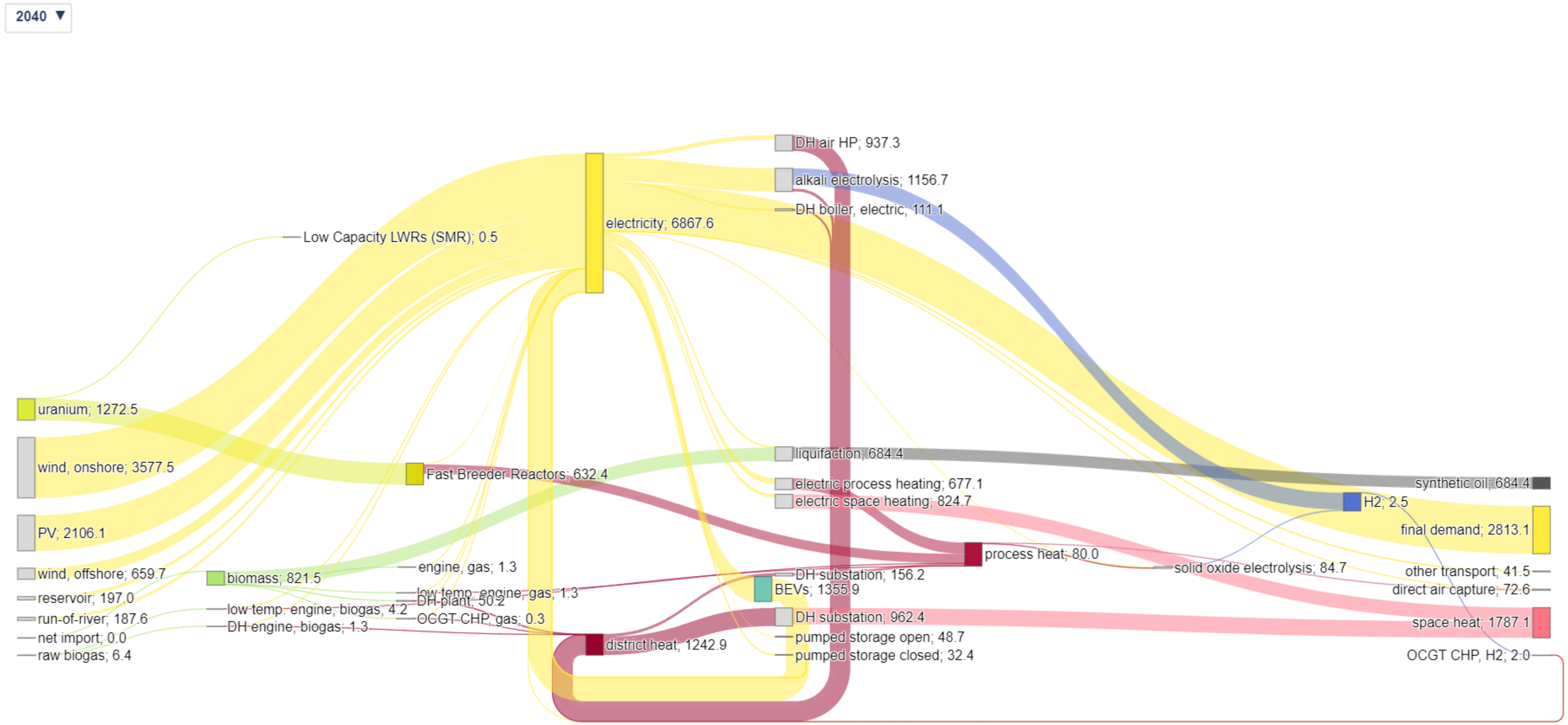


Appendix C | Sankeys | NOAK_mean_all

2040 ▼

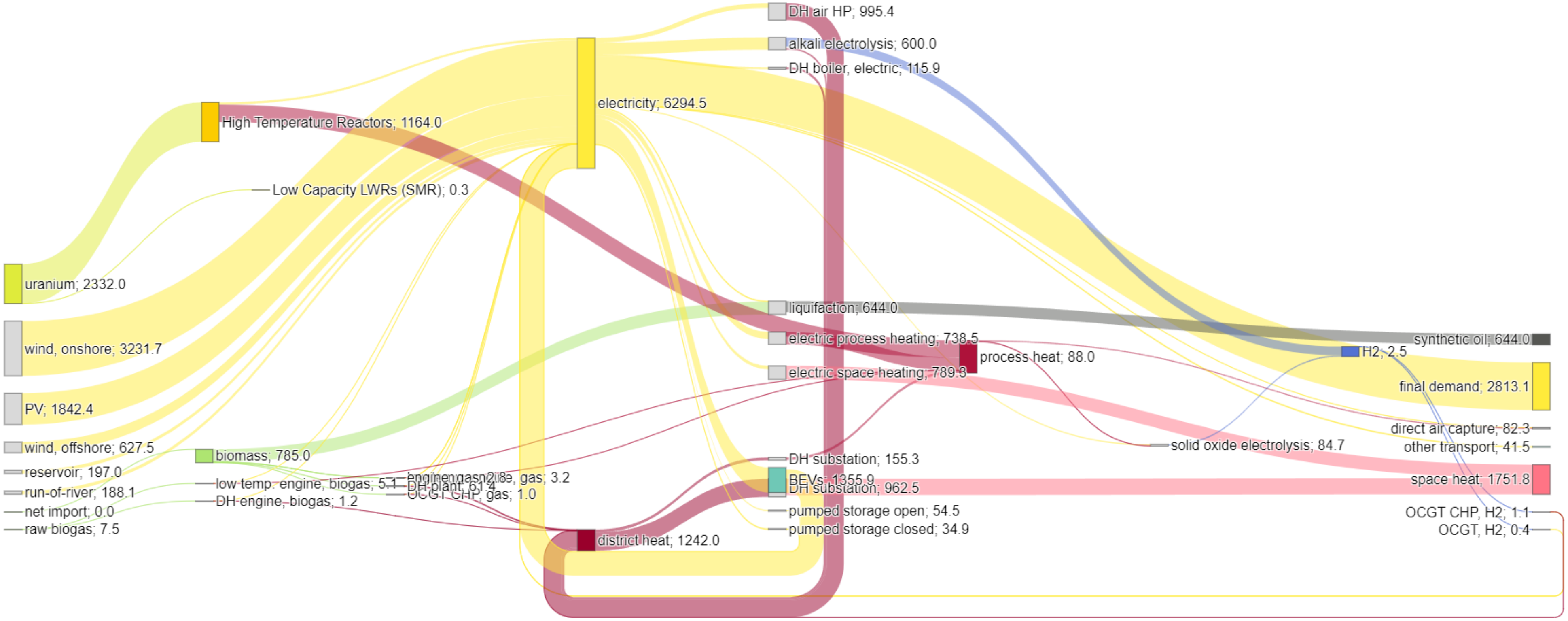


Appendix C | Sankeys | NOAK_mean_noHTR

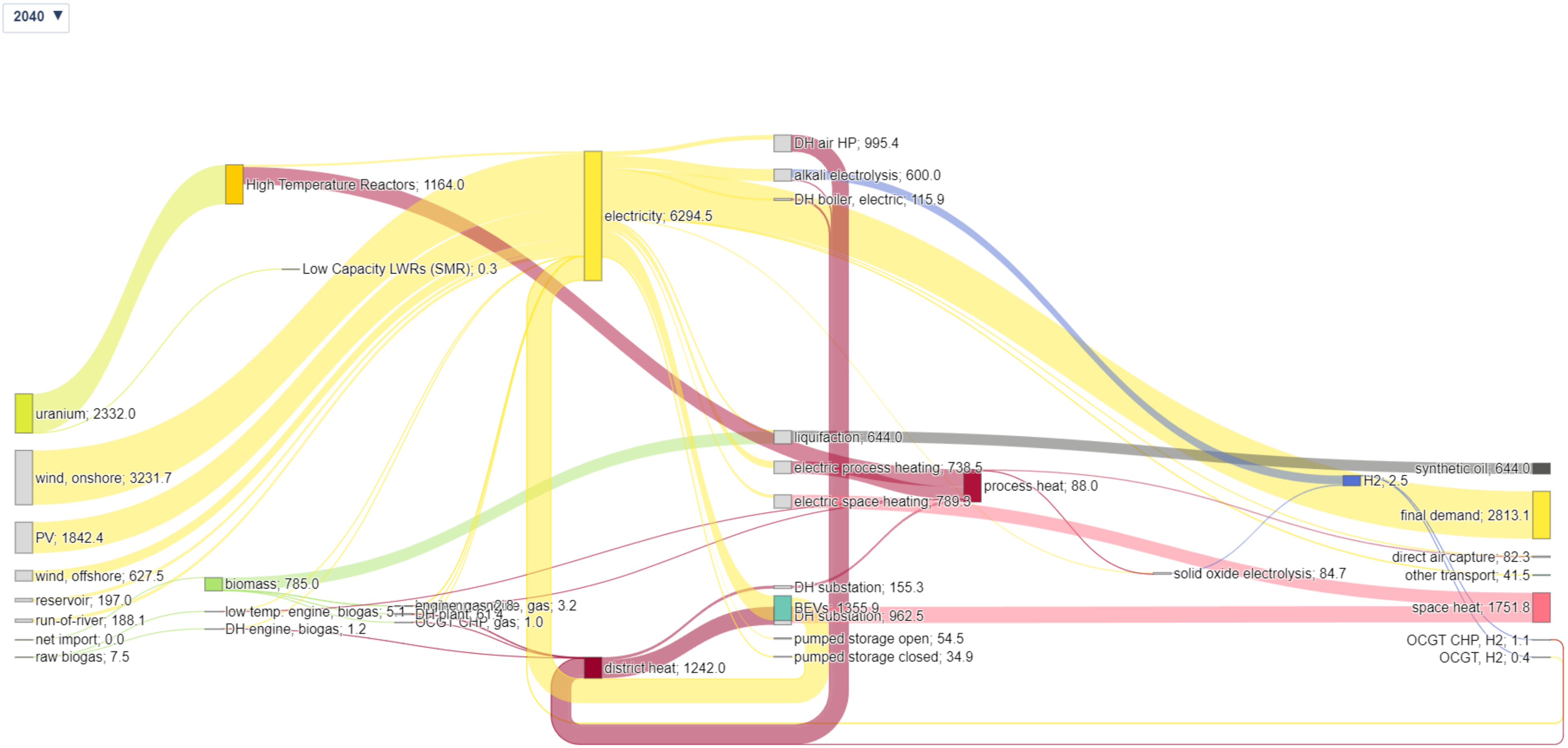


Appendix C | Sankeys | NOAK_mean_noSFR

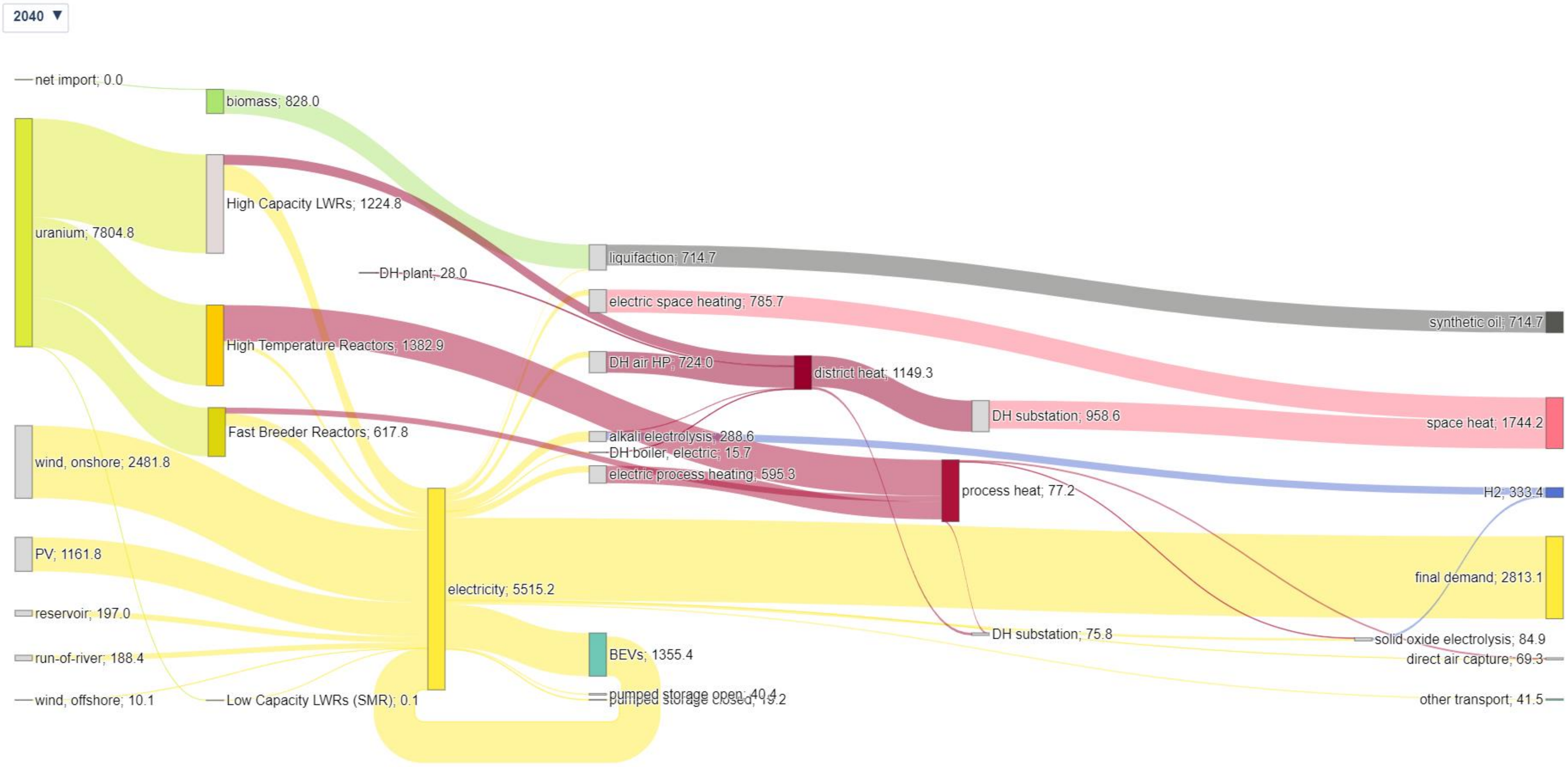
2040 ▼



Appendix C | Sankeys | NOAK_mean_noSMR

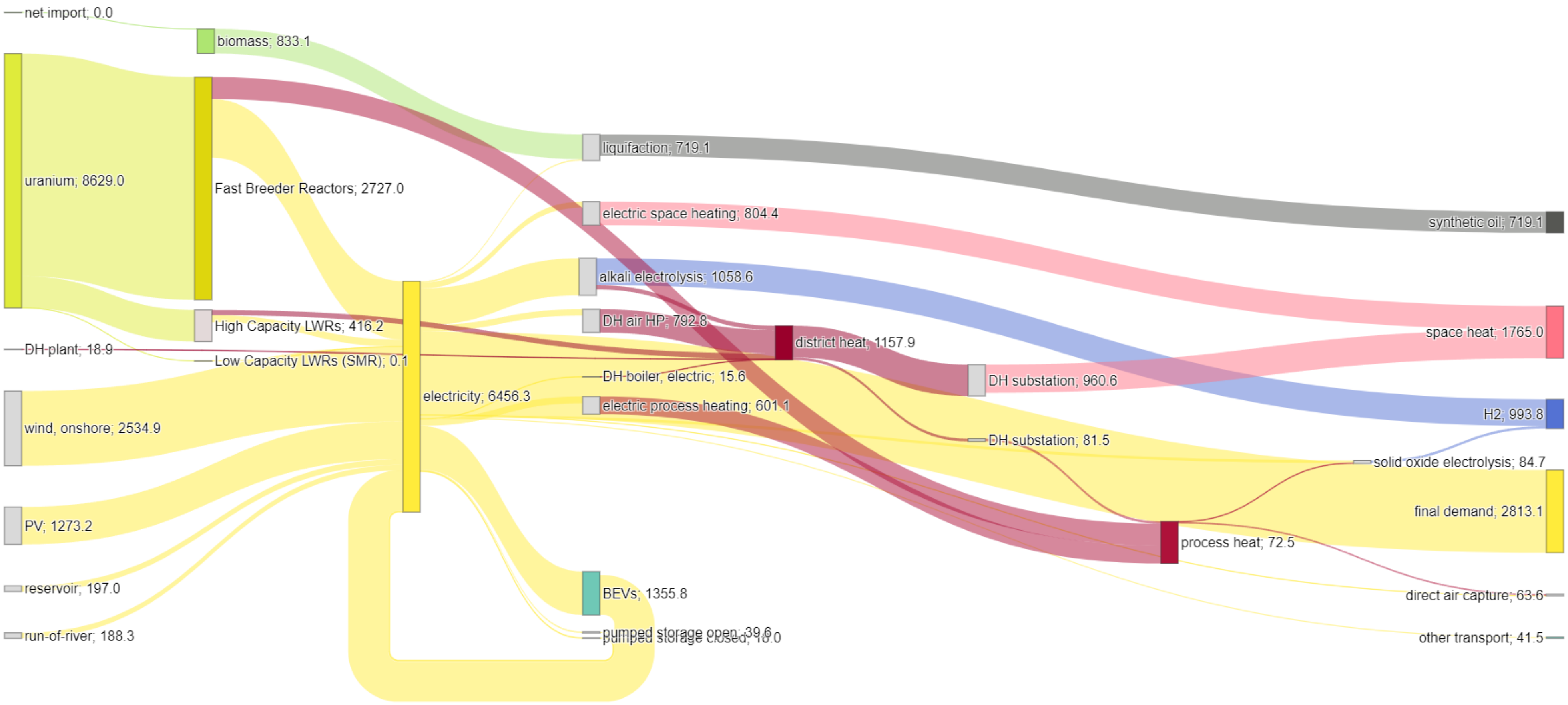


Appendix C | Sankeys | NOAK_min_all

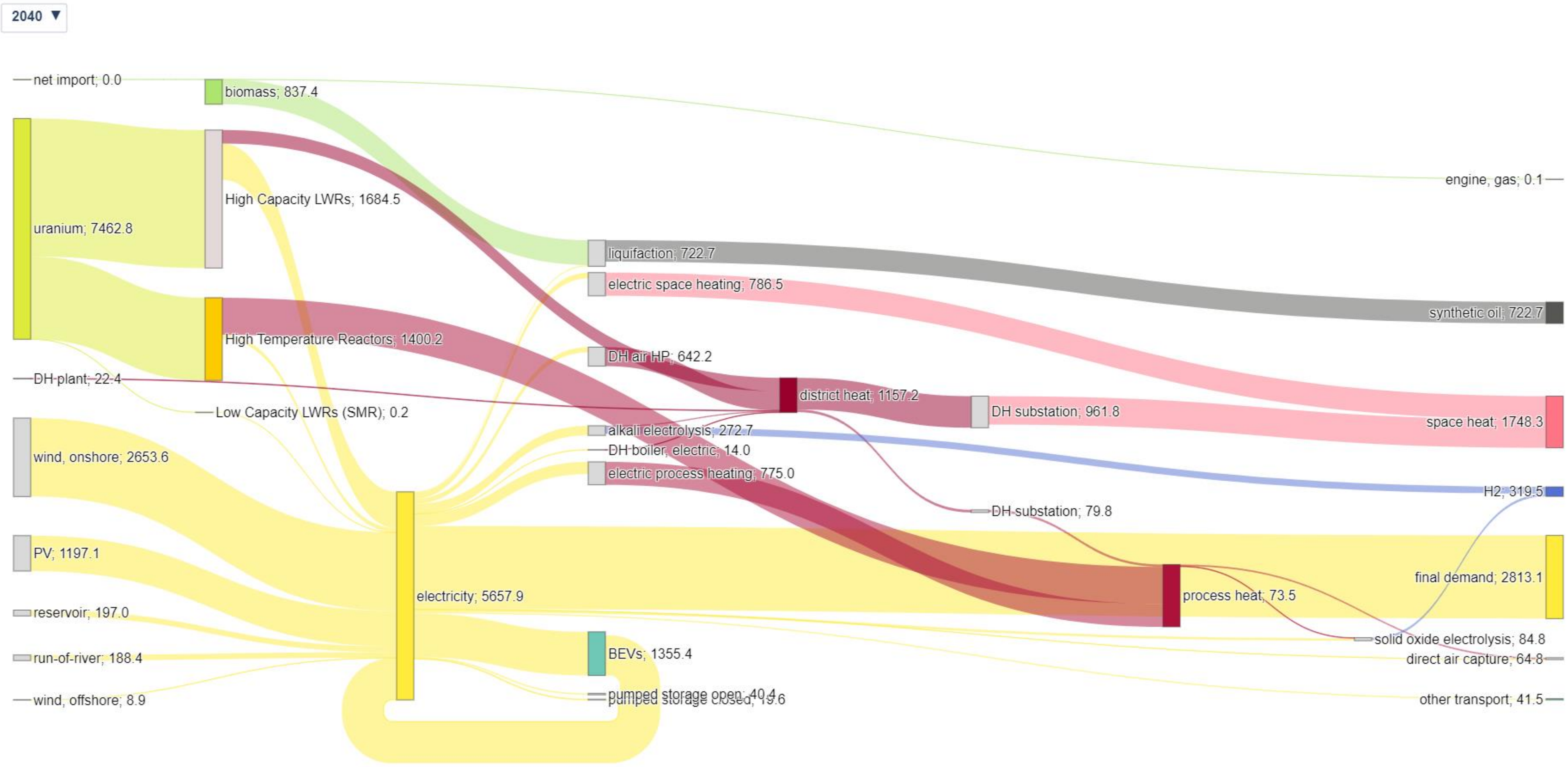


Appendix C | Sankeys | NOAK_min_noHTR

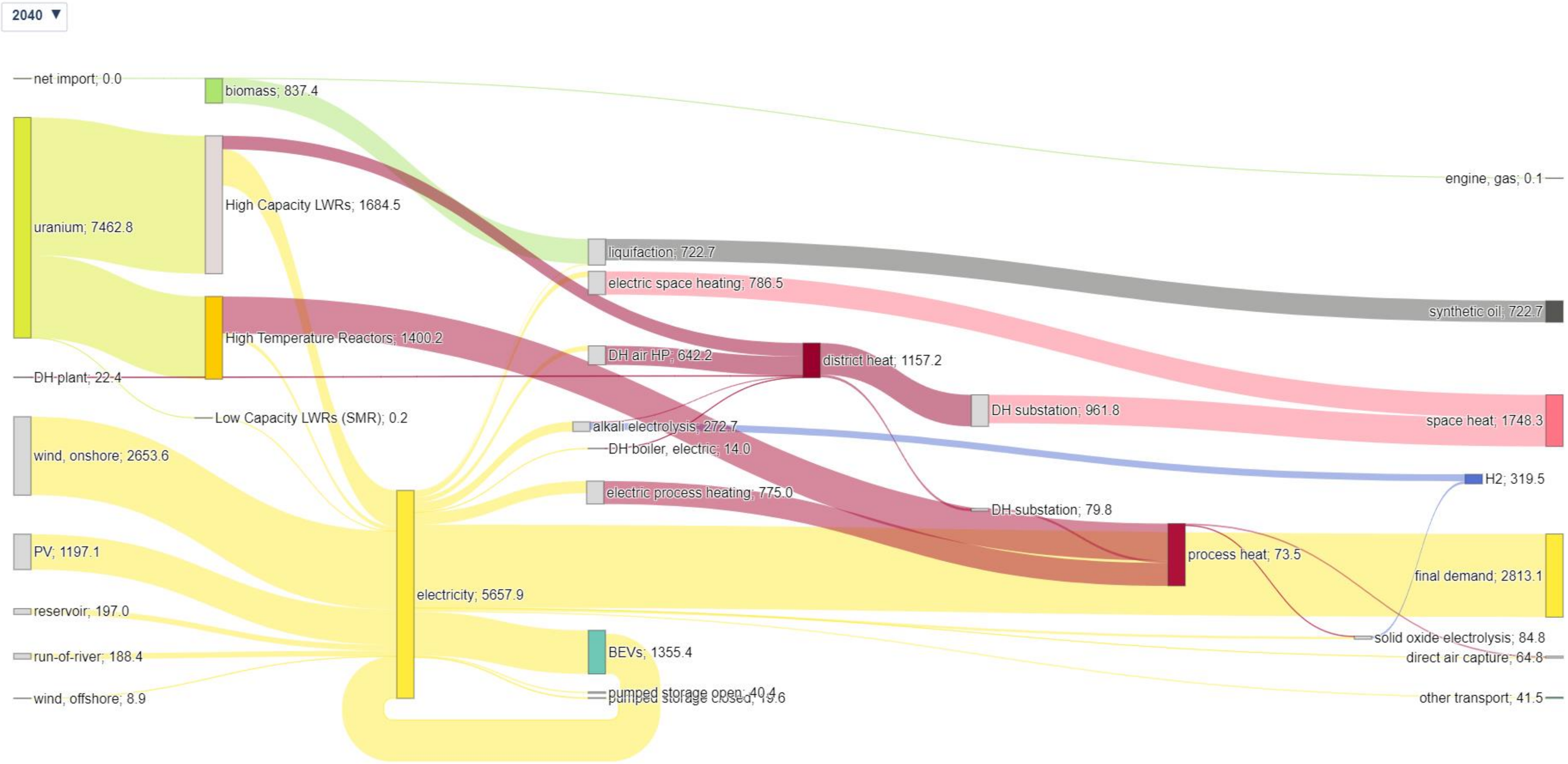
2040 ▼



Appendix C | Sankeys | NOAK_min_noSFR



Appendix C | Sankeys | NOAK_min_noSMR



Appendix D | Input Parameters

Cost type	Reactor	Avg. Capacity (El) (MW)	OCC (USD/kWe)	WACC	Construction Time in years	idc	TCC (USD/kWe)	Lifetime in years	Fuel Cost (USD/MWh)	Capacity Factor	O&M Combined (USD/MWh)
FOAK	SFR	1021.76	9511.466667	10%	7	0.08268707	10297.942	40	11.9026949	0.9	50.4819888
FOAK	LWR-SMR	332.083333	9241.424167	10%	7	0.08268707	10005.5705	40	11.9026949	0.9	47.48862
FOAK	HTR	432.825	9438.519792	10%	7	0.08268707	10218.9634	40	11.9026949	0.9	45.2862263
FOAK	LWR	991.666667	5622.9	10%	7	0.08268707	6087.84115	40	11.9026949	0.9	27.0337039
NOAK	SFR	1120.96	4677.966	10%	7	0.08268707	5064.77332	40	9.16412926	0.9	19.9333169
NOAK	LWR-SMR	590.2	4407.506	10%	7	0.08268707	4771.94978	40	9.16412926	0.9	20.824721
NOAK	HTR	606.040909	5649.653453	10%	7	0.08268707	6116.80677	40	9.16412926	0.9	33.6517708
NOAK	LWR	1121.25	4983.7825	10%	7	0.08268707	5395.8769	40	9.16412926	0.9	20.4450128
NOAK_min	SFR	1120.96	1476	10%	7	0.08268707	1598.04612	40	9.16412926	0.9	13.3127352
NOAK_min	LWR-SMR	590.2	1940	10%	7	0.08268707	2100.41293	40	9.16412926	0.9	15.049721
NOAK_min	HTR	606.040909	2501.33	10%	7	0.08268707	2708.15766	40	9.16412926	0.9	3.12865089
NOAK_min	LWR	1121.25	1782.62	10%	7	0.08268707	1930.01963	40	9.16412926	0.9	8.37201421