Power sector impacts of a simultaneous European heat pump rollout

Alexander Roth
German Institute of Economic Research (DIW Berlin) & TU Berlin

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GEFÖRDERT VOM
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Die Zukunft unserer Energie

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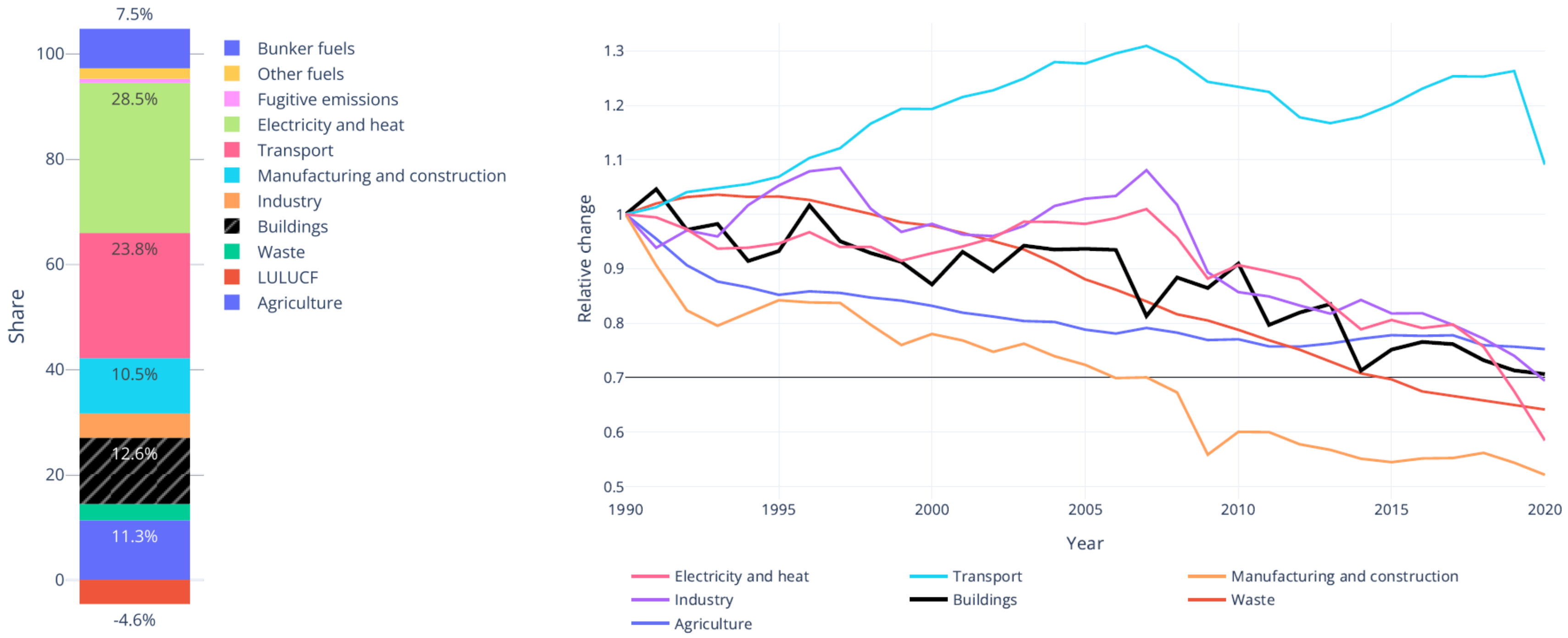
Importance of heating for decarbonization



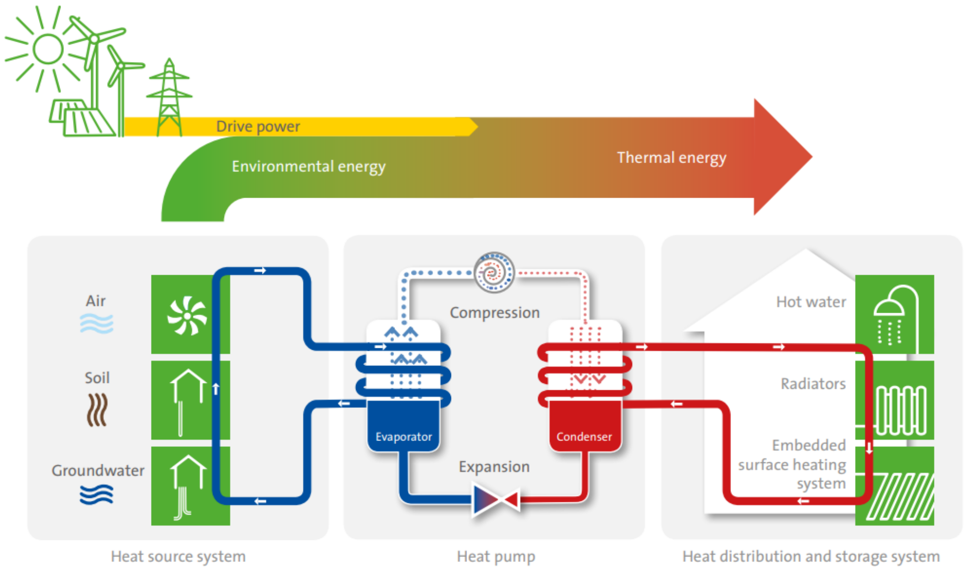
Share in 2019

Relative development (1990 = 1)

Sectoral GHG emissions in the EU 27

Source: Own illustration based on Ritchie et al. (2023)

Heat pumps are central technology



Working principle of a heat pump

Source: European Heating Market Report 2021 (EHI)

Country	Year	Target
European Union	2030	30 million additional heat pumps installed compared with 2022
Belgium	2030	Final energy consumption by heat pumps to increase fivefold over 2018
France	2023	Reach 2.7 million to 2.9 million total heat pumps installed
Germany	2024 2030	Install 500 000 heat pumps per year Reach a heat pump stock of 6 million
Hungary	2030	Final energy consumption by heat pumps to increase sixfold over 2020
Italy	2030	Final energy consumption by heat pumps to increase twofold over 2017
Poland	2030	Final energy consumption by heat pumps to increase threefold over 2020
Spain	2030	Final energy consumption by heat pumps to increase sixfold over 2020
United Kingdom	2028	600 000 annual heat pump installations

Sources: European Commission (2022b); France, Ministry of Ecological Transition (2022); Clean Energy Wire (2022); GOV.UK (2020); Government of Italy (2019); Government of Spain (2019); Toleikyte and Carlsson (2021).

Selected European policy targets for heat pump deployment

Source: The Future of Heat Pumps (IEA, 2022)

Pros	Cons
Efficiency	Increase of peak loads
Integration of renewable energy	Increased electricity demand in winter
Direct use of electricity	Local grid needs

Research question

What is the impact of a simultaneous heat pump roll-put in several European countries?

What is impact of flexibility options, namely thermal heat storage?

Model

- Power sector model (DIETER): linear cost-optimization
- Solves for all 8760 consecutive hours of the year

Input

Techno-economic parameters
- Renewable generators
- Storage

Hourly time-series on country level
- RES availability
- Electricity & heat demand and COPs

Transfer capacities

Model

Total system cost → MIN
- Annualized investment costs
- Fixed & variable costs

Subject to
- Demand = Supply
- Heat demand to be satisfied
- Transmission
- …

Output

Investment decisions (capacity)
- Generation
- Storage

Hourly operation (energy)
- Generation & electrolysis dispatch
- Storages operation
- Heat pump electricity intake

Power flows

Assumptions

- **Target year:** 2030
- **Geography:** nine European countries (CH without HP demand)
- **Grid:** copperplate within country, simple exchange between countries; values from ERAA 2021 (year 2025)
- **Weather resilience:** six weather years (2009-2014)

- Capacity bounds from ERAA 2021 (year 2025)
    - Lower bounds for renewables and gas
    - Upper bounds for other fossil generators
    - Hydro and nuclear power fixed
    - Storage (batteries and hydrogen) free
- CO2 price: 150€

Heating assumptions

- Domestic heat covers space and water heat demand
- Share of heat demand to be covered by heat pumps
  → exogenously set to 25%
- Only air-sourced heat pumps
- Same technology and share for single-, multi-family, and commercial buildings
- Run system-friendly: react to wholesale prices
- Assumed to be additional heat demand

Data

- **Heat:** When2Heat database (Ruhnau et al, 2019))
  - Hourly space and water heat demand for all EU countries
  - Hourly COPs for different HP technologies
- **Renewable time series:** PECD 2021.3 (used in ERAA 2021)
  - Wind (on- and offshore), PV, and hydro run-of-river capacity factors
  - Hydro inflow time series reservoir and pumped-hydro
- **Demand:** ERAA 2021 (year 2030)

Scenarios

Definition of *base* scenarios

Heat share	E/P ratio of thermal storage
0%	-
25%	0
25%	2

Heat demand defined as additional heat demand.

Robustness checks

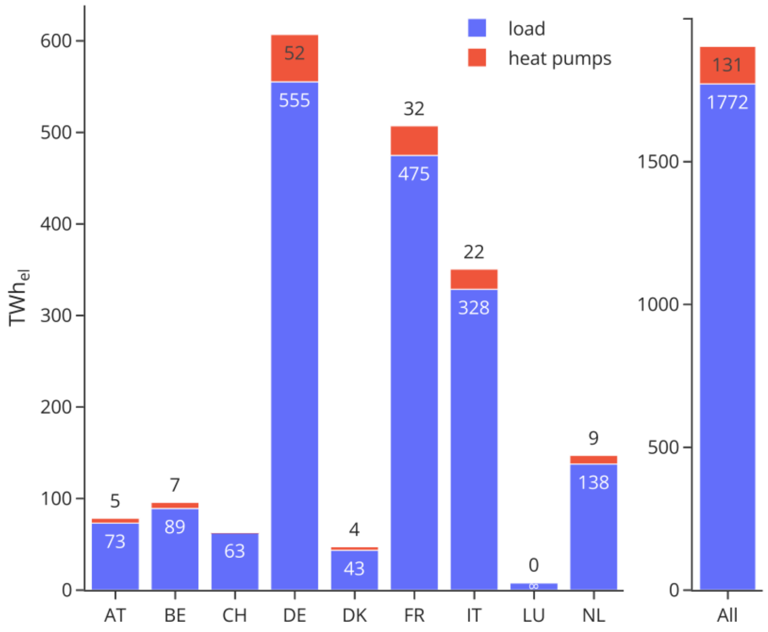
Scenario	Scenario
gas_free	No capacity (lower or upper) for gas-fired power plants.
half_nuc	Nuclear power plant capacities fixed at 50% lower value compared to base.
no_coal	No hard coal or lignite power plants.
no_ntc	No electricity flow between countries.
wind_cap	Upper bounds for on- and offshore wind power capacity at 50% above ERAA 2021 values.

Results

Heat pump capacities and demand

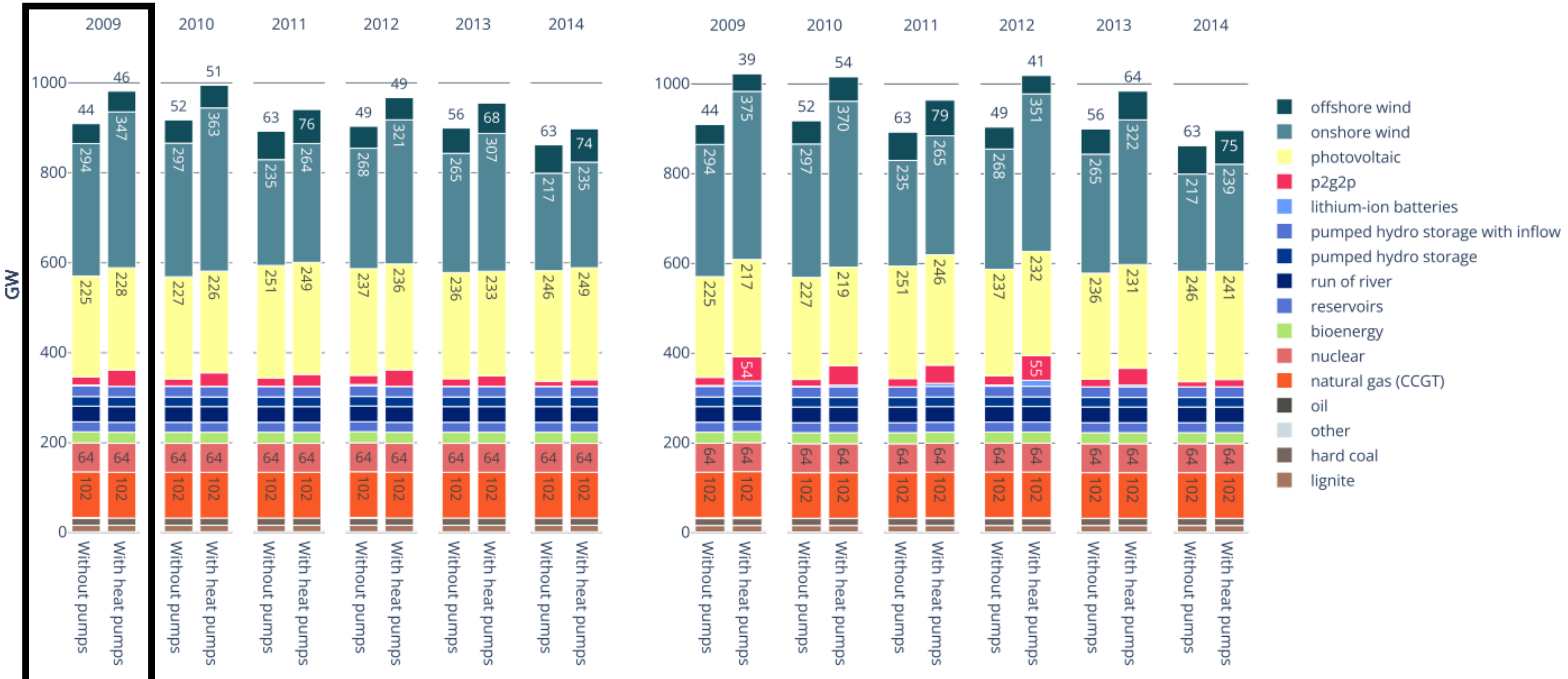
Country	Heat output (GW_{th})	Heat storage (GWh_{th})	Electricity input (GW_{el})
AT	5.5	11.0	3.5
BE	8.8	17.7	5.1
CH	0.0	0.0	0.0
DE	63.8	127.5	39.7
DK	3.9	7.8	1.9
FR	41.1	82.2	20.9
IT	29.2	58.4	13.9
LU	0.7	1.3	0.4
NL	12.5	25.0	6.8
All	165.4	330.9	92.0

Capacities



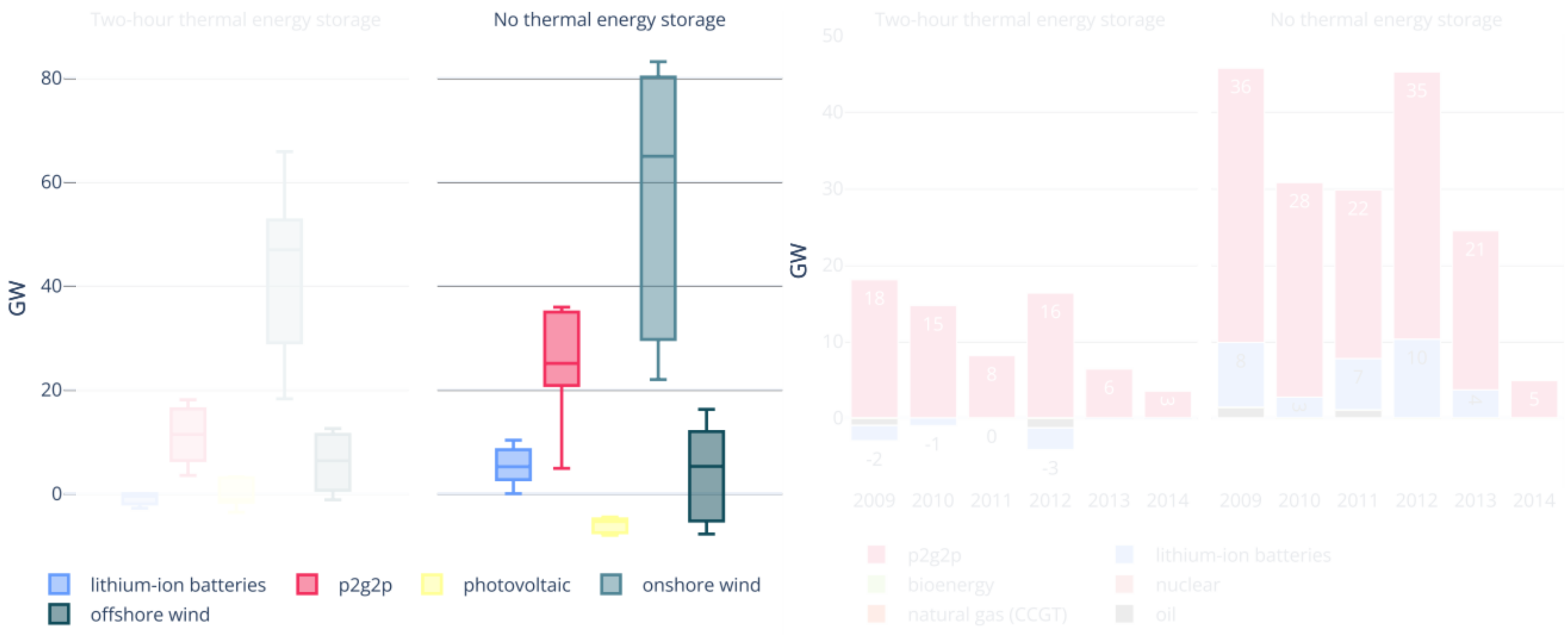
Electricity demand

Capacities



(a) Two hour thermal storage (b) No thermal storage

Additional capacities

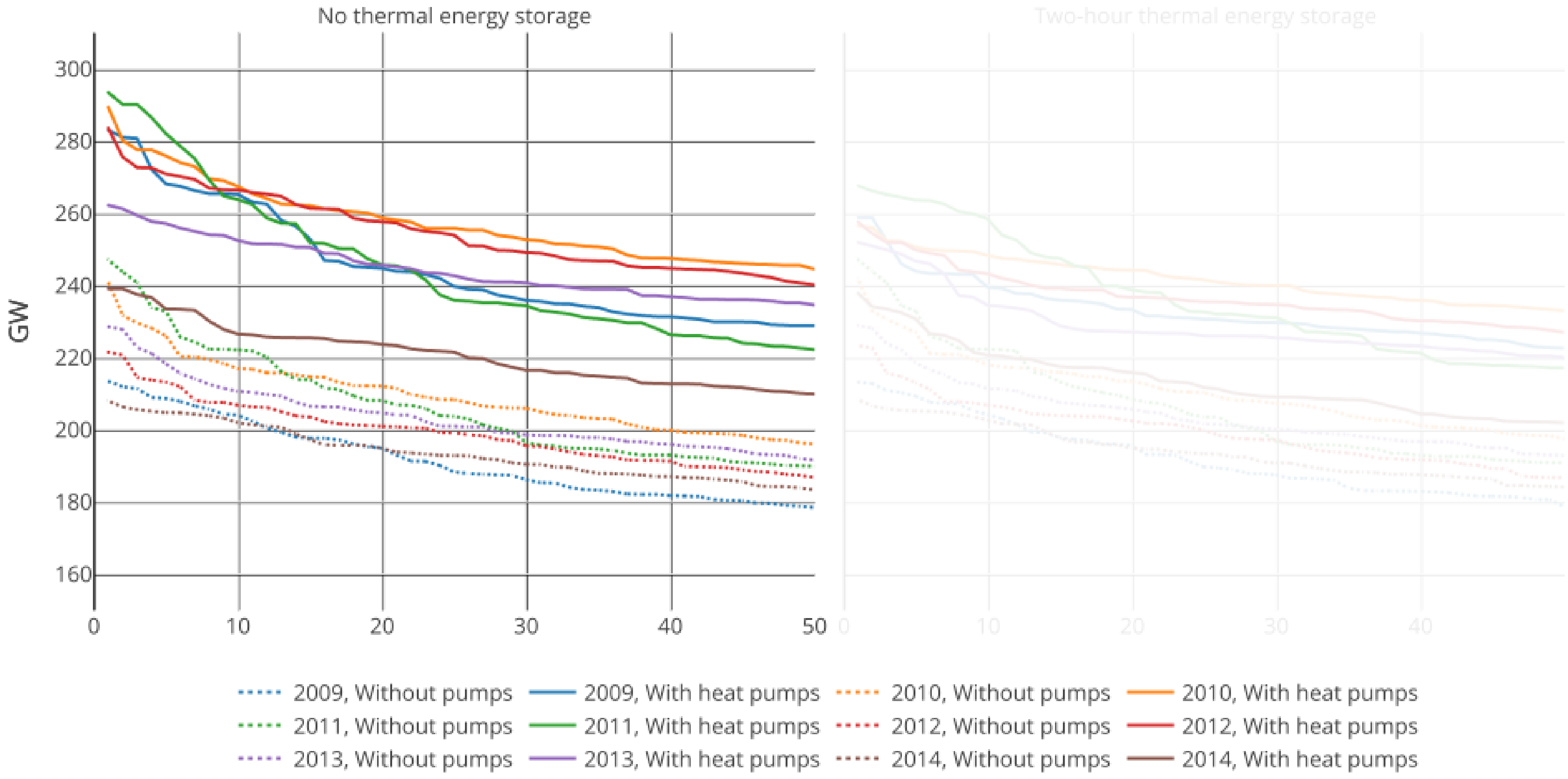


(a) All capacities

(b) Firm capacities, per year

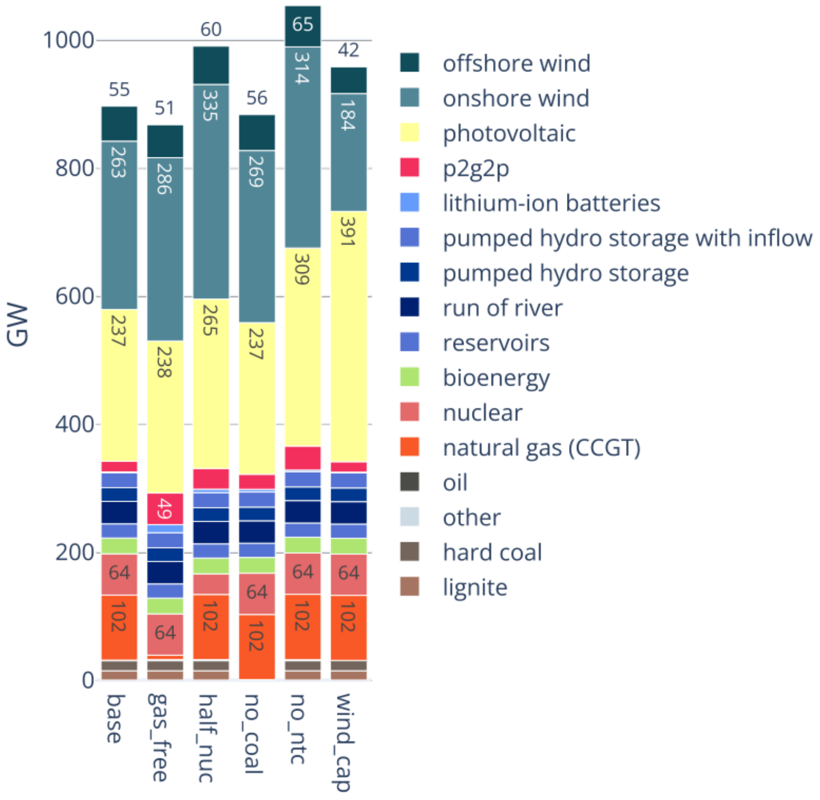
- Wind power expansion
- Additional storage
- Thermal storage:
  - Reduces need for firm capacity
  - Substitute for batteries
- Strong weather variability

Peak loads

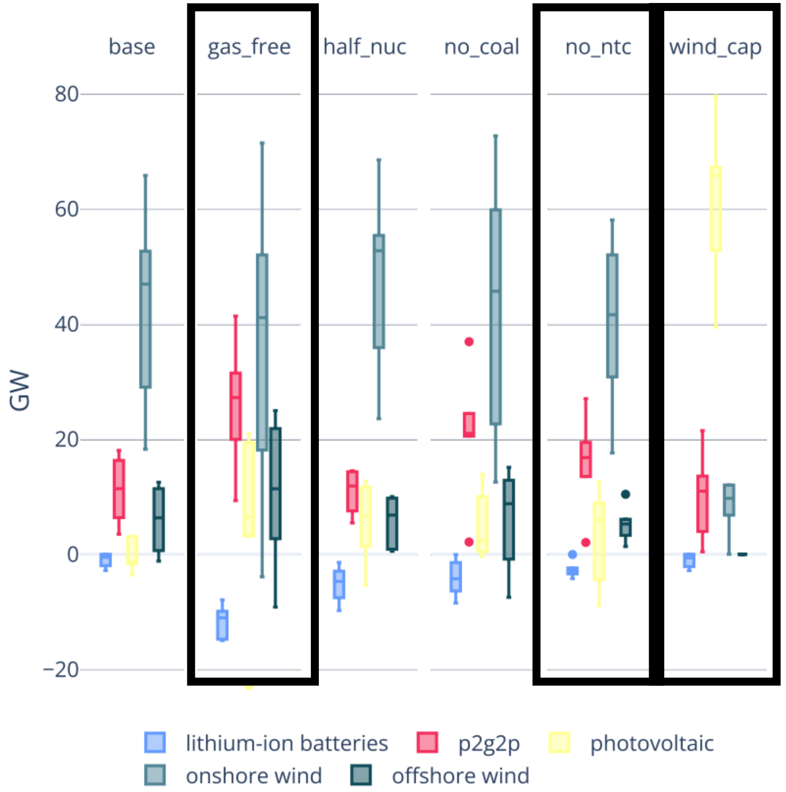


Load duration curves

Robustness: Capacities



Capacities without heat pumps



Additional capacities with heat pumps

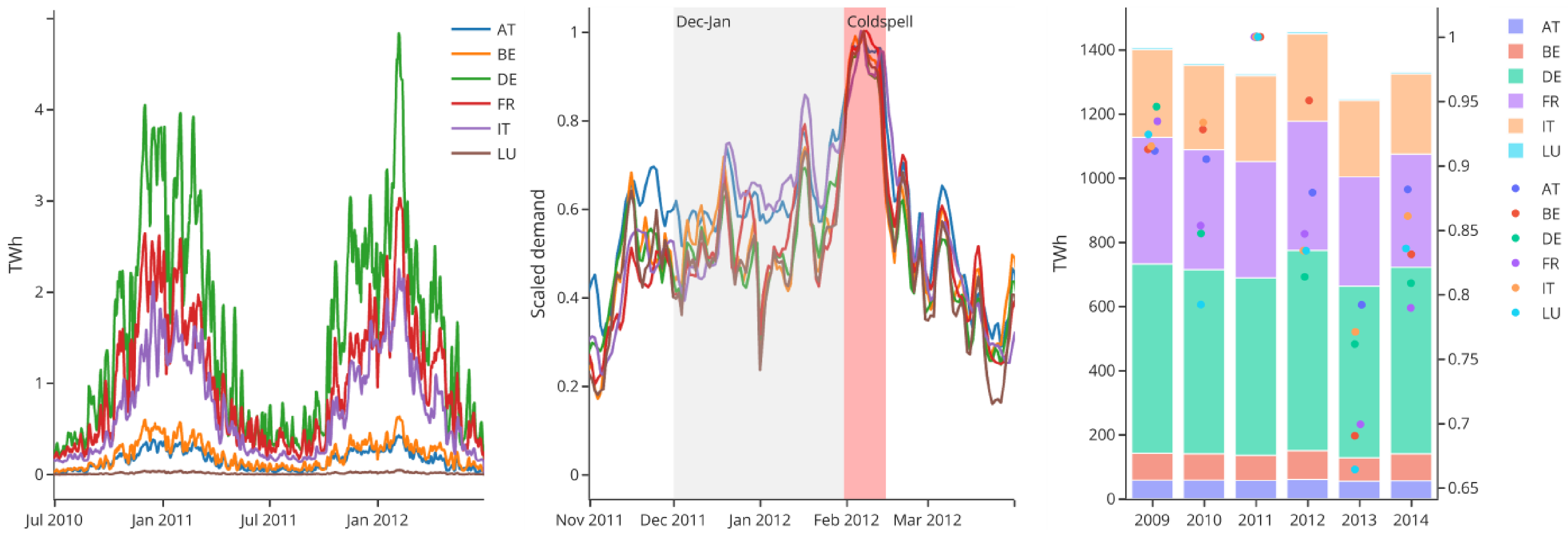
- *gas_free:* additional firm capacites in from of storage
- *no_ntc:* more long-duration storage in general; few changes compared to *base* due to HP expansion
- *wind_cap:* massive PV expansion

System costs

- No interconnection more expansive; yet little impact of HPs
- Wind cap leads to much higher costs

Heating patterns

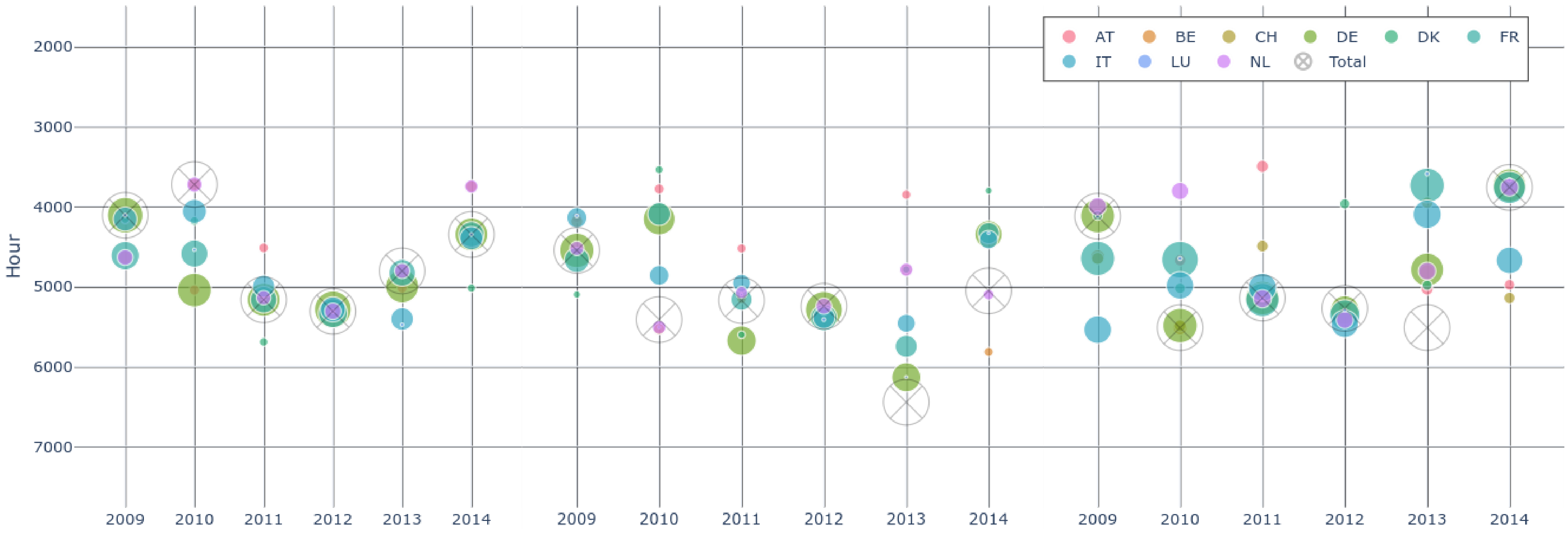
Heating facts



(a) Daily (b) Daily scaled to max. per year (c) Yearly and max. hour

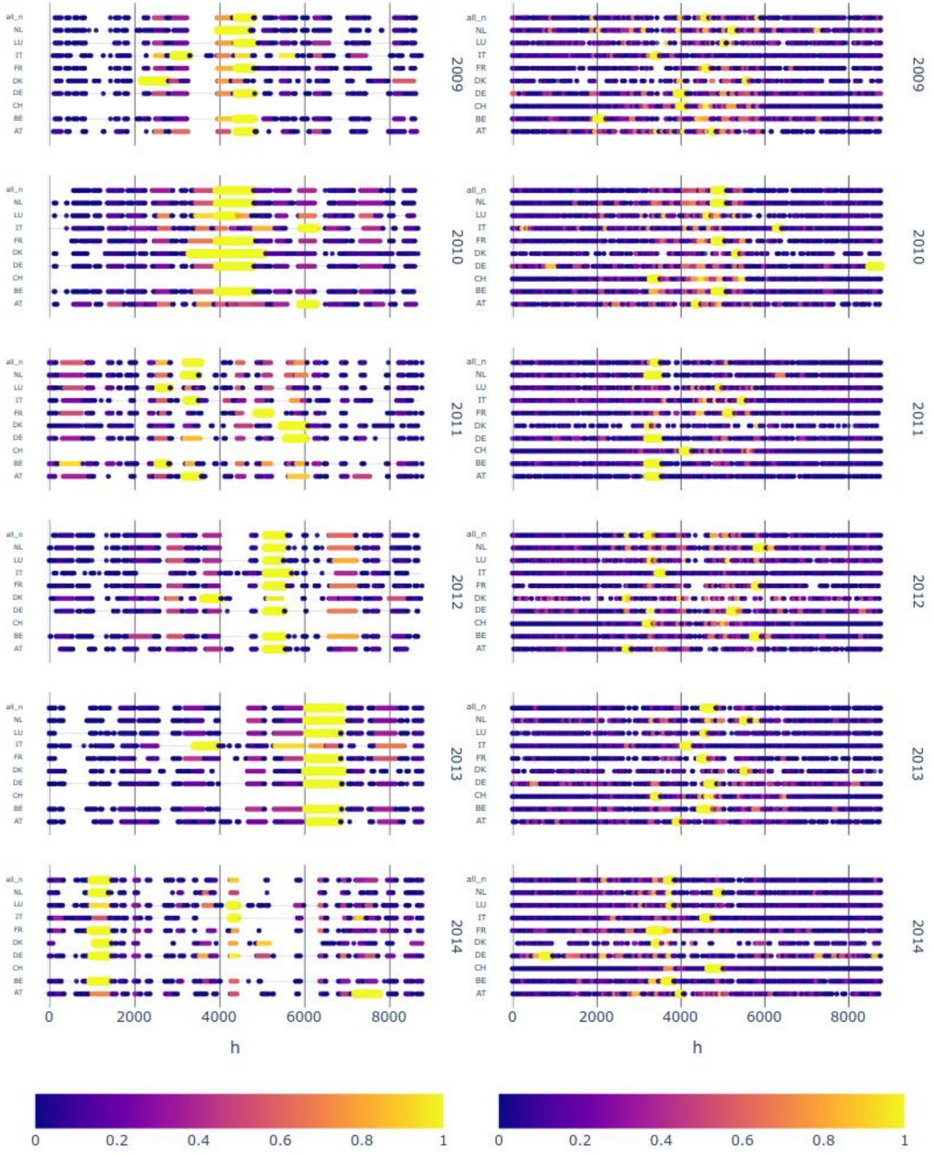
Note: In panel (c), yearly heat demand is shown on the left axis. The maximum hourly heat demand, scaled to the overall maximum hourly heat demand of the entire period, is depicted on the right axis.

Maximum heat demand



(a) Maximum heat demand (b) Maximum heat pump load (c) Maximum residual load

Heat deviation and residual load



(a) Maximum heat devition events (b) Maximum residual load event

Conclusion

- Heat pump generate energy demand and load peaks that need to be covered
- (Small) thermal heat storage can reduce firm capacity needs substantially
- Interconnection between countries with limited effect → overlapping cold spells
- Need for policy? Incentives from “smart” heat pumps & thermal heat storage (?)

Outlook

- Additional weather years & countries
- More realistic differentiation between heat pump technologies
- Endogenous thermal heat storage (vs batteries)

Thank you very much for your attention

aroth@diw.de

Appendix

Costs

Table 4: Cost and technology parameters

(a) Electricity storage and reservoirs

Technology	Interest rates [years]	Lifetime [years]	Availability [years]	Overnight costs energy [1000 EUR]	Overnight costs charging power [1000 EUR]	Overnight costs discharging power [1000 EUR]	Efficiency charging	Efficiency discharging	Marginal costs charging [EUR]	Marginal costs discharging [EUR]
Lithium-ion batteries	0.04	20	0.98	300	50	10	0.97	0.97	0.3	0.3
Power-to-gas-to-power		23	0.95	0.2	305	850	0.73	0.6	1.2	1.2
Pumped hydro (open/closed)		80	0.98	10	550	550	0.97	0.91	0.56	0.56
Hydro reservoirs		50	0.98	10	200	-	1.00	0.95	0	0.1

(b) Electricity generation

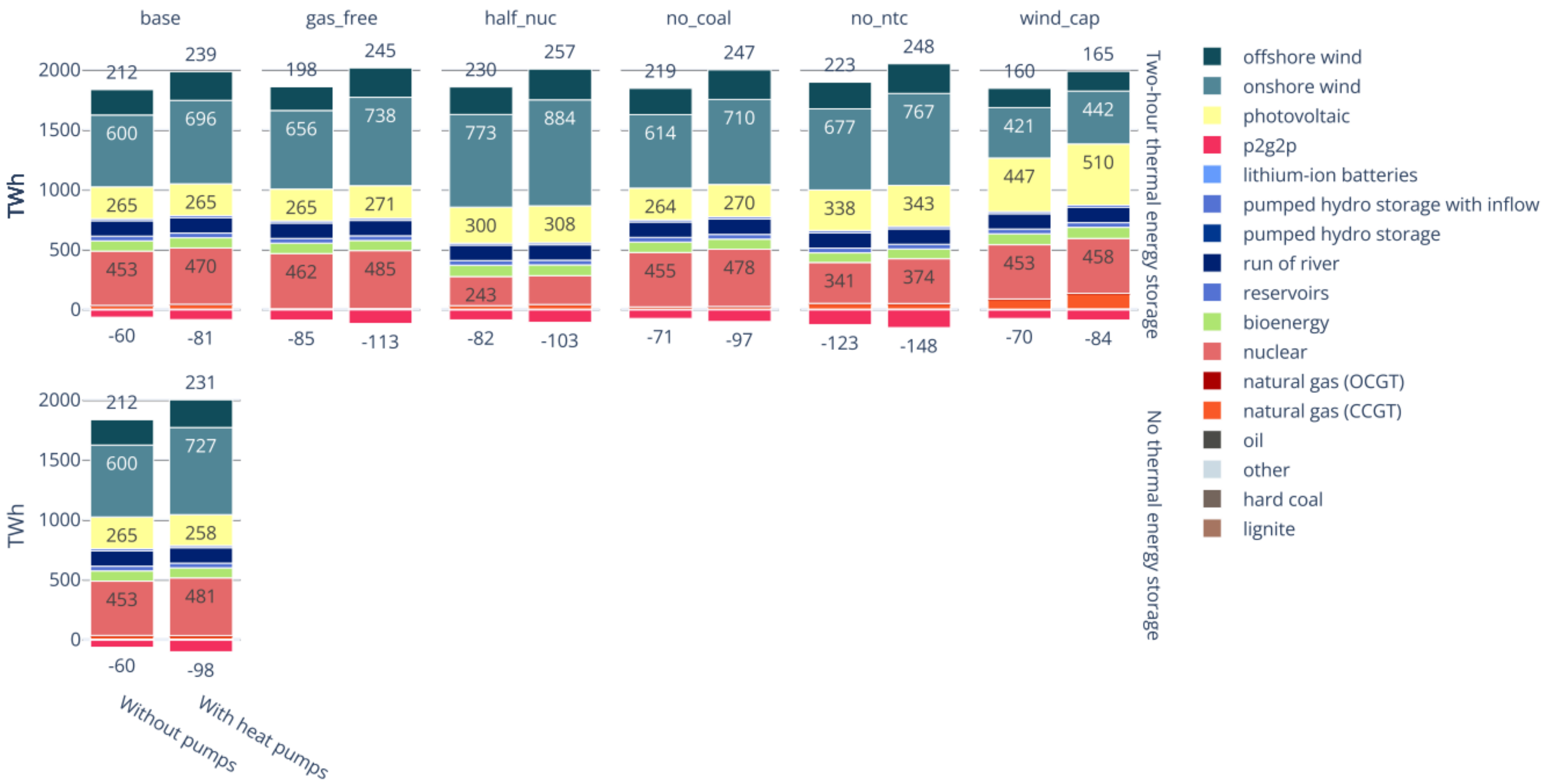
Technology	Interest rates	Lifetime [years]	Availability	Overnight costs [1000 EUR]	Fixed costs [1000 EUR]	Efficiency	Carbon content [t/MWh]	Fuel costs [EUR/MWh]
Closed-cycle gas turbine	0.04	25	0.96	830	28	0.61	0.20	26.0
Bioenergy		25	1.00	900	9	0.45	0.00	10.0
Hard coal		35	0.96	1,300	30	0.43	0.34	10.1
Lignite		35	0.95	1,500	30	0.38	0.40	4.0
Nuclear		40	0.91	6,000	30	0.34	0.00	1.7
Oil		25	0.90	400	7	0.35	0.27	41.7
Other		30	0.90	1,500	30	0.35	0.35	18.1
Solar photovoltaic		40	1.00	597	10	1.00	0.00	0.0
Wind onshore		50	1.00	3,000	30	0.90	0.00	0.0
Wind offshore		30	1.00	1,795	39	1.00	0.00	0.0
Run-of-river		30	1.00	1,036	13	1.00	0.00	0.0

Bounds

Table 5: Assumptions on capacity bounds [in GW]

Technology	Austria		Belgium		Denmark		France		Germany		Italy		Luxembourg		Netherlands		Switzerland	
	low	up	low	up	low	up	low	up	low	up	low	up	low	up	low	up	low	up
Natural gas (CCGT)	4.0	inf	8.1	inf	4.0	inf	7.2	inf	25.4	inf	40.5	inf	0	inf	12.4	inf	0	inf
Oil	0	0.16	0	0.2	0	2.5	0	1.3	0	1.0	0	0	0	0	0	0	0	0
Other	0	0.96	0	1.4	0	1.3	0	5.7	0	8.8	0	6.4	0	0.1	0	4.2	0	0.6
Hard coal	0	0	0	0	1.2	1.2	0	0	12.3	12.3	0	0	0	0	2.7	2.7	0	0
Lignite	0	0	0	0	0	0	0	0	14.6	14.5	0	0	0	0	0	0	0	0
Nuclear	0	0	0	0	0	0	61.8	61.8	0	0	0	0	0	0	0.5	0.5	2.2	2.2
Bioenergy	0.6	0.6	0.9	0.9	6.8	6.8	2.3	2.3	7.2	7.2	4.5	4.5	0.08	0.08	1.9	1.9	0.4	0.4
Run-of-river hydro	6.1	6.1	0.1	0.1	0	0	13.6	13.6	4.7	4.7	6.2	6.2	0.04	38	0.04	0.04	4.2	4.2
Solar PV	5.0	inf	7.5	inf	15.4	inf	18.2	inf	74.5	inf	28.6	inf	0.3	inf	18.7	inf	5.5	inf
Onshore wind	5.5	inf	3.6	inf	16.4	inf	24.1	inf	64.0	inf	15.7	inf	0.3	inf	6.0	inf	0.2	inf
Offshore wind	0	inf	2.3	inf	10.0	inf	2.5	inf	11.1	inf	0.3	inf	0	inf	5.9	inf	0	inf
Lithium-ion batteries																		
... power in/out	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf
... energy [GWh]	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf
Power-to-gas-to-power																		
... power in/out	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf
... energy [GWh]	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf	0	inf
Pumped hydro storage (closed)																		
... power in	0.3	0.3	1.2	1.2	0	0	2.0	2.0	7.4	7.4	7.4	7.4	1.0	1.0	0	0	1.9	1.9
... power out	0.3	0.3	1.2	1.2	0	0	2.0	2.0	7.4	7.4	7.3	7.3	1.3	1.3	0	0	1.9	1.9
... energy [GWh]	1.8	1.8	5.3	5.3	0	0	10	10	242	242	70.4	70.4	5.0	5.0	0	0	70	70
Pumped hydro storage (open)																		
... power in	5.2	5.2	0	0	0	0	1.9	1.9	1.4	1.4	2.1	2.1	0	0	0	0	2.1	2.1
... power out	6.0	6.0	0	0	0	0	1.9	1.9	1.6	1.6	3.3	3.3	0	0	0	0	10.7	10.7
... energy [GWh]	1,732	1,732	0	0	0	0	90	90	417	417	309	309	0	0	0	0	8,800	8,800
Reservoirs																		
... power out	2.5	2.5	0	0	0	0	8.9	8.9	1.3	1.3	9.6	9.6	0	0	0	0	0	0
... energy [TWh]	0.8	0.8	0	0	0	0	10	10	0.2	0.2	5.6	5.6	0	0	0	0	0	0

Generation



base
gas_free
half_nuc
no_coal
no_ntc
wind_cap
TWh
2000
1500
1000
500
0
212
239
600
696
265
265
453
470
-60
-81
198
245
656
738
265
271
462
485
-85
-113
230
257
773
884
300
308
243
-82
-103
219
247
614
710
264
270
455
478
-71
-97
223
248
677
767
338
343
341
374
-123
-148
160
165
421
442
447
510
453
458
-70
-84
Two-hour thermal energy storage
212
231
600
727
265
258
453
481
-60
-98
No thermal energy storage
Without pumps
With heat pumps
offshore wind
onshore wind
photovoltaic
p2g2p
lithium-ion batteries
pumped hydro storage with inflow
pumped hydro storage
run of river
reservoirs
bioenergy
nuclear
natural gas (OCGT)
natural gas (CCGT)
oil
other
hard coal
lignite

Residual load duration curves

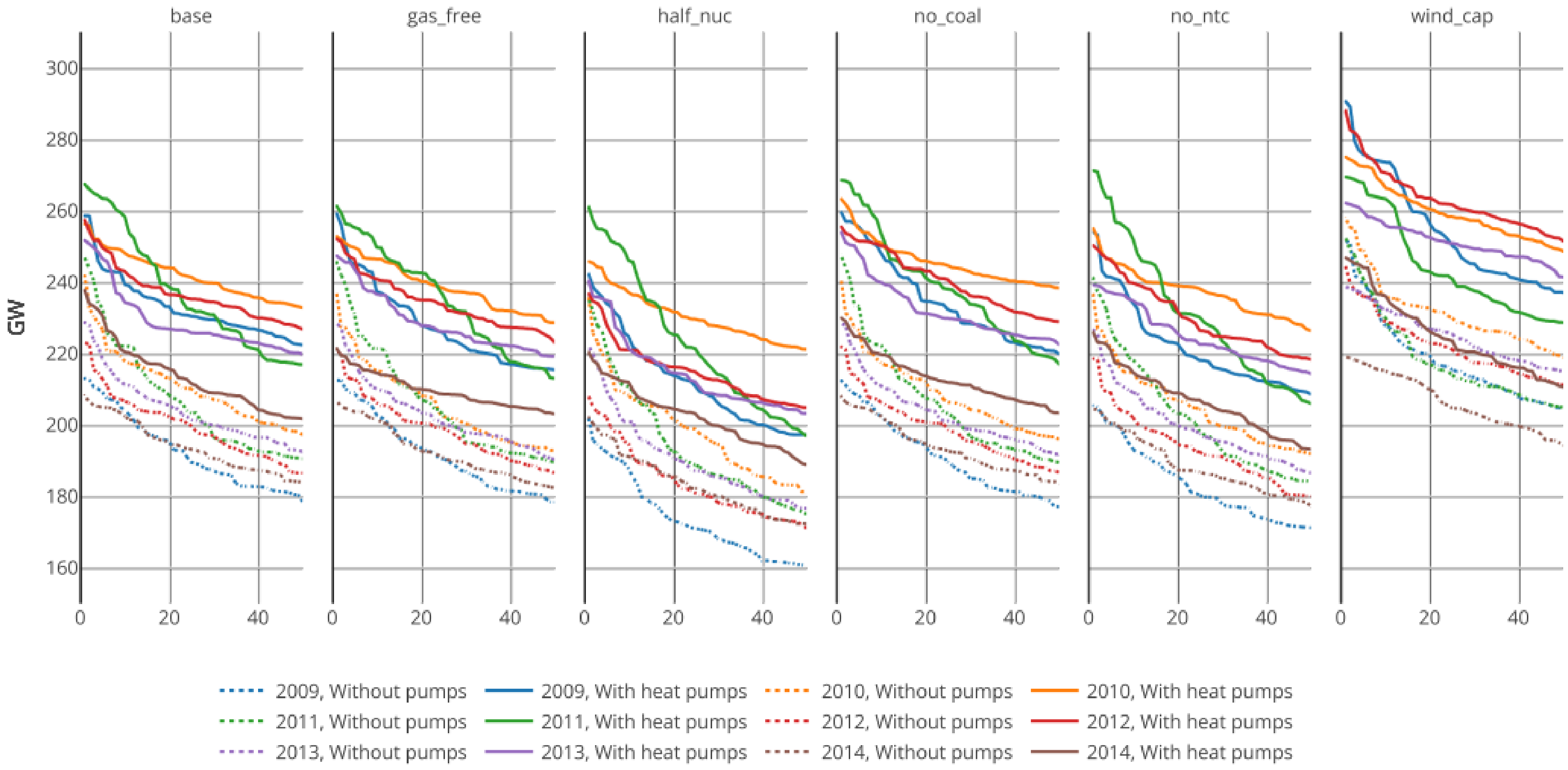


Figure 12: All residual load curves