Ea Energy Analyses

Value of Demand Flexibility in the European Power Sector

Final Report

03-10-2023

Key findings

- This report explores different scenarios for the European power and district heating system each representing varying degrees of demand flexibility. The scenarios comply with the EU's objective of becoming climate neutral by 2050.
- When we compare the "Reference" scenario, which assumes frozen policy with regards to flexibility and minimal advancement in demand response (DR) technologies, with the "Flex" scenario, where regulatory changes, technological advancements, and heightened consumer awareness enable demand response, we observe the following advantages:
  - A socio-economic benefit of €15.5 billion annually by the year 2050.
  - A substantial reduction in consumer costs, amounting to approximately €26 billion annually by 2050.
  - A decrease in average consumer power prices (wholesale) from €61/MWh to €55/MWh.
  - The abatement of 40 million tons of CO2 in 2030.
  - A reduced need for approximately 300 GW of battery capacity and 90 GW less gas peak capacity. Additionally, an integration of 100 GW more solar capacity into the energy mix.
  - Investments in interconnectors between bidding zones decreased by 21% (61 GW)
- The modelling considers only benefits of demand response in whole-sale electricity markets including the need for investments in interconnectors between bidding zones. Any positive (or negative) effects of demand response on distribution grid cost and internal transmission grid cost are not considered in the modelling. Possible revenues from selling ancillary services are not considered either.
- These findings underscore the potential benefits associated with embracing demand response and fostering a flexible energy landscape.
- Please note that the costs related to realizing the potential for load-shift among certain consumers, including households, services, industries, and electric vehicle (EV) owners, have not been factored into the analysis.

Introduction

Project context

Danfoss is actively engaged in assessing the role of demand-side flexibility within the forthcoming European power system landscape. Against this backdrop, we have prepared a long-term analysis spanning the milestone years of 2025, 2030, and 2050. The primary objective of this analysis is to quantify the holistic value that various forms of demand flexibility can contribute.

Our evaluation hinges on a set of key metrics that encompass socioeconomic impact, monetary advantages for consumers, reductions in CO2 emissions and fuel consumption, and power prices. To gain a thorough understanding, these critical aspects will be investigated through the lens of three distinct scenarios, each representing varying degrees of demand flexibility.

The analysis will be conducted by utilizing the Balmorel power system model to examine European day-ahead markets. This approach will focus on optimizing the intricate interplay between supply and demand dynamics, with the primary aim of minimizing costs for the overall system solution.

Note, that the modelling considers only benefits of demand response in whole-sale electricity markets including the need for investments in interconnectors between bidding zones. Any positive (or negative) effects of demand response on distribution grid cost and internal transmission grid cost are not considered in the modelling. Possible revenues from selling ancillary services are not considered either.

BALMOREL
Energy system model

Balmorel energy system modelling tool

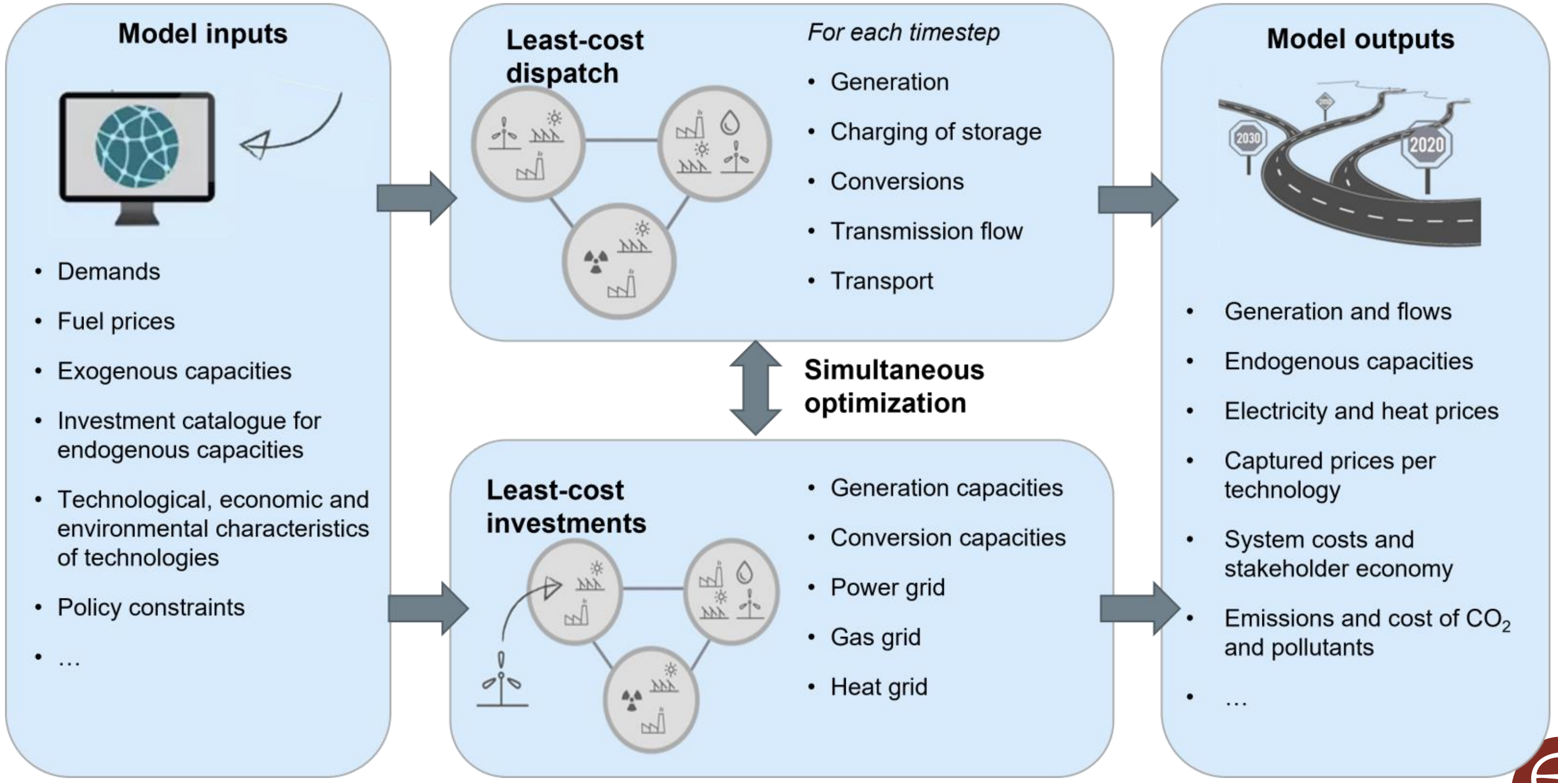
Model developed to support **technical and policy analyses** of power systems.

Optimization of **economical dispatch and capacity expansion solution** for the represented energy system.

Characteristics: open-source, customizable, scalable, transparent

Balmorel is a fundamental partial-equilibrium model of the power and district heating system. The model finds least-cost solutions based on assumptions such as the development of fuel prices, demand development, technology costs and characteristics, renewable resources and other essential parameters.

The model is capable of **simultaneous investment and dispatch optimisation**, showing optimal solutions for **power generation and interconnector capacity, dispatch, transmission flow and electricity prices**.

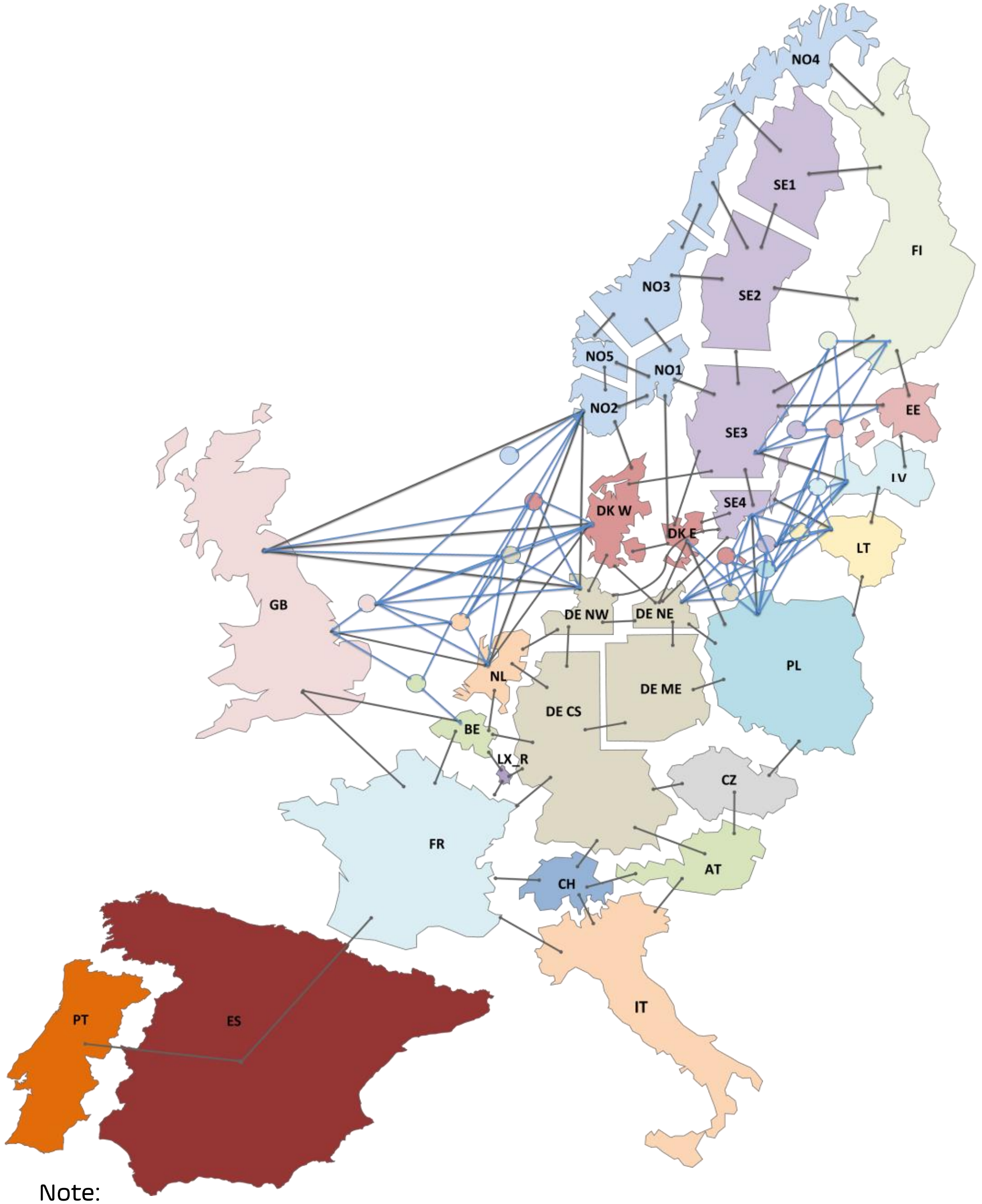


Model dimensions

Main evaluation measures
- Power prices and market values
- Generation & capacity balances
- CO2 and pollutant emissions
- Socio-economic system costs

Temporal scope
- Selected optimization years
- Time aggregated investment optimization
- Hourly dispatch optimization

Geographical scope
- Nordics (bidding zones)
- Germany (4 regions)
- Baltics
- Central Europe, UK and Italy
- Iberian peninsula



Note:
Oval shapes in the North and Baltic seas represent existing & future offshore wind locations in an aggregated matter.
Illustrated lines represent the options of transmission capacities.

Nomenclature

Acronym	Term	Acronym	Term
CAPEX	Capital costs	Ind.H	Individual Heating
CHP	Combined Heat and Power	LDC	Load Duration Curve
DH	District Heating	OPEX	Operation expenditures
DSR	Demand Side Response	PDC	Price Duration Curve
EU	European Union	PtX	Power to X
EVs	Electric Vehicles	PV	Photovoltaics
FLH	Full Load Hours	TYNDP	Ten Year Development Plant
H2	Hydrogen	V2G	Vehicle to Grid
HSDC	Hyper Scale Data Centers	VRES	Variable Renewable Energy Sources

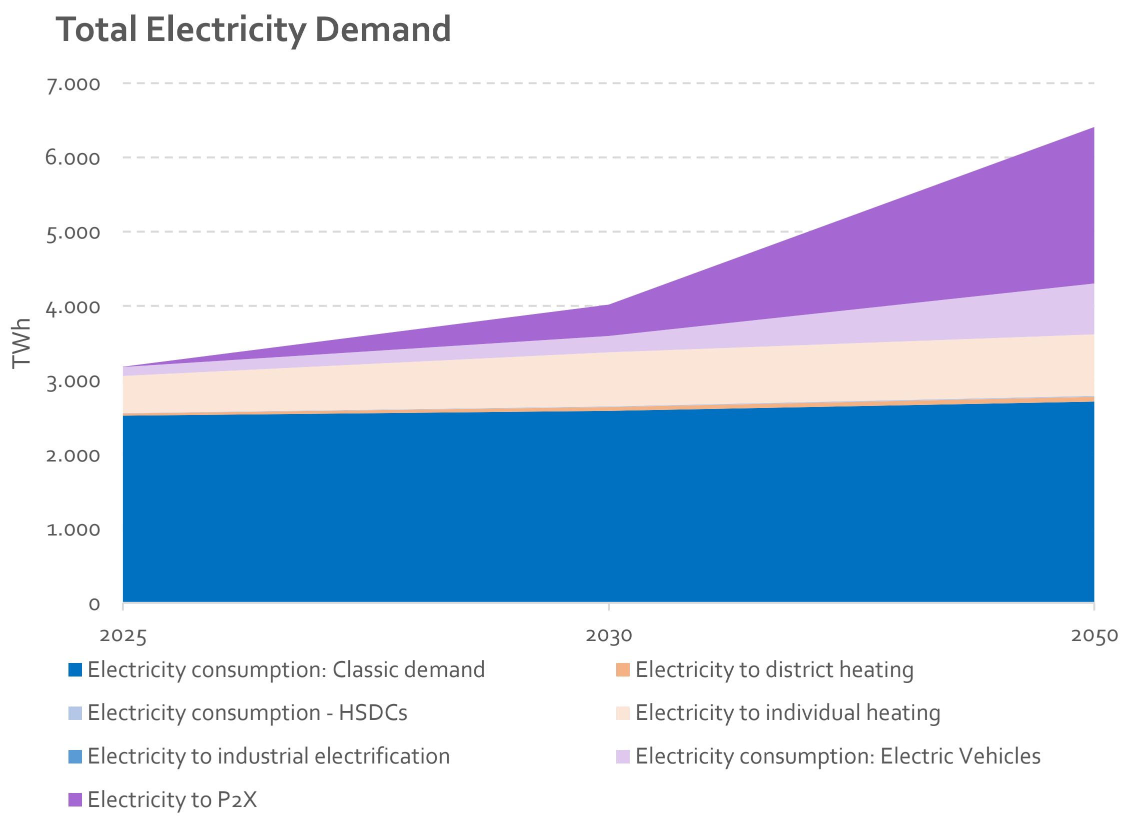
Power System Expectations

Electricity demand in Europe

The envisioned electrification of heating, industry and transport sectors is expected to increase electricity twofold towards 2030.

The following sources are used for demand projections:

- REPowerEU for hydrogen production targets towards 2030.
  - REPowerEU has been developed in the wake of Russia's invasion of Ukraine and assumes 10 mill. ton domestic hydrogen production (330 TWh) in the EU already by 2030.
  - The EU Commission MIX-scenario have been used for the long-term hydrogen demand.
- TYNDP's Global Ambition scenario for the development of total demand for classic demand, electric vehicles and individual heating.
- Electricity use for district heating is subject to model optimisation.



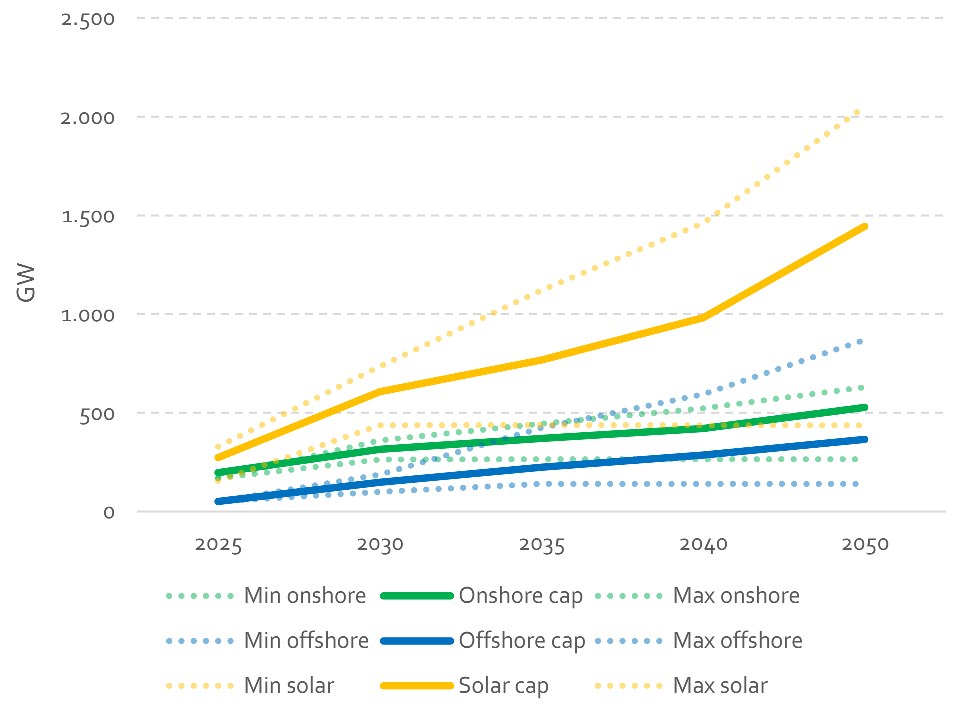
Demand buckets in the model

Demand bucket	Description	Associated cost of flexibility
Classic	Classic electricity demand mainly for households, the industry and service sector. Contains demand types not explicitly covered under the other categories. EU 2021 mix (approx.): • 43% industry • 28% service • 26% households • 3% agriculture	No direct costs. The model includes an inertia which ensures that demand flexibility is only activated when there is a price difference of 15 €/MWh.
Electric vehicles	Demand includes all electricity for road transport. Initial profile is based on charging patterns matching transport demand (Estimated for individual countries based on empirical data from Norway)	No direct costs. The model includes an inertia which ensures that demand flexibility is only activated when there is a price difference of 15 €/MWh. V2G activities face the occurring market costs (market clearing spot prices), essentially obtaining revenues from power arbitrage. No direct costs. The model includes an inertia which ensures that demand flexibility is only activated when there is a price difference of about 55 €/MWh
Individual heating	Includes electricity consumption for space heating in buildings. The demand is supplied by heat pumps and electric boilers.	No direct costs. The model includes an inertia which ensures that demand flexibility is only activated when there is a price difference of 10 €/MWh.
District heating	Heat demand for district heating is included. Heat pumps and electric boilers are among the options to supply the district heating demand. Other options are fuel-based district heating generation from heat only boilers or CHP. Depending on the scenario the model may invest in steel tanks and pit storages	Investment and operational cost for additional electric boilers or heat pump capacity. Using alternative options for heat generation yields additional cost. Investment cost and operational costs of steel tanks and pit storages.
Power-to-X	Demand for production of e-gasses, e-liquids and hydrogen based on EU commission scenarios. Modelled as electricity consuming generation facilities (electrolysers). Depending on scenario model optimised hydrogen storages can be installed to enable flexible use of electrolysers, while demand is modelled constant.	Investment and operational cost for electrolysers and cavern storages included.

Generation capacity in Europe

- The development in new capacity is driven by demand development, technology costs and resource assumptions. Moreover, important political targets are taken into account, including minimum buildout for renewable energy, coal phaseout plans and nuclear plans.
- Wind and solar: As a minimum level for renewable energy, countries are expected to fulfil the levels of wind and solar power set out in ENTSO-E TYNDP-scenario National trends towards 2030. Key national are included as well, Germany for example, is expected to pursue higher targets for wind and solar power as set out in the Government's Easter Package from April 2022, aiming for 215 GW solar power and around 120 GW of onshore wind in 2030. Additionally, 80% of the ambitious 30 GW offshore wind target by 2030 is assumed realised. Beyond 2030, investments are based on model optimisation. For onshore wind and solar PV, country specific caps are employed to reflect a realistic deployment that considers planning and grid constraints at the local level. These constraints are gradually relaxed over time.
- Nuclear capacity is determined exogenously. The capacity based on plans from World Nuclear Association for decommissioning but with new plants being built in the UK, Finland and Poland. The total capacity declines from around 100 GW in 2021 to ~90 GW in 2050.
- Thermal capacity: Current plans for decommissioning of coal-fired capacity are considered. Other than that, decommissioning of and investments in thermal power capacity is determined by the model. Investment in biomass capacity (wood chips, wood pellets, straw) is constrained at 30 GW by 2030 (corresponding to a fuel input of approx. 1.900 PJ) to reflect that the current pipeline of new biomass capacity is limited. Towards 2050, the biomass constraint is lifted to 40 GW.

Buildout requirements and levels in the model area



Note:
- Min and max show assumptions on minimum and maximum possible buildout pathways.
- No difference between the two means, means that a exact capacity is installed.
- "Cap" shows capacity as a result of model optimisation.
- Spain and Portugal are not included in the present graph.

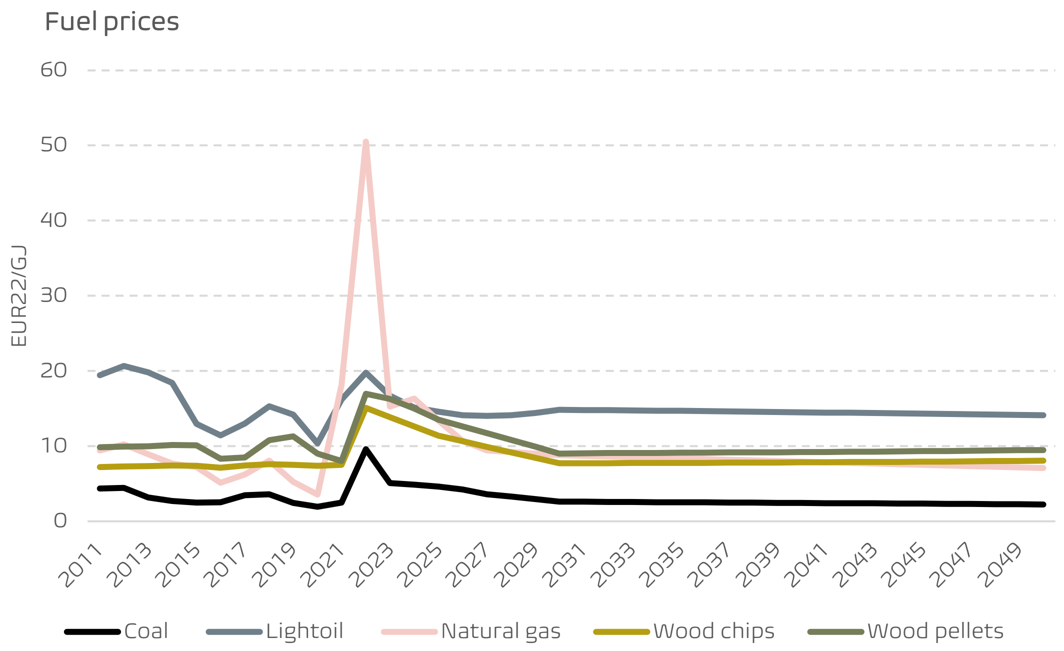
Fuel and CO_2 prices

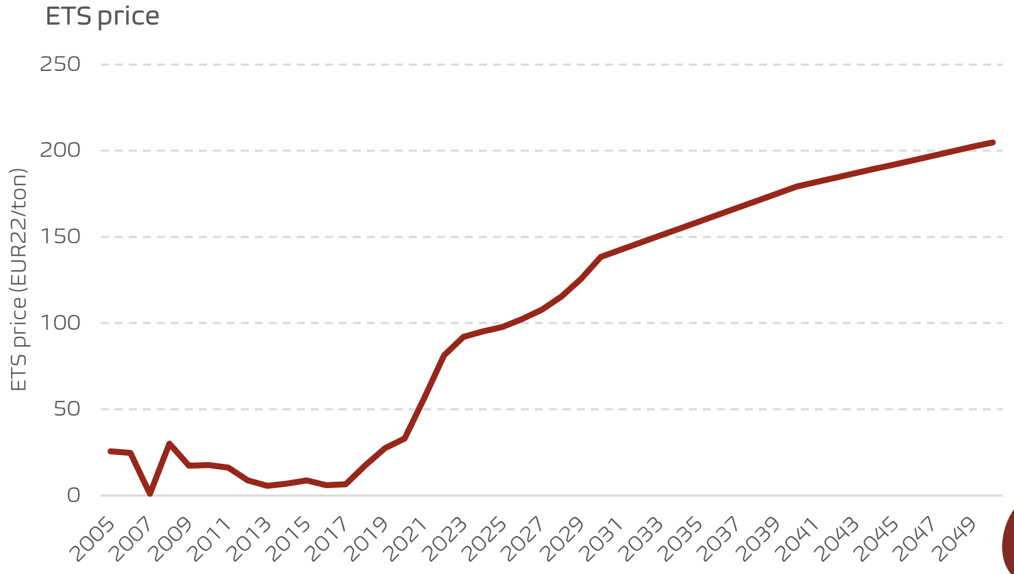
Fuel prices

- Futures (April 2023). Until and including 2026
- Long term. Prices expected to converge to long term equilibrium prices in 2030
  - IEA World Energy Outlook 2022
  - Announced Pledges scenario
  - Natural gas: LNG import price (Japan).
- Current high gas prices expected to normalise over time, but outlooks are difficult in current situation. Towards 2030, reduced dependence on natural gas and high global buildout of renewables lowers demand for fossil fuels and thus prices

CO2-prices

- Forward prices (April 2023). Until and including 2026
- Long term. Prices expected to converge to Announced Pledges scenario from WEO2022 in 2030 and onwards.
- High CO_2-prices – also going forward to 2030. However, current prices are also to some extent affected by high gas prices.





Study structure

Analysed scenarios

Ea Energy Analyses' reference projection towards 2050 will be utilised as a basis for the present study, with key flexibility aspects varying across three scenarios.

I. A "Reference" scenario reflecting frozen policy and limited development of DR technologies. The reference displays relatively low levels of flexibility, including inflexible electricity consumption patterns among a certain portion of the PtX capacity.

II. The PtX sector is expected to provide the highest level of flexibility in the system in upcoming years, due to its demand magnitude but also characteristics. Therefore, an intermediate scenario ("PtX Flex") will be analysed to shed light on the value that PtX related flexibility brings to the system on top of reference case.

III. Finally, the most flexible scenario ("Flex"), will reflect the addition of further demand-side flexibility actions in each demand category, showcasing the overall emerged value from the deployment of different flexibility measures.

An overview of the varying aspects between scenarios can be seen in the following slide:

Definition of scenarios

Demand bucket	Reference	Reference + PtX flexibility ("PtX Flex")	Flexibility scenario ("Flex")
Classic	2,5% fuel-shift (permanent reduction in demand) 5 % load-shift (up to 2 hours). 25% realised in 2025, 50% in 2030, 100% by 2050.	As *Reference*	10% fuel-shift (permanent reduction in demand) 20% load-shift (up to 2 hours). 25% realised in 2025, 50% in 2030, 100% by 2050.
Electric vehicles	20% of total load for electric road transport will participate in flexible charging and be able to move planned charging by up to 4 hours. 15% of total load V2G "fit". 25% realised in 2025, 50% in 2030, 100% by 2050.	As *Reference*	65% of total load for electric road transport will participate in flexible charging and be able to move planned charging by up to 4 hours. 50% of total load V2G "fit". 25% realised in 2025, 50% in 2030, 100% by 2050.
Individual heating	Fixed consumption pattern.	As *Reference*	Flexible heat generation by adjustments to initial demand profile. Average demand can be moved 3 hours. 25% realised in 2025, 50% in 2030, 100% by 2050.
District heating utilities	Flexibility consists of the option to fulfil the heat demand by electricity or other heat generation, depending on the power prices. The model may invest in steel tanks only.	As *Reference*	As *Reference* plus: The model may invest in steel tanks and pit storages. Load-shift among district heating consumers: 2025: 4 hours flex, 25 % realised 2030: 5 hours flex, 50 % realised 2050: 6 hours flex, 75 % realised
Power-to-X	75% of PtX demand operates flexible 25% of PtX demand follows a fixed load curve (flat throughout the year).	100% flexible PtX load. Model optimised hydrogen storages can be installed to enable flexible use of electrolysers, while demand is modelled constant. Cost of storage reflects those of large-scale caverns, assuming a hydrogen backbone infrastructure is available to connect hydrogen producers directly to consumers and centrally localised large scale hydrogen caverns.	As *Reference + PtX flexibility*

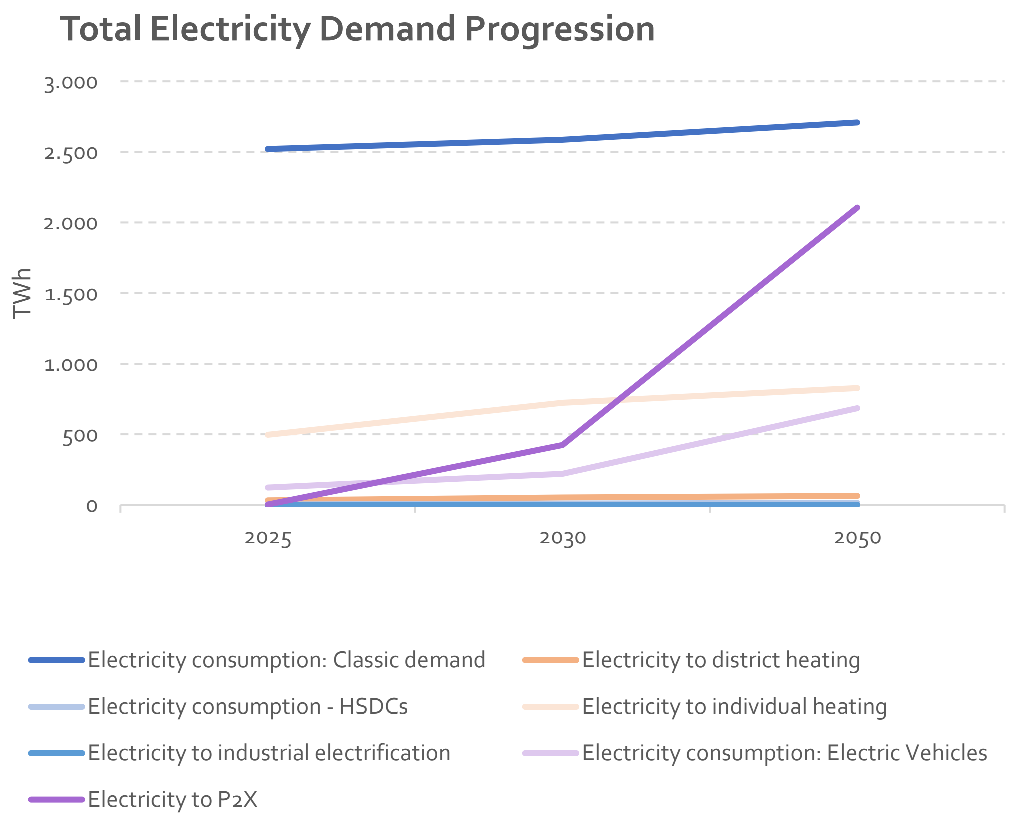
Factors affecting the realisation of scenarios

- Several factors affect the uptake of demand response technologies including
  1. Regulatory Environment: Government policies and regulations can greatly impact demand response adoption. Supportive policies, incentives, and mandates can encourage the implementation of demand response programs.
  2. Technology Availability and Maturity: The availability and maturity of demand response technologies play a crucial role. If advanced and cost-effective technologies are readily accessible, it becomes easier for consumers and businesses to implement demand response strategies.
  3. Consumer Awareness and Education: Lack of awareness or understanding of demand response can be a barrier. Effective education and outreach programs can help consumers and businesses make informed decisions.
  4. Electricity prices and Grid needs: The economic benefit of being flexible depends on the state of the grid and the composition of power supply etc. Stronger incentives will encourage more demand response.
- The reference scenario is intended to reflect a situation where factors 1-3 do not improve considerably compared to today (factor 4 is considered within the modelling*).
- The flexibility scenarios show developments, where the regulatory environment, technology development and consumer awareness facilitate demand response.

* The modelling considers benefits of demand response in whole-sale electricity markets including the need for investments in interconnectors between bidding zones. Any positive (or negative) effects of demand response on distribution grid cost and internal transmission grid cost are not considered in the modelling. Possible revenues from selling ancillary services are not considered either.

Demand-side flexibility measures in Europe

- Electric vehicles demand includes all electricity for road transport. This demand is flexible, and an increasing share can be moved for 4 hours. Thus, the modelling accounts for smart charging. Vehicle-to-grid solutions can also be enabled.
- Electricity for individual heating includes electricity consumption for space heating in buildings, which is modelled as heat demand. The demand is supplied by heat pumps, direct electric heating and electric boilers. A part of the individual heat demand can be considered flexible, with the option of load-shifting in future hours.
- Electricity for district heating is based on model optimization. Heat pumps and electric boilers are among the options to supply the district heating demand. Other options are fuel-based district heating generation from heat only boilers or CHP.
- Electricity for P2X is included based on the consumption of e-gasses, e-liquids and hydrogen. A P2X efficiency of 70% is assumed for hydrogen and 60% for e-gasses and e- liquids. If profitable, storages can be installed to move portions of the demand, hence providing further flexibility to the system.
- The level of flexibility in the classic demand is rising from 2020 towards 2050 against the average hourly demand. The demand can be moved for 2 hours by paying an activation price. This demand includes industry that also have flexibility to move production to low price hours.



Note:
- HSDCs: Hyper Scale Data Centers
- Classic demand reflects power use for: Industry, Service, Households, Agriculture.
- Illustrated annual demand levels reflect the analysed "Flex" scenario as described in upcoming sections.

Flexibility on classic demand: Low VRE week (W48), 2050

Assumptions on demand response for classic electricity demand (households + industry) are based on an estimate of long-term flexibility against the average demand in 2050.

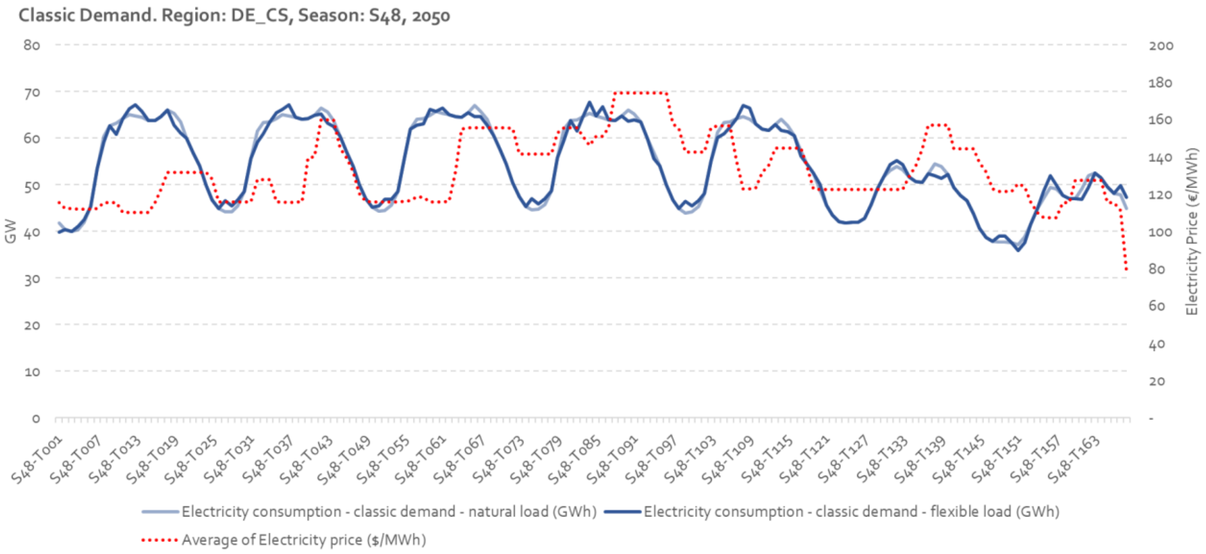
Demand response is implemented as a potential to shift of demand in time for up to 2 hours. For comparison, ENTSO-E reported average DSR (Demand side response) of roughly 9% of average demand in 2040 in the TYNDP 2018 Global Climate Action scenario.

50% of flexibility is activated at a cost of 15 €/MWh, while the remaining 50% of flexibility is activated at 30 €/MWh, meaning that the difference between achievable electricity prices has to be at least 15 €/MWh, before load shifting takes place.

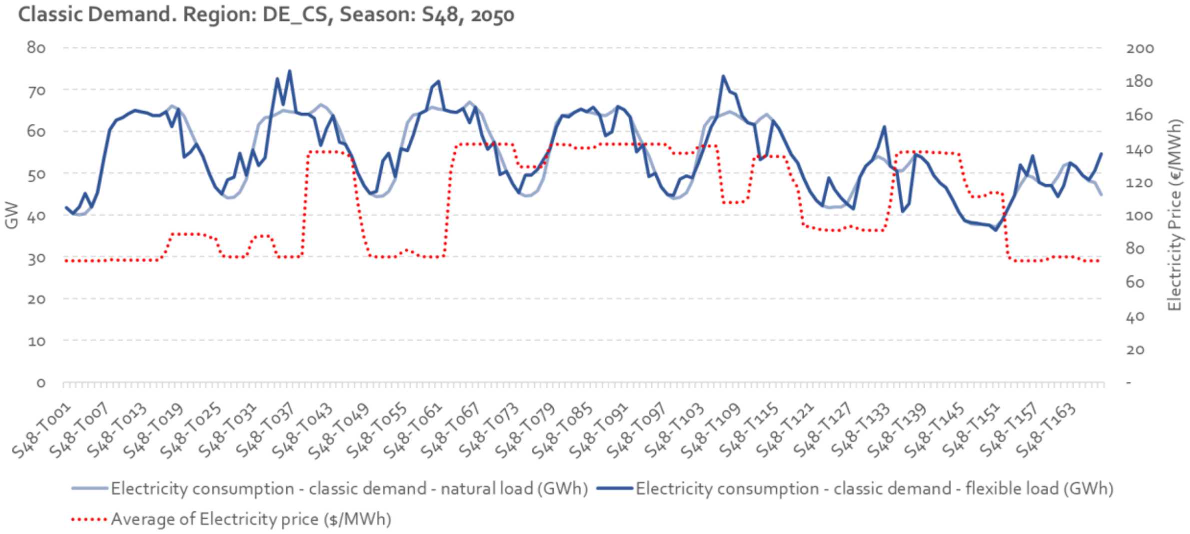
Deployment of locally distributed battery solutions (for example residential batteries in combination with rooftop PV) are not considered in the modelling and could provide a portion of this flexibility potential.

Utility scale batteries are not included in the estimates here as they are subject to explicit optimisation.

Reference



Flex



Note:
- Illustrations reflect demand behavior in a low renewable energy week with high electricity prices. Chosen region reflects Munich in Germany. Season "S" correspond to the reflected week number.

Flexibility on electric vehicles

Charging patterns

Charging patterns for electric vehicles are assumed to be flexible relative to an initial charging profile. The initial charging profile is based on estimates of immediate charging profiles according to driving patterns (Full blue line for weekdays and full grey line for weekends).[1] These charging profiles would ensure EV's are fully charged as fast as possible after driving. Thus, charging profile follow peak commuting hours with a little time lag. Charging patterns are based on research on personal vehicles, but are used here to represent all electricity use for road transport.

Only a share of all vehicles are assumed to be flexible, which leads to certain minimum (red dashed line) and maximum (blue dashed line) loads for charging electric vehicles at all times. The resulting potential load patterns exclude option for vehicle-to-grid technologies, which could significantly increase flexibility options, albeit at a higher cost, to take into account technology needs and lifetime reductions on batteries due to additional cycling.

Illustration of charging patterns and limits (2030)

[1] *Source: Liu, Z., Nielsen, A. H., & Wu, Q. (2016). Optimal Operation of EVs and HPs in the Nordic Power System. Technical University of Denmark, Department of Electrical Engineering.*

Limits on flexibility of electric vehicles

Time shifting

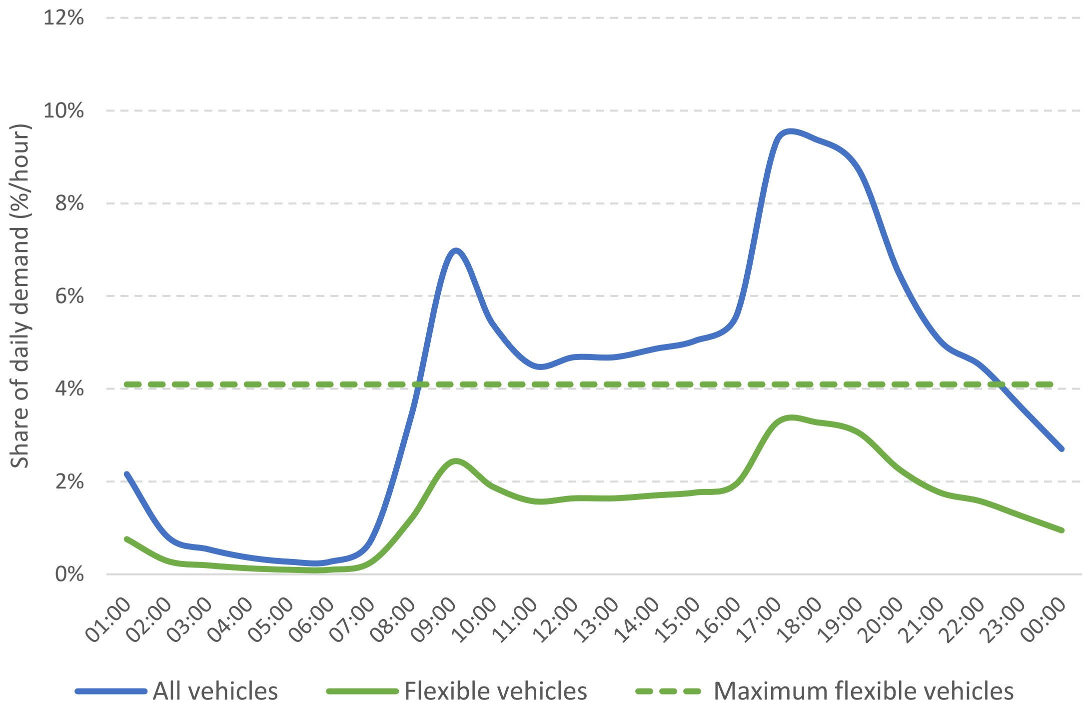
Flexibility is implemented as a potential to shift the average charging load (of the flexible vehicles) of up to 4 hours in time. Energy demand has to be served over a 24 hour period, and all energy demand has to be served by 7 am in the morning, where all EVs are charged to the desired level

Restriction on flexibility

Flexibility of charging for electric vehicles is subject to a number of restrictions, which develop over time

- Only a fraction of vehicles participate in flexible charging, meaning the remaining vehicle will follow the initial charging pattern at all time. The maximum charging is limited to a multiple of the estimated peak demand of the initial profile
- Maximum charging for flexible vehicles cannot exceed 125% of the peak of their initial charging profile.
- Flexibility is activated at a cost of 15 €/MWh independent of time difference. This means, the difference between achievable electricity prices has to be at least 15 €/MWh, before load shifting takes place. For an average personal vehicle with annual driving ranges of 15.000 – 20.000 km and electricity demand of around 3 MWh/year, this corresponds to 45 €/year.

Illustration of charging patterns and limits (2030)

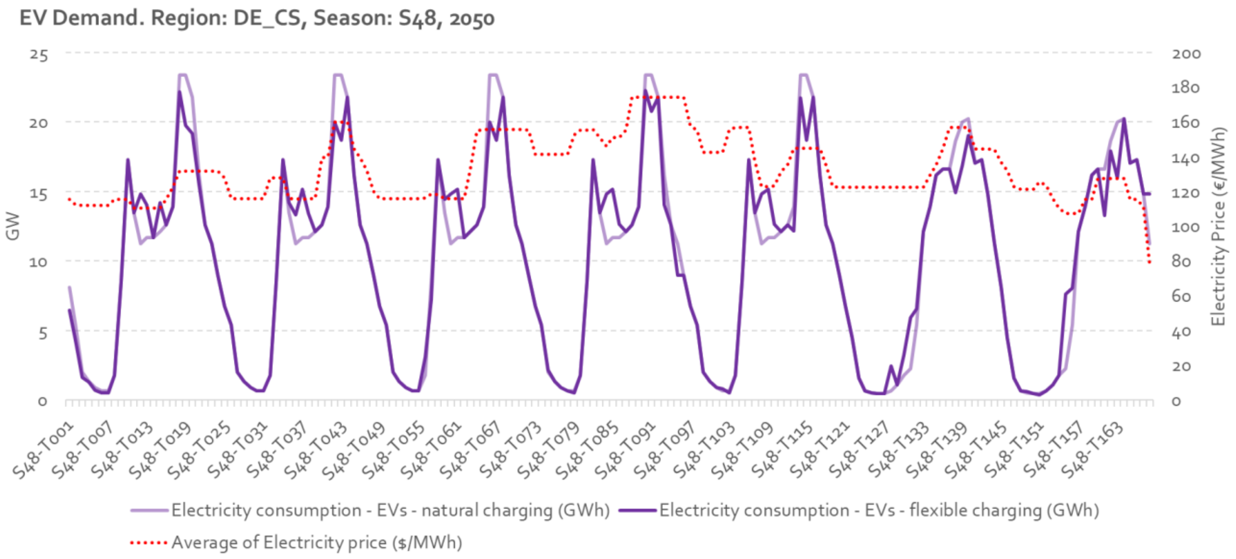


Flexibility on electric vehicles

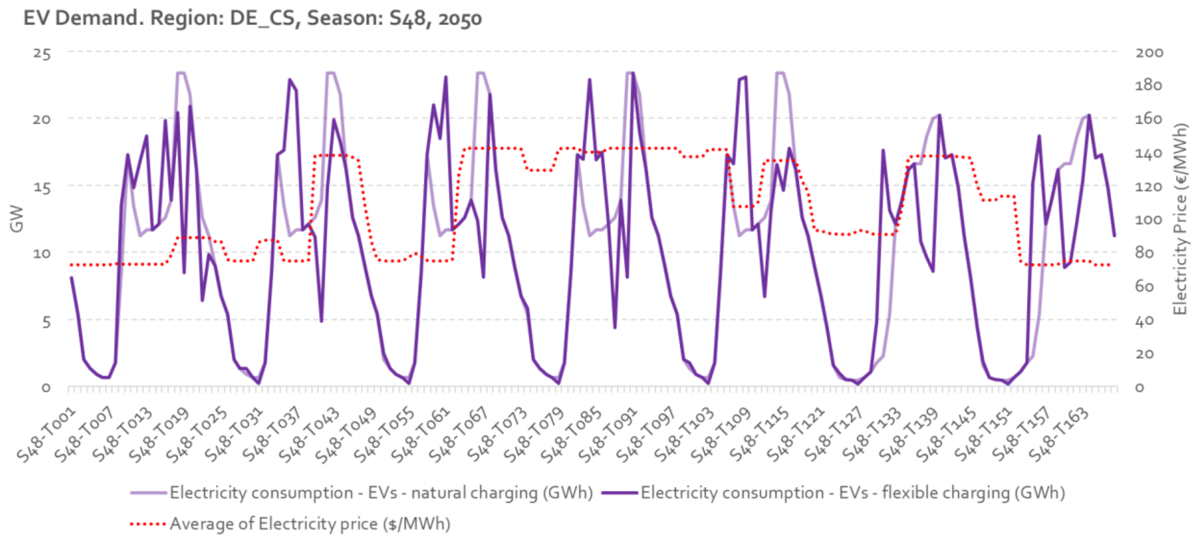
The resulting maximum capacity to increase charging or interrupt charging (providing upregulation to the system) is shown on the right. These flexibilities are well below technical accumulated battery loading and volume in the system, which are up to 18 times higher.

Flexibility in charging patterns is used in dispatch optimisation as illustrated, showing a move away from peak load in initial charging profile at the expense of higher peaks.

Reference



Flex



Note:

- Illustrations reflect demand behavior in a low renewable energy week with high electricity prices. Chosen region reflects Munich in Germany. Season "S" correspond to the reflected week number.

Limits on flexibility from individual heating

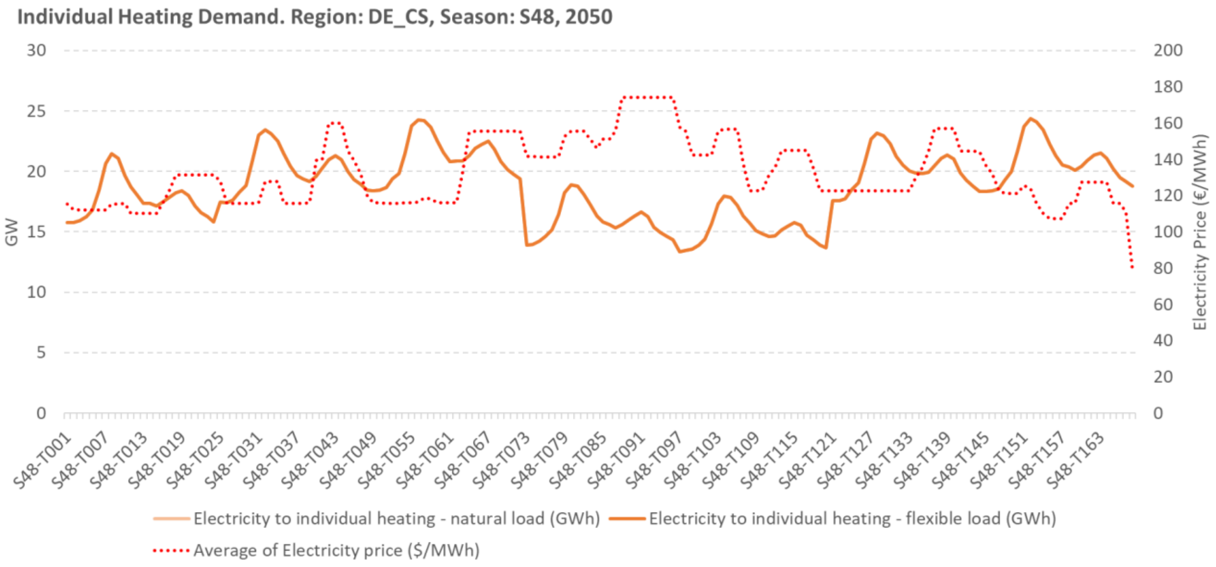
Electricity used for heating can be flexible by exploiting heat capacity in buildings and hot water tanks. The initial demand profile follows the heat demand, which is dependent on hot water usage and outside temperature. An increasing share of buildings are participating in providing flexibility to the system by allowing the average seasonal demand to be shifted by up to 2 hours.

Load for buildings not participating in flexible heating will have to be served at all times. Maximum load for individual heating cannot exceed maximum annual peak demand, which is well below the total cumulative installed technical capacity of heat pumps.

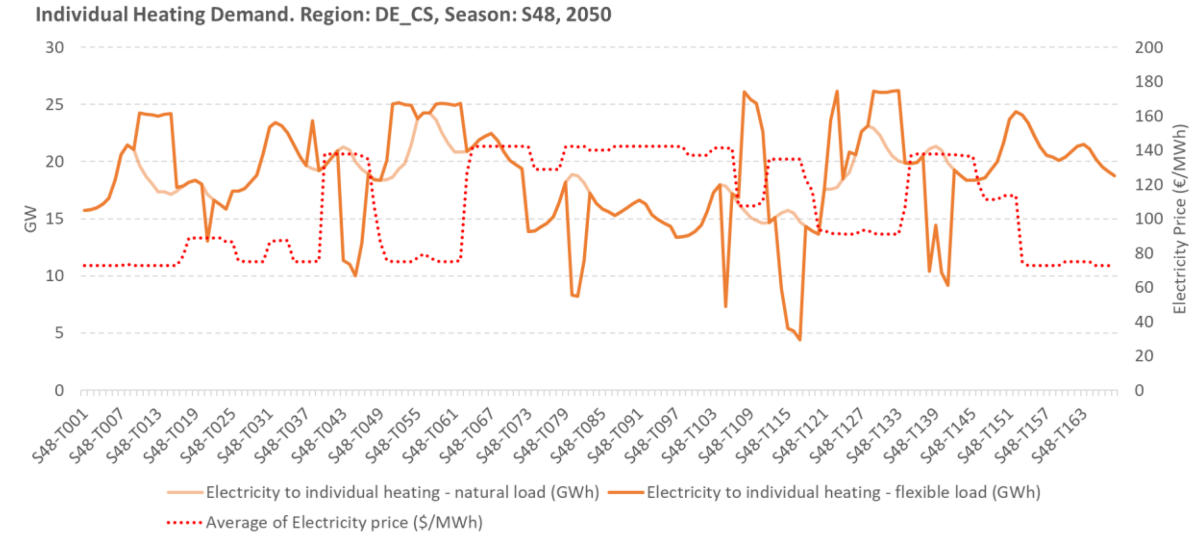
Heat demand has to be supplied within 24 hours and thus cannot be shifted across days.

Flexibility is activated at a cost of 10 €/MWh, meaning the difference between achievable electricity prices has to be at least 10 €/MWh, before load shifting takes place.

Reference



Flex

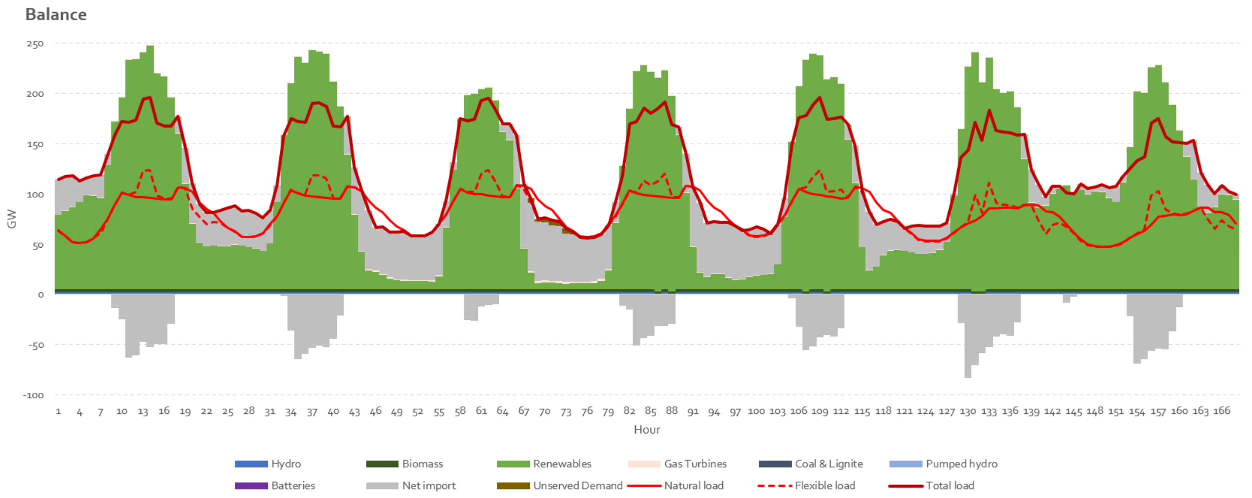


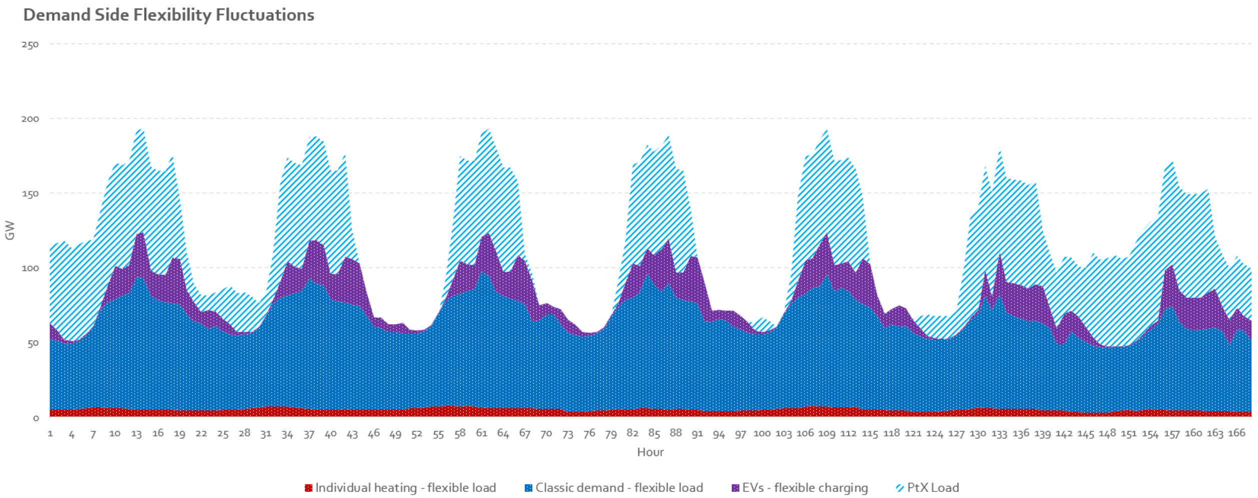
Note:
- Illustrations reflect demand behavior in a low renewable energy week with high electricity prices. Chosen region reflects Munich in Germany. Season "S" correspond to the reflected week number.

PtX flexibility and VRE correlations: *Germany, Flex, 2050*

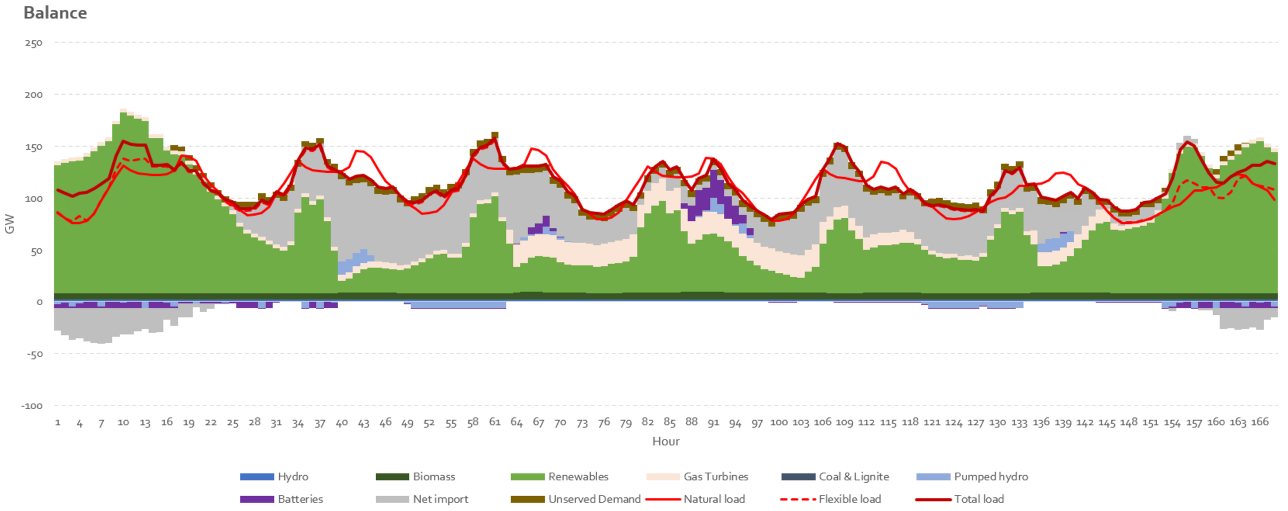
The following illustrations provide a weekly overview of the power system in a selected country. From a power system perspective, high flexibility is provided in the system via both PtX activities and interconnectors. In terms of PtX activities, there is a strong correlation of high VRE generation and electricity utilisation in the PtX sector (PtX Load). This means that PtX mostly alleviates system pressure rather than contributing to it. For an overview of the same weeks across the different scenarios refer to the Appendix.

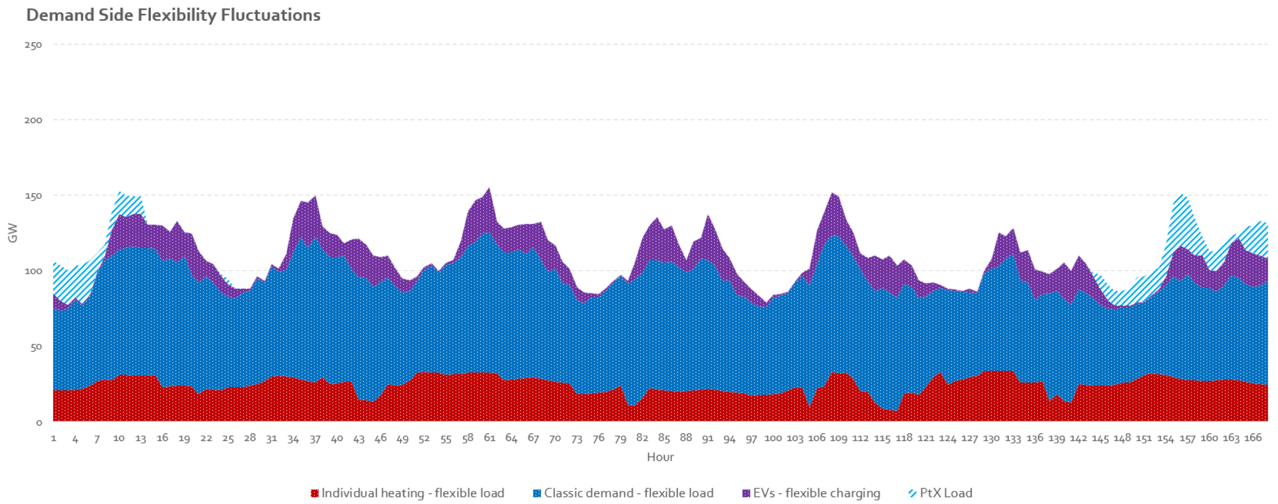
High VRE Week (Week 28)





Low VRE Week (Week 48)





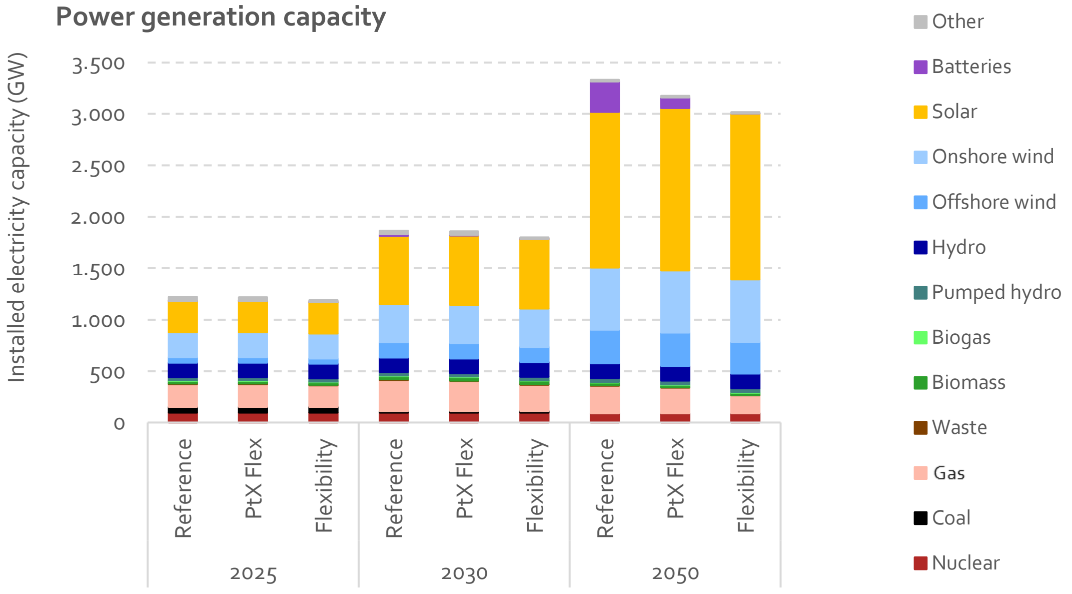
Model Results

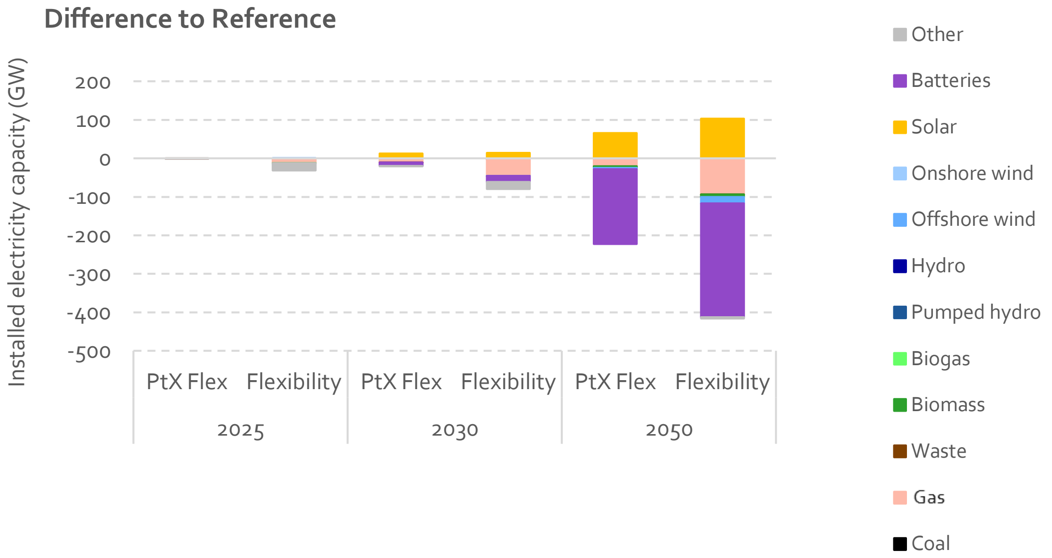
Power Generation Capacities

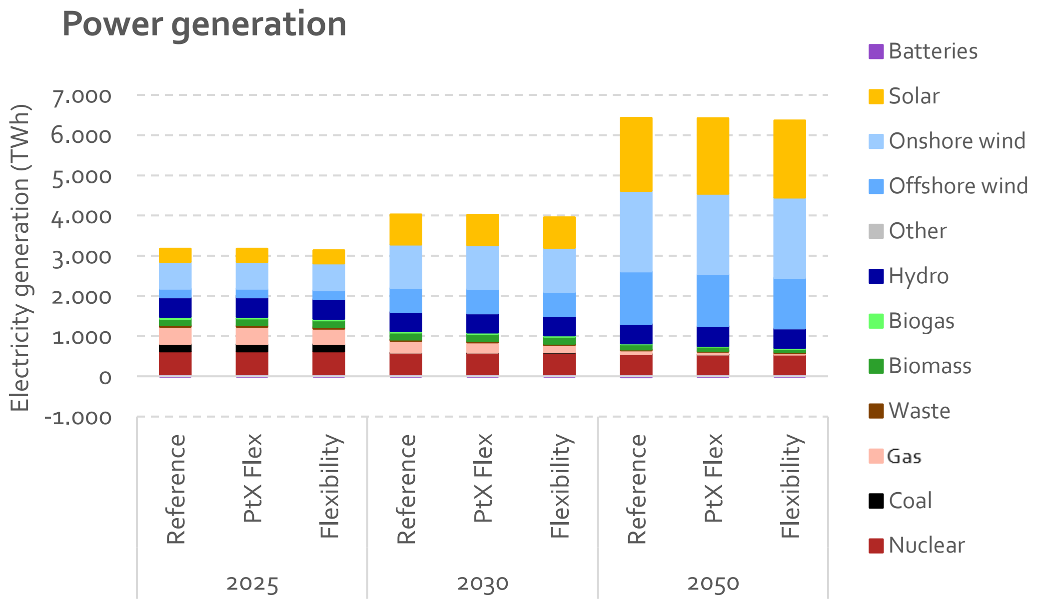
Two main patterns can be identified between the developed scenarios and the reference case when moving to 2050:

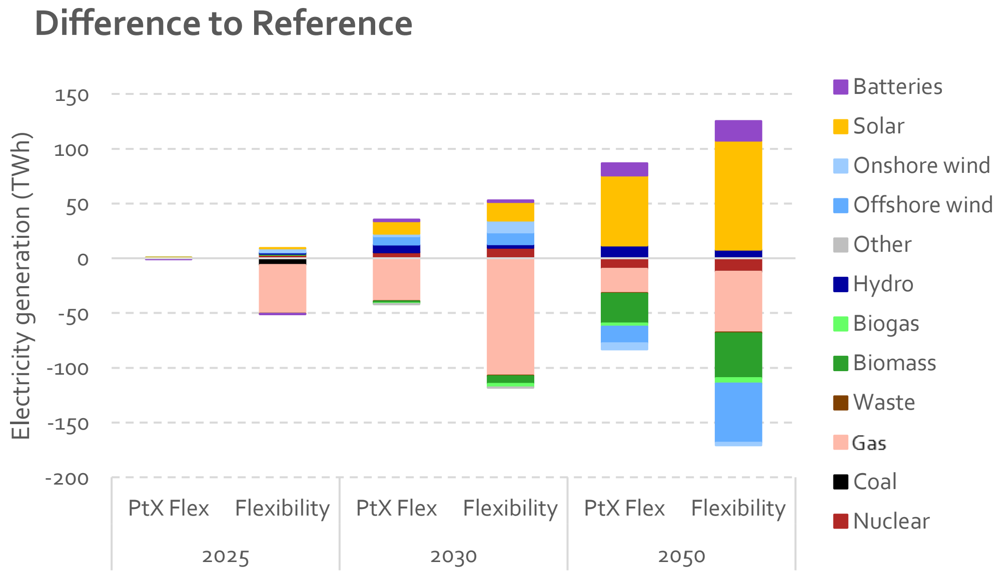
I. While transitioning to a totally flexible PtX operation behaviour ("PtX Flex"), battery investments, which aid the model to shift power from cheaper time slices to more expensive ones, are replaced by higher solar PV capacities and H2 storages. The additional flexibility in the hydrogen sector help save investments in batteries in the power sector. Using PV with low LCOE, hydrogen is stored and utilised across time segments.

II. When adding further demand side flexibility measures to the system, similar patterns as in "PtX Flex" are observed, approximately exaggerated by 50%, in parallel to an additional decrease of 93 GW of gas and 17 GW of offshore wind generators. With the opportunity of more flexible demand, opportunities of reducing the contribution of more expensive marginal generators (gas peakers) or further marginal investments (offshore wind) can be harvested. Similar, but of smaller magnitude effects, can be also observed among other categories in earlier years.









Power generation

Observing higher total electric storage contributions to the power mix even during lower overall capacities signalise that the system still finds value in shifting power across timesteps but with lower peaks that in the reference.

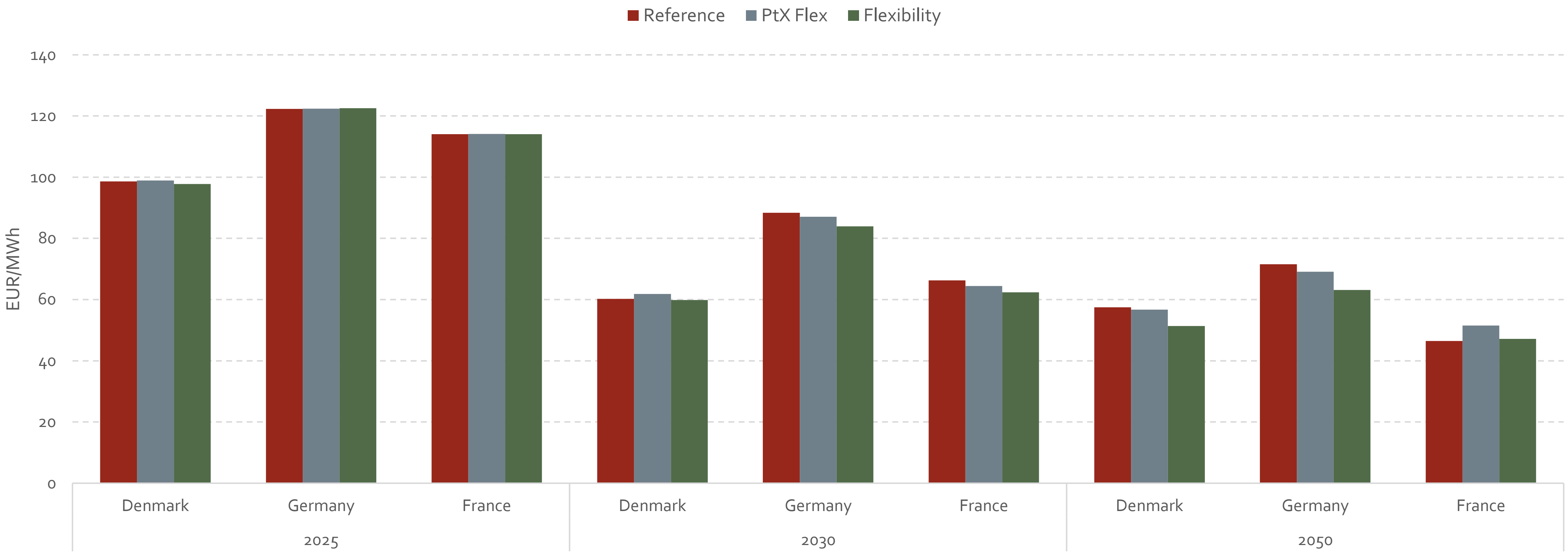
Higher power contributions from VRE sources in 2025 and 2030 correspond to the fact that higher flexibility allowances provide a freedom of capacity redistribution to the model, which in its turn harvests higher FLHs. In parallel, a lower level of VRE curtailment also aids such tendencies due to the ability of flexible demand being able to shift quantities towards time-slices with high VRE penetration.

On the other hand, 2050 generation differences mainly follow the total installed capacity differences (discussed in the previous slide), topped up by lower needs of expensive peaker generator contributions.

Electricity Prices in selected countries

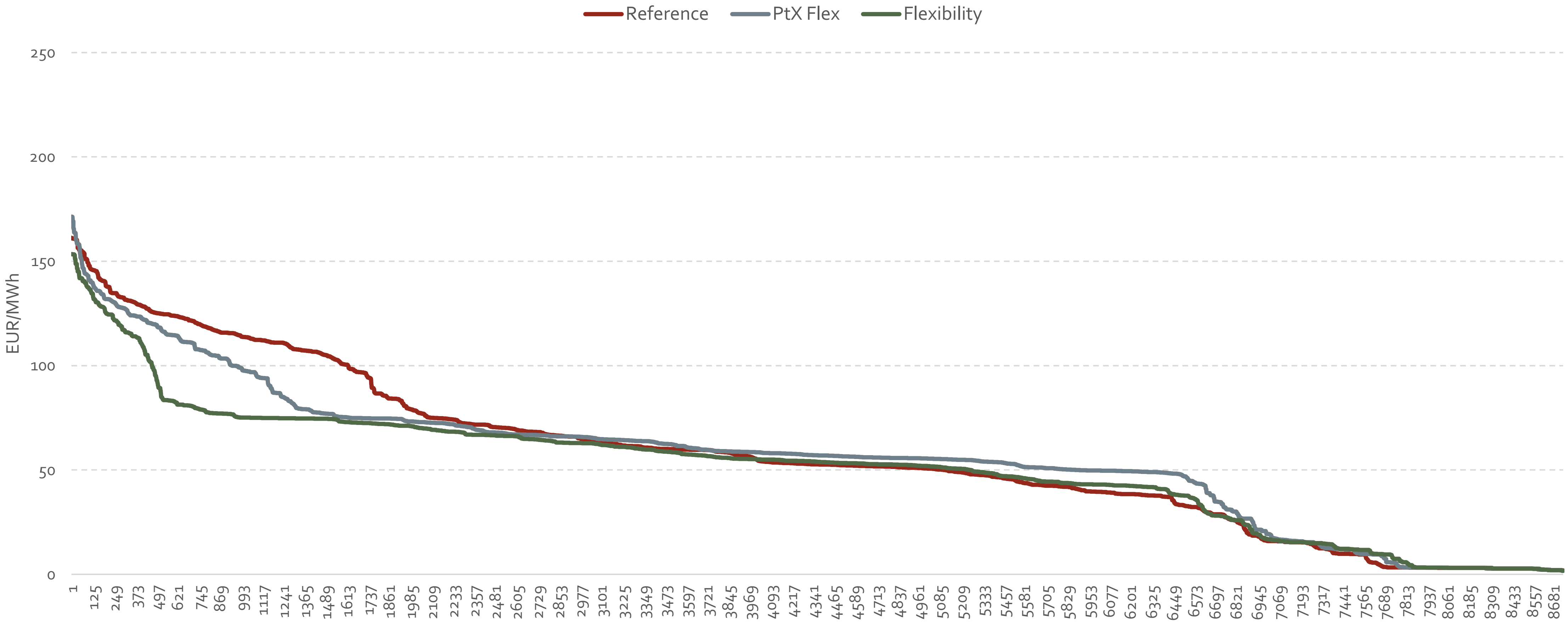
An overview of the resulting annual average electricity prices in selected countries can be found below. Average prices reflect the average hourly marginal generator's costs in the market. However, such averages provide a low level of insights in terms of the spread and magnitude that the individual hourly prices reflect. Metrics such as Price Duration Curves (PDCs) can illustrate the tendencies of the market across scenarios, while demand-weighted prices can reflect the level of prices when such demand levels are more active.

On the whole, it is evident that average electricity prices drop when flexibility means increase, due to the lower dependency on more expensive marginal generators or to excessive investment needs for satisfying the peak load of specific time slices.



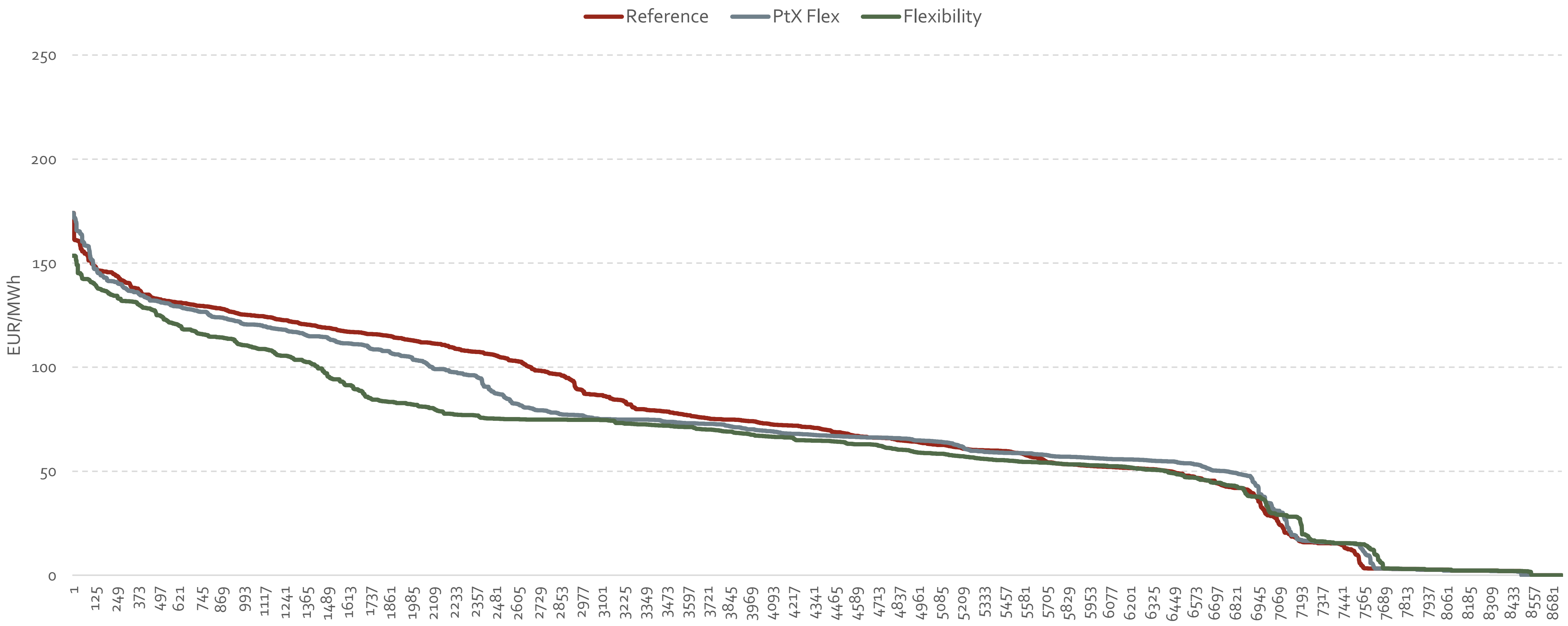
Price Duration Curves

Denmark - 2050

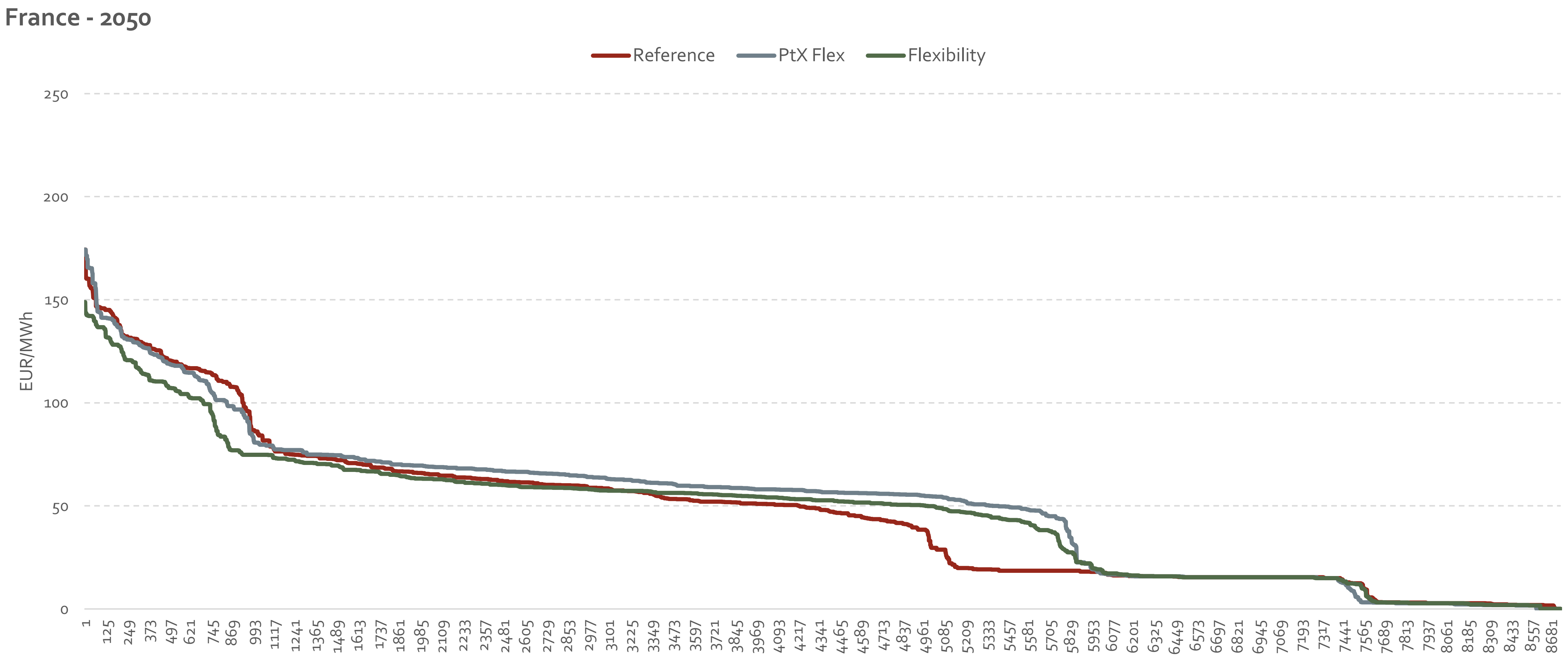


Price Duration Curves

Germany - 2050

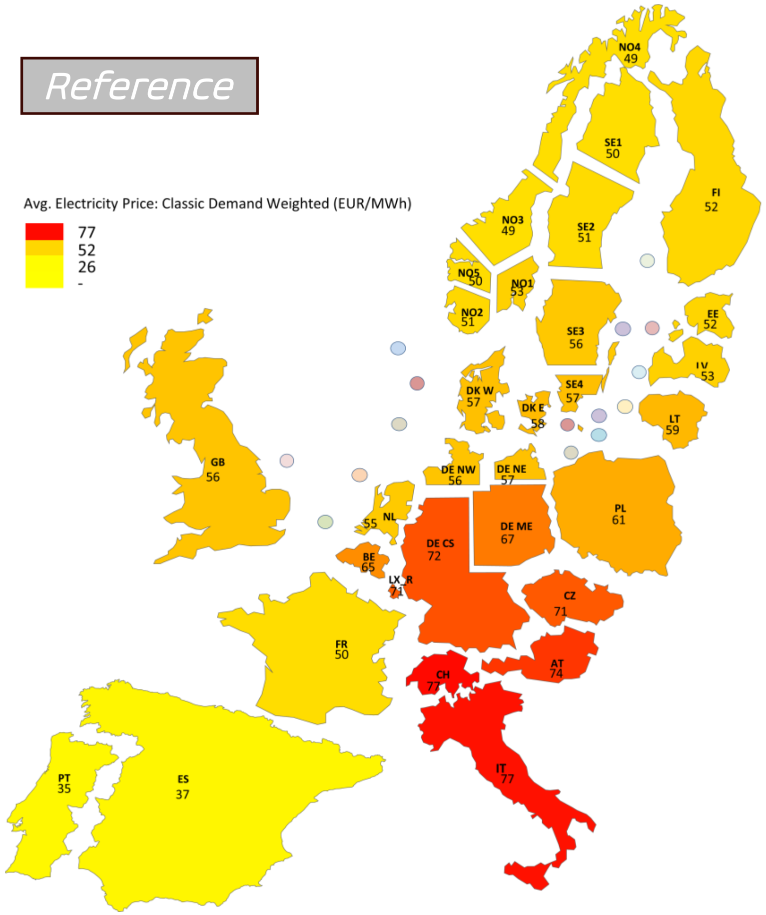


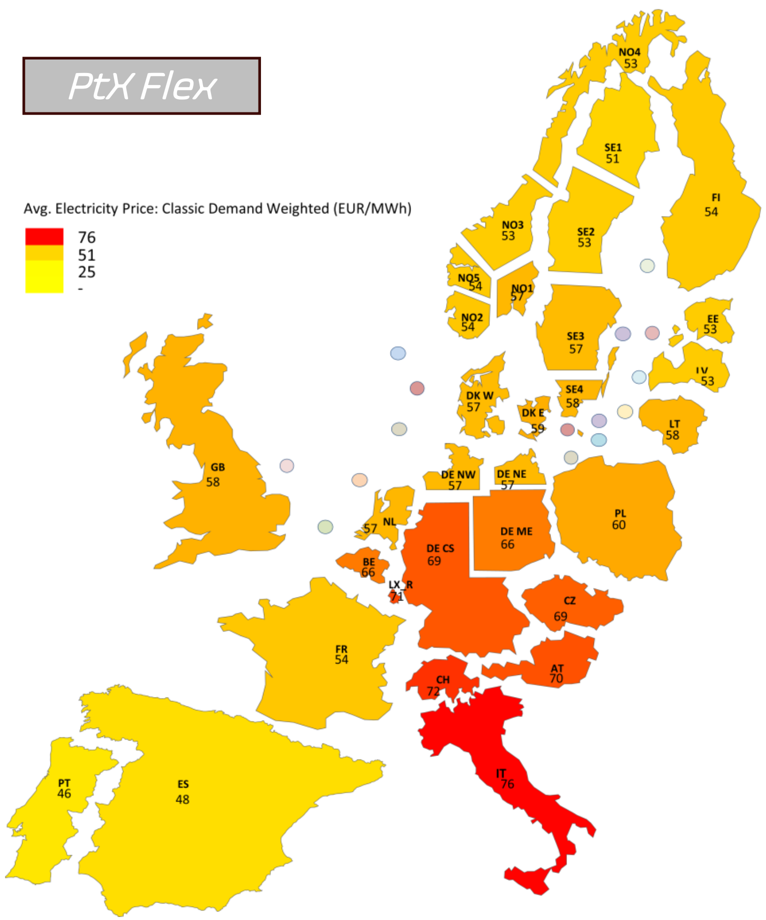
Price Duration Curves

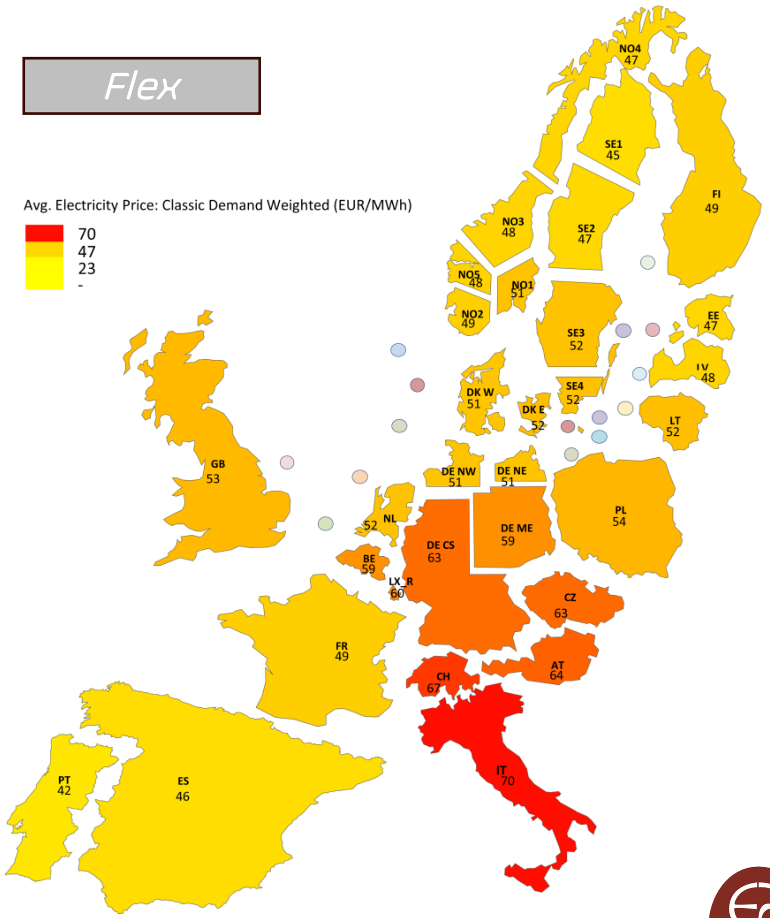


Demand Weighted Electricity Prices (2050)

The average demand-weighted electricity prices across the modelled geography are illustrated below for classic demand consumers. In most countries demand weighted prices drop, in some countries up to -11 €/MWh, however within the Iberian peninsula price rise on average by 7 to 8 €/MWh. Similar illustrations across years can be found in the Appendix.

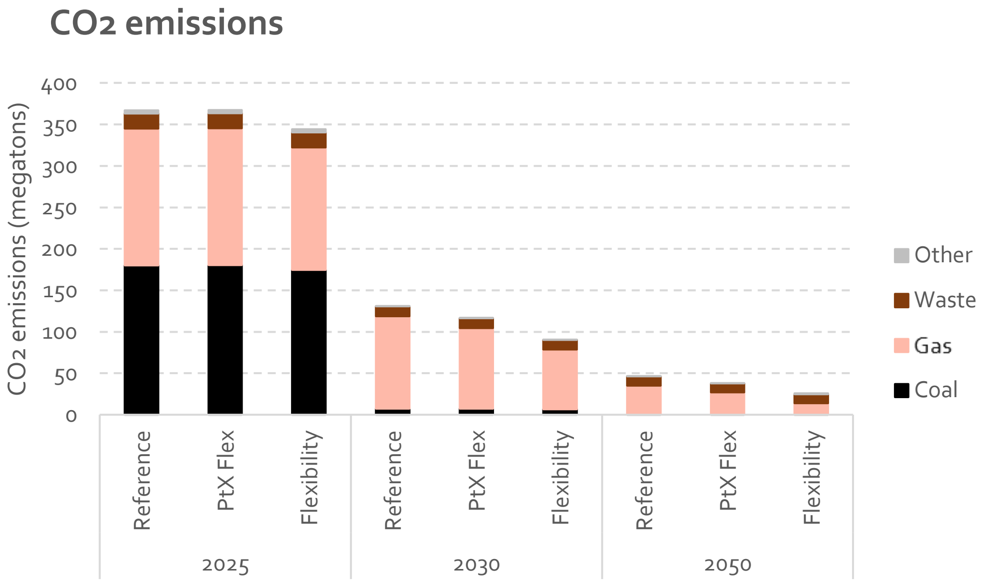


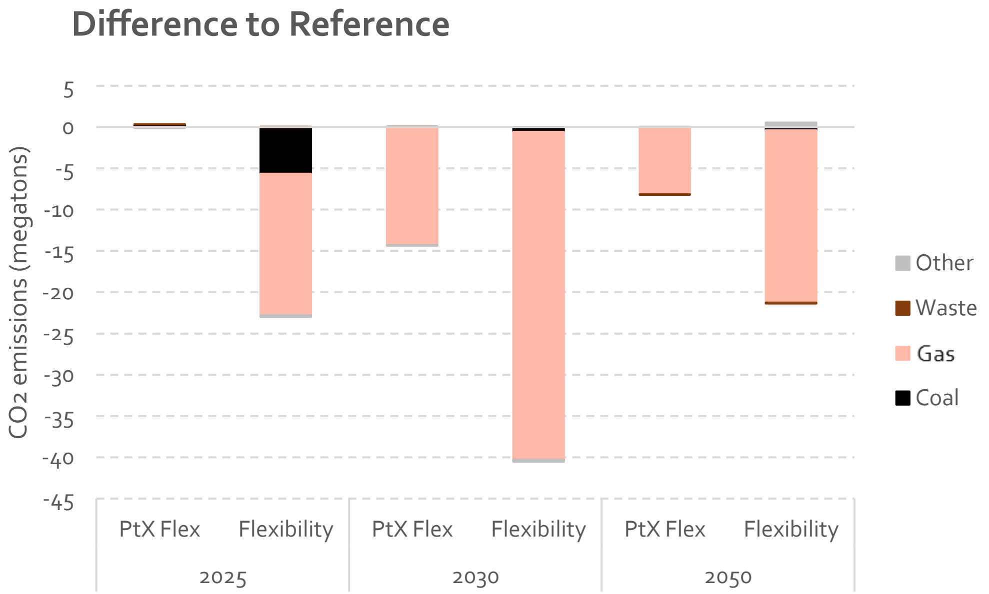


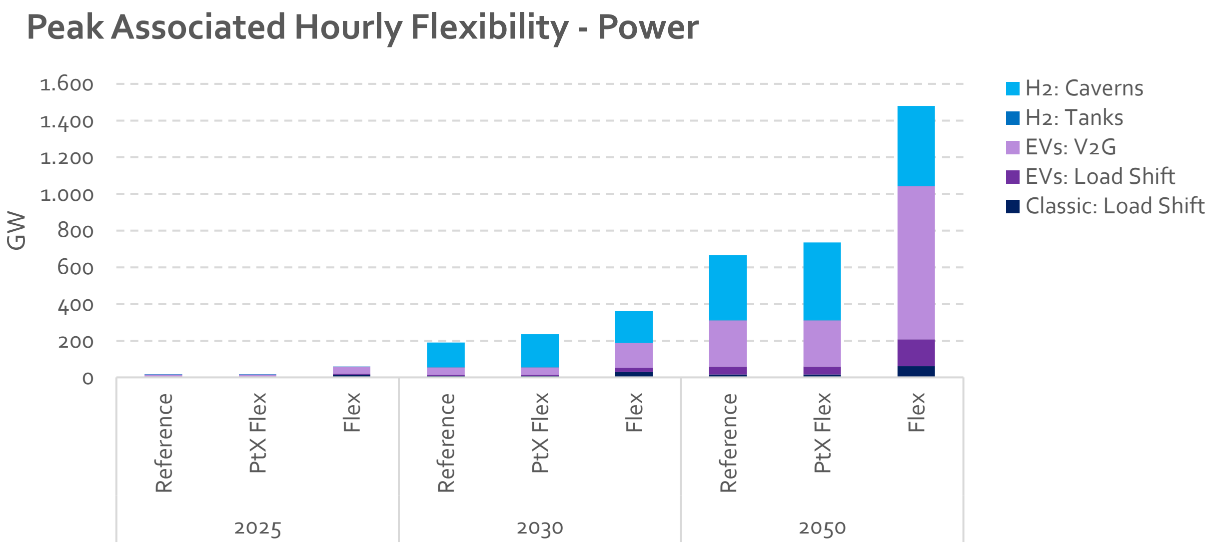


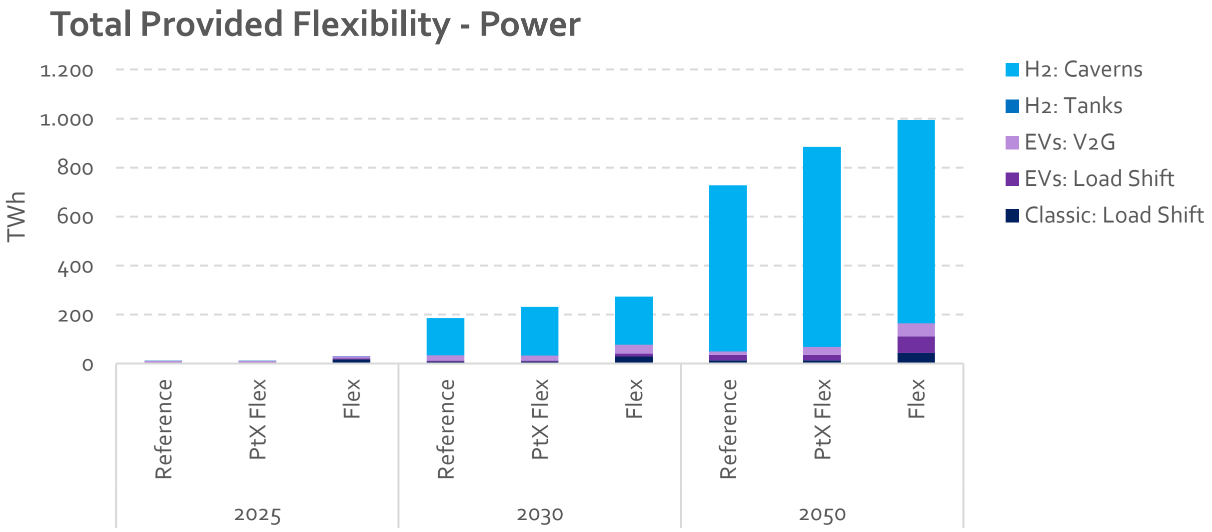
Emissions

- The total CO2 emissions from the power sector decline towards 2050. The green transition with more VRE and phase-out of fossil fuel use for power generation results in the majority of electricity being supplied by green generation.
- However, there are still further reductions to be seen as additional flexibility can help shift generation away from fossil fuels to solar, wind and hydro instead. In 2030, the PtX flex scenario provides additional CO2 savings of around 15 megaton. In the Flexibility scenario this almost triples to 40 megaton of reduced CO2 emissions compared to the Reference scenario.
- In 2050, the reductions in CO2 emissions are smaller due to the fact that there is less fossil fuel use in the power sector and therefore the effects of added flexibility will have a reduced effect on emission savings. However, the results show a not insignificant effect of around 20 megatons in the Flexibility scenario.
- If the EU are to reach their climate goals going towards 2050, the usage of natural gas in the long run have to shift to more green gases.
- *Note that in the modelling, gas supply is assumed to come from natural gas with a CO2-emission factor of 56 kg/GJ. Assuming EU gas supply is decarbonized by 2050, CO2 savings would be close to zero. The presented savings could then be financial rather than emissions based.*







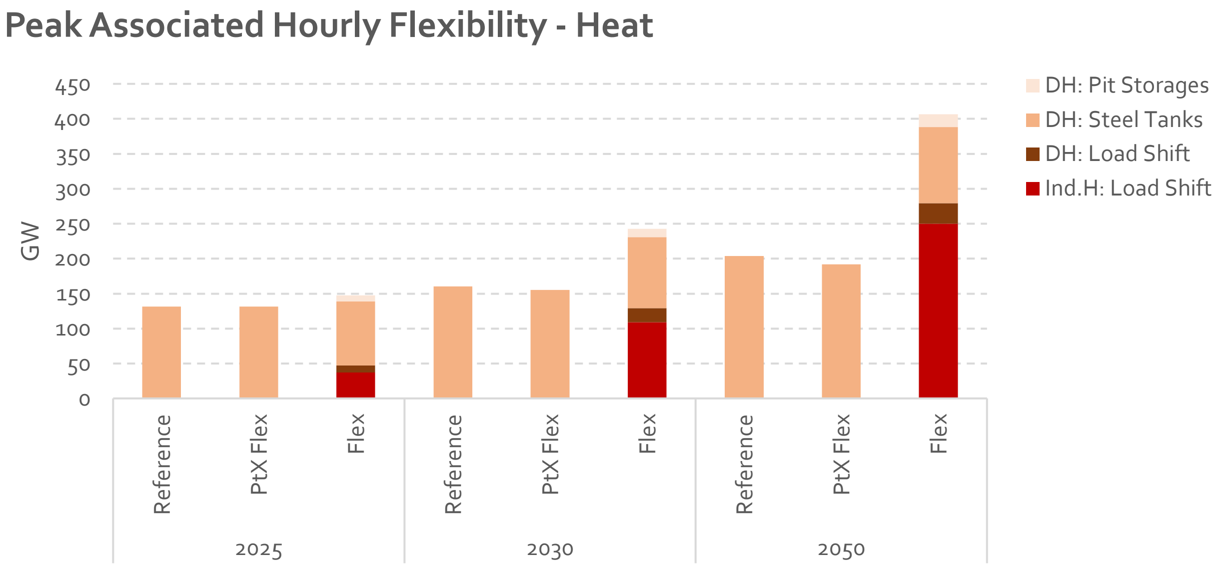


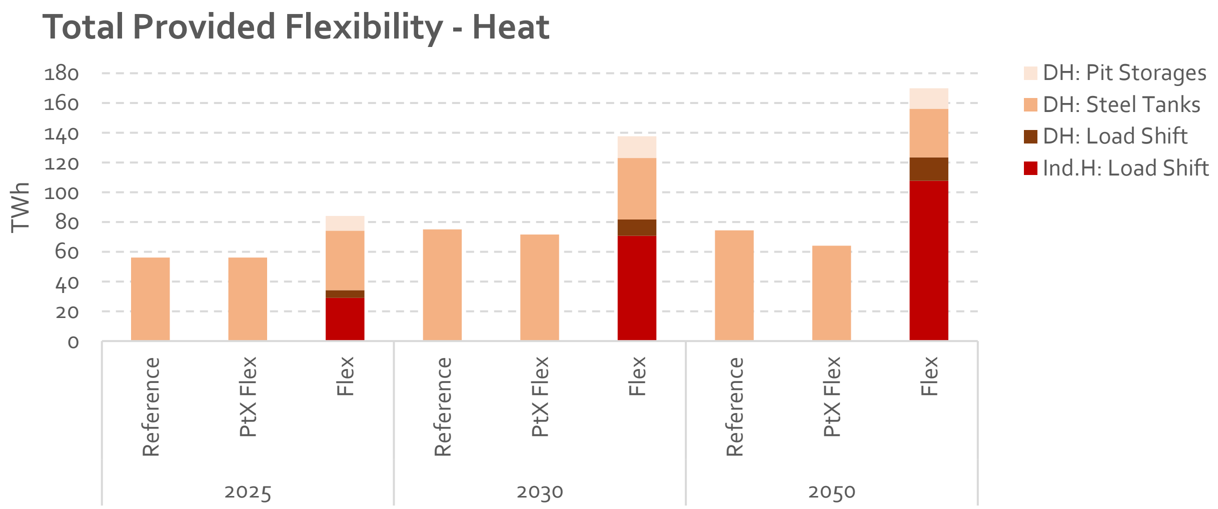
Note:
H2 flexibility is approximated in terms of Electricity input. This corresponds to the H2 storage loading/unloading capacity divided by the electrolysis efficiency in the respective year.

Total flexibility provision: Power

Based on the structured scenarios, the following observations can be made:

- Even though EV V2G hourly capacities almost quadruple in Flex, the total harvested flexibility only nearly doubles, revealing the fact that such flexibility is utilised for a relatively low number of periods but at large capacities.
- The allowances of classic demand load shift (up to 2 hours) rise to 43 TWh in 2050.
- The PtX sector provides vast majority of power side flexibility to the system by absorbing high levels of cheap power (renewable penetration). Nevertheless, the effects of additional flexibility measures on the demand side do not prove to be of competing nature with PtX flexibility, rather of an additive one (total Electricity to PtX flexibility via H2 storages rose from 817 to 829 TWh in 2050 when moving from PtX Flex to Flex scenario).





Total flexibility provision: Heat

Based on the structured scenarios, the following observations can be made:

- The potential of individual heating flexibility significantly increases while moving towards 2050.
- Its rising capacity more than doubles the total utilised heat flexibility in the Flex scenario, bringing it up to ~108TWh in 2050.
- A combination of seasonal heat storages (pit storages) with the possibility of load shift in district heating directly competes and halves the use of steel tanks. A combination of heat shifting across longer periods in parallel to intraday storages prove to be of more utility to the system's economics.

Note:
DH: District Heating.
Ind.H: Individual Heating.

Total Flexibility Capacities & Provision: Overview

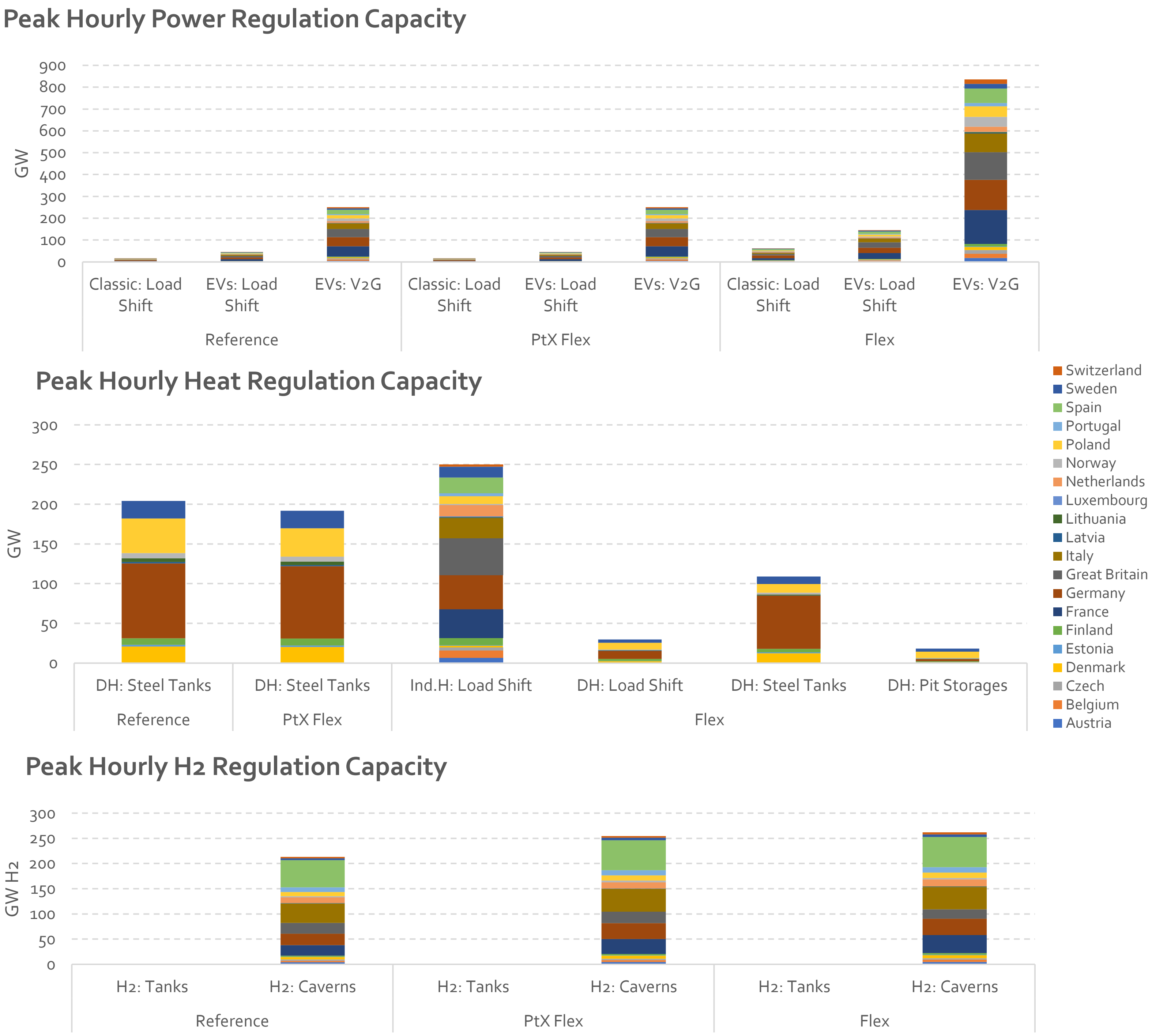
		Reference			PtX Flex			Flex		
Demand bucket	Flex type (GW)	2025	2030	2050	2025	2030	2050	2025	2030	2050
Classic	*Load shift*	4	7	15	4	7	15	14	30	62
Electric Vehicles (EVs)	*Load shift*	2	7	45	2	7	45	6	23	145
	V2G	11	40	251	11	40	251	37	134	836
Individual Heating	*Load shift*	-	-	-	-	-	-	37	109	250
District Heating	*Load shift*	-	-	-	-	-	-	10	20	30
	Storage: Steel tanks	132	160	204	131	155	192	91	102	109
	Storage: Pit storages	-	-	-	-	-	-	9	12	18
Electricity to PtX*	*Storage: Pressurised tanks*	1.22	1.22	1.15	1.63	1.63	1.54	1.63	1.63	1.54
	Storage: Caverns	-	135	354	-	179	423	-	173	435
Demand bucket	Flex type (TWh)	2025	2030	2050	2025	2030	2050	2025	2030	2050
Classic	*Load shift*	5	8	13	5	8	13	17	28	43
Electric Vehicles (EVs)	*Load shift*	1	4	22	1	4	22	4	12	68
	V2G	5	22	14	5	21	33	9	37	54
Individual Heating	*Load shift*	-	-	-	-	-	-	29	71	108
District Heating	*Load shift*	-	-	-	-	-	-	5	11	16
	Storage: Steel tanks	56	75	74	56	72	64	40	41	33
	Storage: Pit storages	-	-	-	-	-	-	10	15	14
Electricity to PtX*	*Storage: Pressurised tanks**	0.33	0.04	0.03	0.44	0.04	0.05	0.44	0.04	0.05
	Storage: Caverns	-	152	679	-	198	817	-	196	829

Note: Electricity to PtX flexibility is approximated in terms of the H2 storage loading/unloading capacity divided by the electrolysis efficiency in the respective year.

Mapping of flexibility abilities (2050)

A mapping of the total resulting flexibility potential across the modelled demand categories can be seen on the right.

- Due to the nature of each category, not all peak capacities are expected to operate in the same timesteps.
- Peak H2 regulation capacities are illustrated in terms of hydrogen units. Conversion to electricity equivalent would require division by the corresponding electrolysis efficiency (electricity to H2) in each respective year (2025: 57%, 2030: 57%, 2050: 60%).
- Naturally, larger flexibility potentials lie within countries with higher levels of electricity and heat demand (DE, FR, GB).

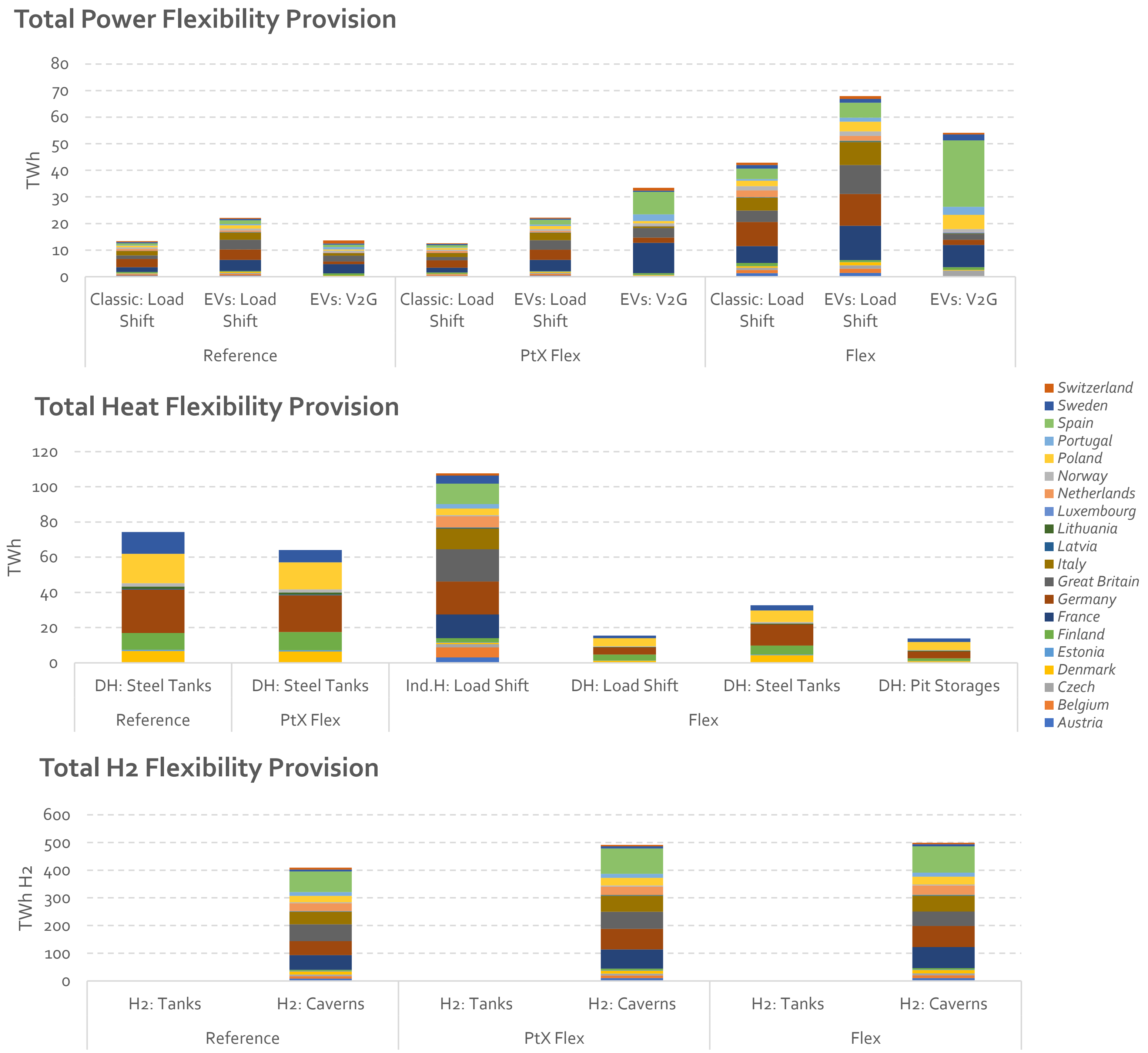


Note:
Y-Axes differ.
DH: District Heating.
Ind.H: Individual Heating.

Mapping of flexibility provision (2050)

A mapping of the resulting flexibility provision across the modelled demand categories can be seen on the right for each scenario.

- Naturally, larger flexibility potentials lie within countries with higher levels of electricity, heat and H2 demands (DE, FR, GB).
- In parallel, countries with high penetration of renewables (southern countries with high PV capacities (ES, IT)), and north-central countries with rising onshore and offshore wind generations (DE, FR, GB)) bring forward noticeable opportunities linked to hydrogen production flexibility.
- During hours with low power prices, production of H2 is preferred for distribution during higher price hours.



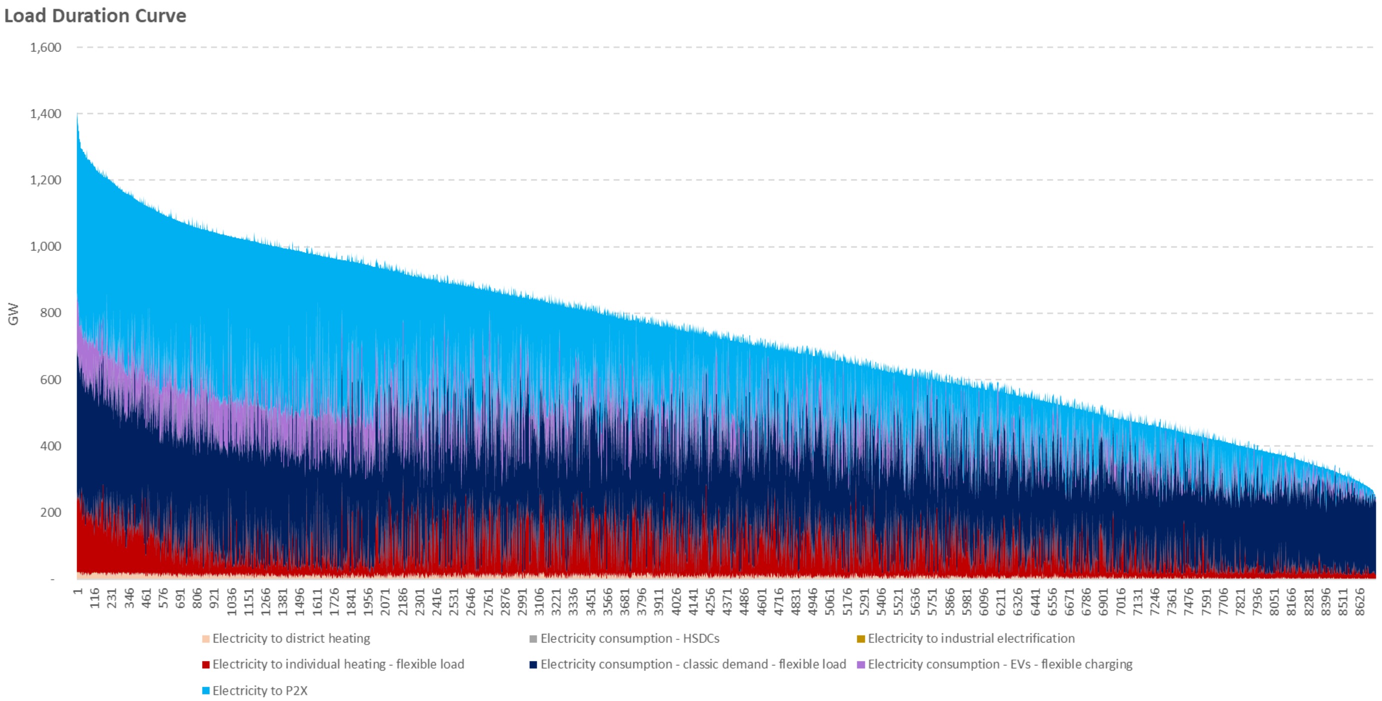
Note:
Y-Axes differ.
DH: District Heating.
Ind.H: Individual Heating.

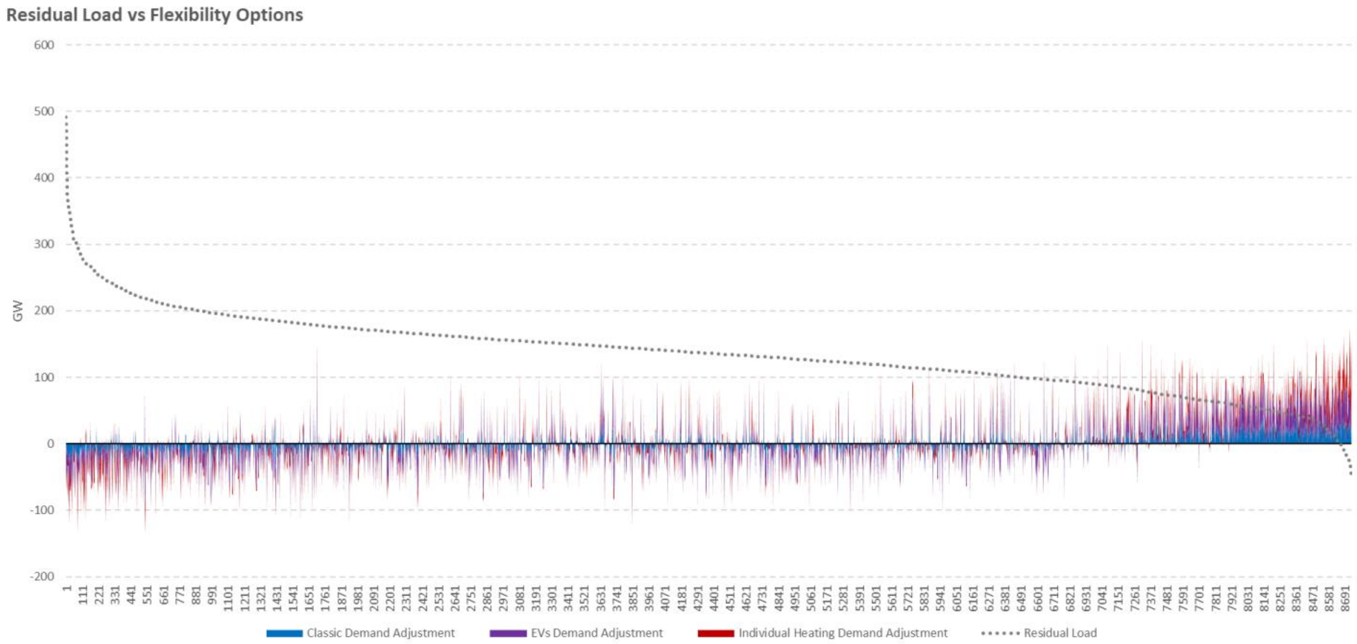
Residual Load Curve & Flexible Demand Shift (Flex, 2050)

- The resulting Load Duration Curve (LDC) in the most flexible analysed scenario ("Flex", 2050) showcases a peak electricity demand of roughly 1,400 GW and a minimum of approximately 240 GW. Electricity to PtX poses as the most significant contributor to those peaks, however this demand is more of a flexibility measure to the system absorbing high levels of renewable power during lower price hours (see next slide), rather than a burden.

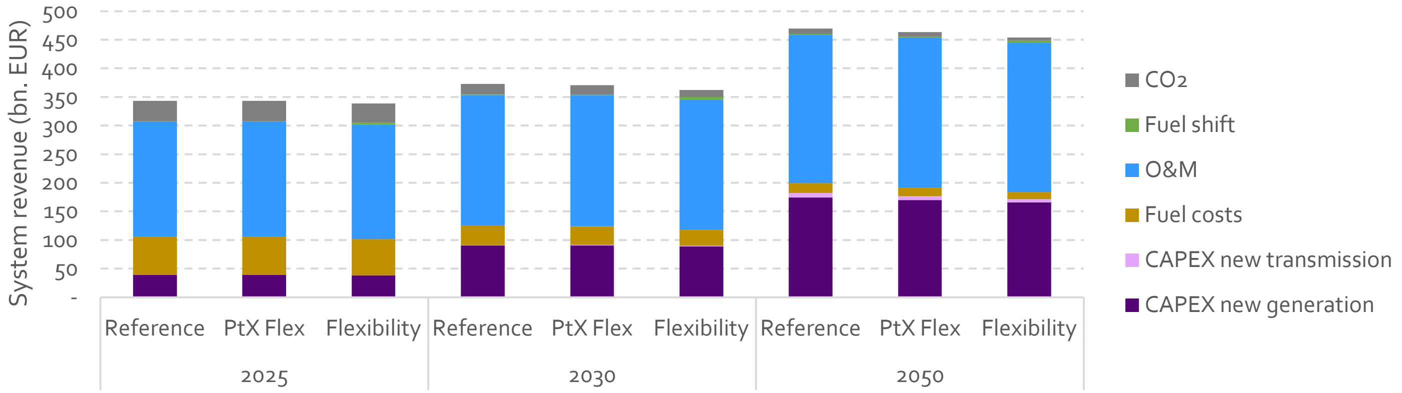
- Residual load is defined as the remaining net load after deducting the total Variable Renewable Energy (VRE) generation in the system (Solar PV and Onshore/Offshore Wind power). In systems with high shares of renewables, residual load is a metric of the system's temporal stress level, and the behaviour of flexible loads can highlight the value and magnitude that each provides to the system.

- On the bottom right figure, it becomes evident that all demand types which are eligible to load shifting are doing so when the system is more strained for power, and therefore is characterised by high power prices. In the Flex scenario, all 3 categories are down regulating their expected demands by on average 10GW in 2050. However, when up regulating, EVs are doubling their average change to 20GW with the other types sticking to 10GW. This is an evidence that EVs prefer to adjust their power consumption more rapidly than spending it and supporting their operation during other hours. The duration curves of these 3 demand category adjustments to their natural load profiles can be found in the Appendix.

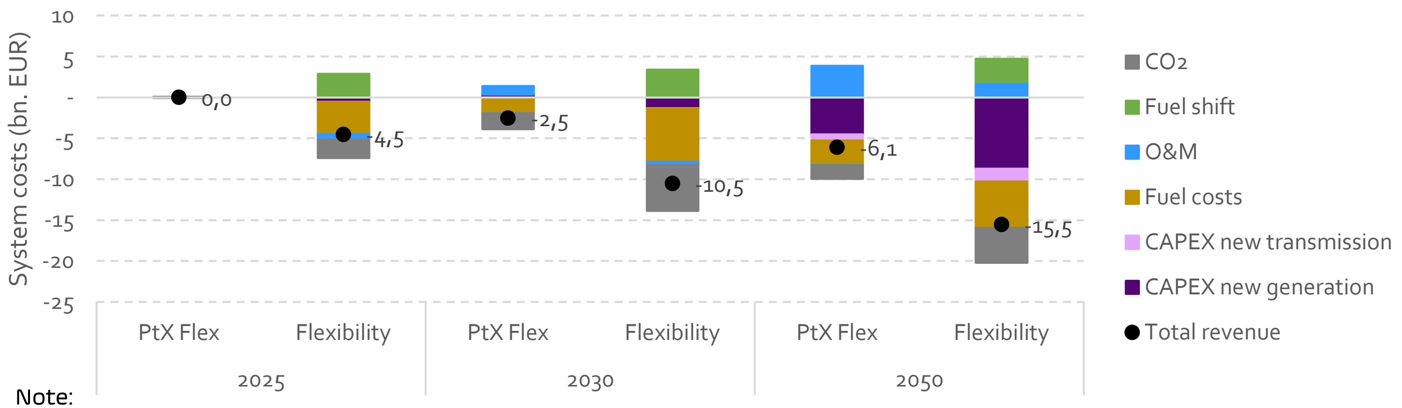




System costs



Total cost savings



Note:
Illustrated system costs reflect annualized values.

vs Reference:	2025		2030		2050	
	PtX Flex	Flex	PtX Flex	Flex	PtX Flex	Flex
Bn.€ of Total Annualised System Cost Savings:	0.0	-4.5	-2.5	-10.5	-6.1	-15.5
€/MWh Savings per Total Electricity Demand:	0.0	-1.44	-0.63	-2.66	-0.95	-2.44
% of Total System Cost Savings:	0.00%	-0.44%	-0.24%	-1.00%	-0.54%	-1.37%

Socioeconomics

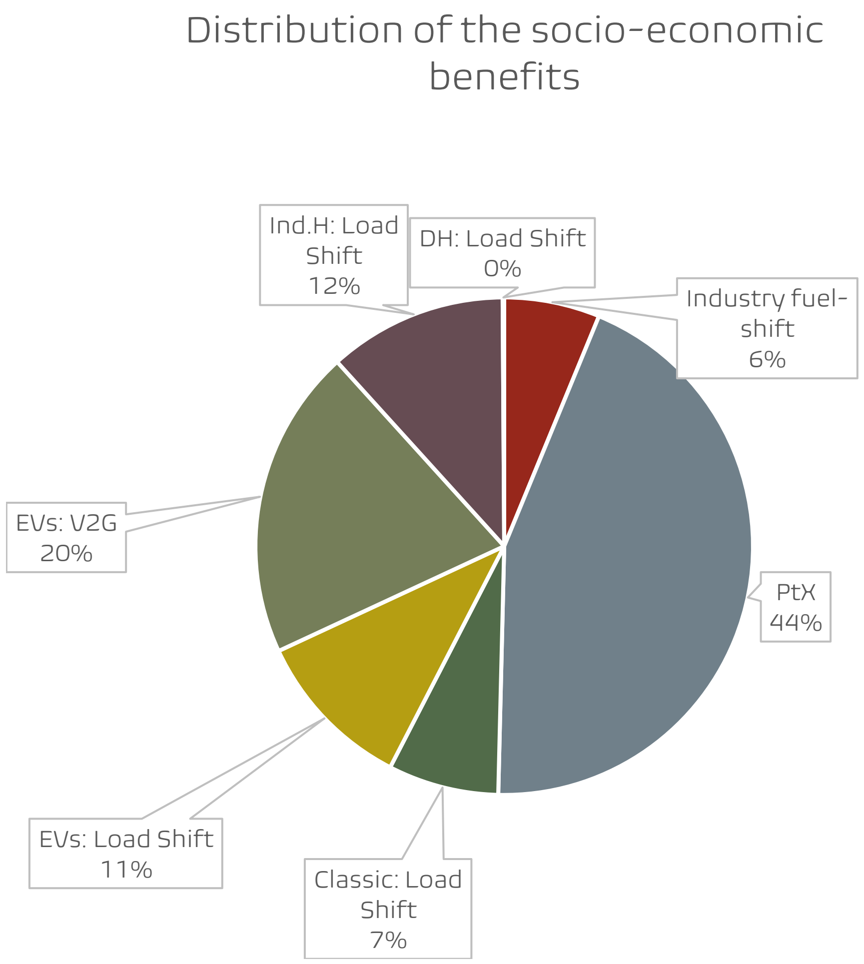
The total annualized system cost savings from the utilisation of the deployed flexibility measures stretch to 1.37% in 2050 when compared to the Reference scenario.

- Higher demand side flexibility allowances translate to replacement of conventional generators (e.g. gas based) with variable renewable energy sources (VRES). Such changes decrease the system's reliance to expensive fuel based sources and the corresponding emission costs.
- Fuel shift allows industrial consumers to change to boilers during high power price hours. The utilization of the boilers is represented as a socioeconomic cost in figure. The benefits are included as savings in the other categories, mainly capex of power generation facilitates, fuel cost and CO2 cost. Approximately half of the total fuel shift (20.4 out of 40 TWh) takes place in Germany and Italy. Nevertheless, such costs are overturned by other category savings, with the net system savings increasing with the addition of further flexibility measures.

Distribution of benefits between DR measures

- The figure shows the socio-economic benefit (Flex vs. Reference) in 2050 divided on the different sources of demand response*
- More than 40% of the total socio-economic benefit stem from the more flexible electricity use at PtX plants, whereas EV's (load-shift and V2G) contribute with around 30% of the total benefit.

*Note this division of the socio-economic benefits is associated with some level of methodological uncertainty. Benefits related to heat storages are not depicted.



Average Consumer Electricity Price Outlook

An estimation of a European-wide average electricity price can be approximated when evaluating the total consumption related costs with the overall consumption across the modelled geography. The consumption costs and quantities reflect electricity utilised in the following categories: Classic demand, Electric Vehicles and Individual Heating.

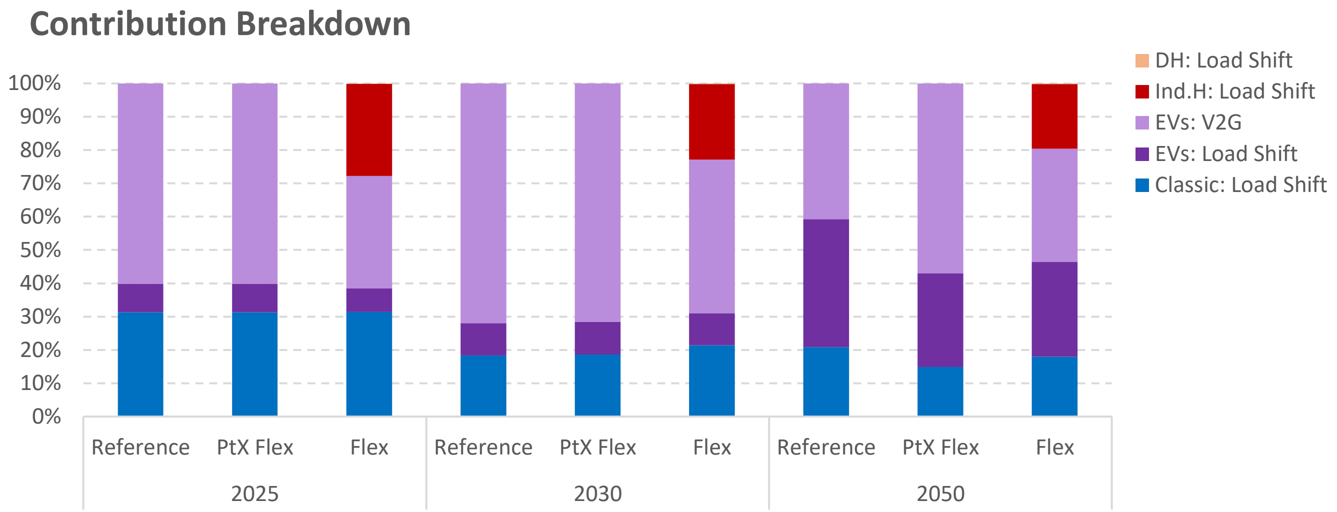
Scenario	Year	Total Consumer Cost (Bn.€)	Consumption (TWh)	Avg. Electricity Price (€/MWh)
Reference	*2025*	355	3,143	113
	2030	272	3,533	77
	2050	257	4,225	61
PtX Flex	*2025*	355	3,143	113
	2030	271	3,533	77
	2050	262	4,225	62
Flex	*2025*	349	3,142	111
	2030	255	3,530	72
	2050	231	4,223	55

Appendix

Load-shift Flexibility Economy

The system benefits reaped from load-shift and V2G demand-side flexibility can be seen on the right per scenario and year.

The system benefits from load shift and V2G in 2050 almost triple with the introduction of various and more ambitious flexibility measures.

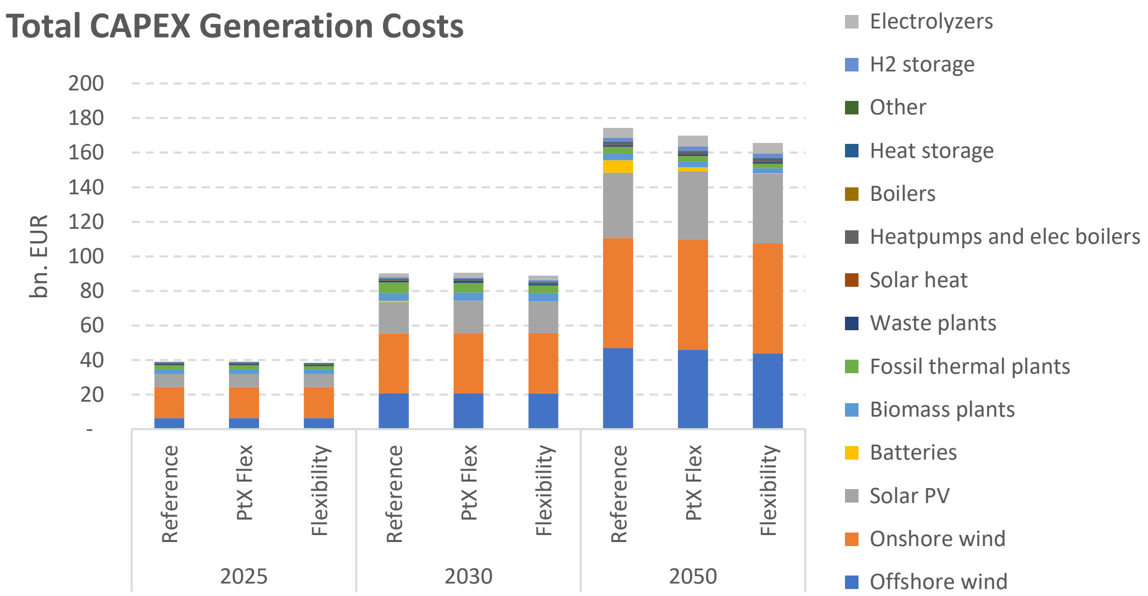


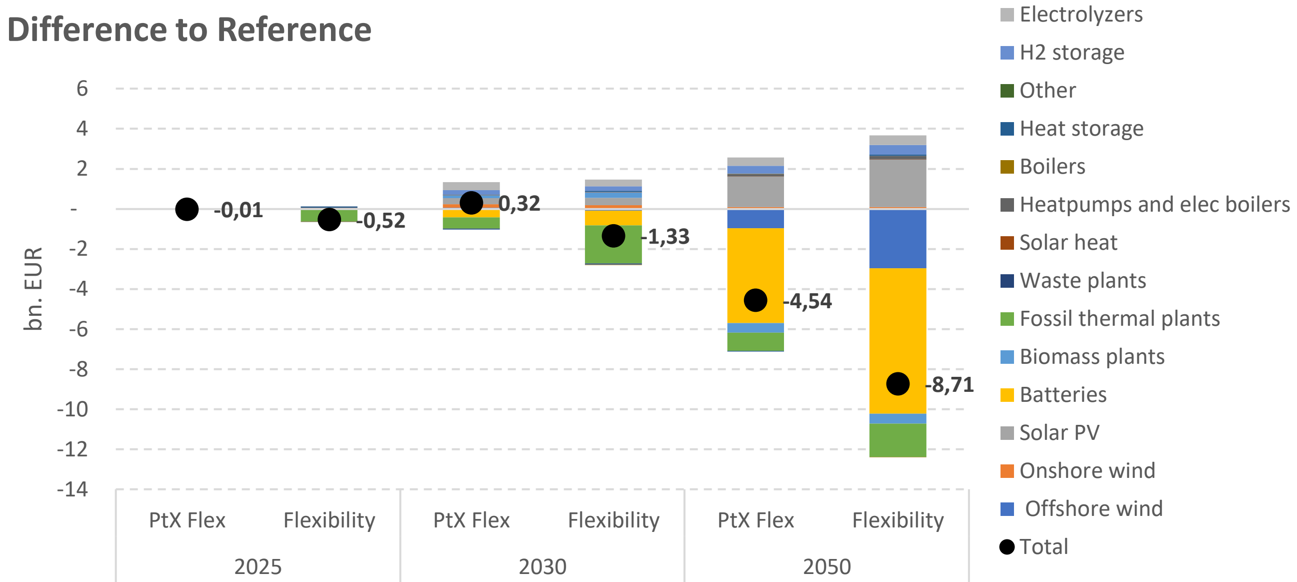
Note: Total system benefits rise as moving to more flexible scenarios, so the breakdown naturally changes and does not reflect a direct competition.

System Benefits Attributed to Demand Side Flexibility Actions (M€)

Year	Load type	Reference	PtX Flex	Flex
2025	Classic: Load Shift	266	266	740
	EVs: Load Shift	73	73	167
	EVs: V2G	512	511	793
	Ind.H: Load Shift			650
	DH: Load Shift			4
2025 Total		851	850	2,354
2030	Classic: Load Shift	486	482	1,288
	EVs: Load Shift	255	252	579
	EVs: V2G	1,905	1,851	2,769
	Ind.H: Load Shift			1,367
	DH: Load Shift			10
2030 Total		2,646	2,585	6,013
2050	Classic: Load Shift	561	592	1,718
	EVs: Load Shift	1,037	1,125	2,725
	EVs: V2G	1,100	2,269	3,259
	Ind.H: Load Shift			1,868
	DH: Load Shift			16
2050 Total		2,698	3,985	9,586

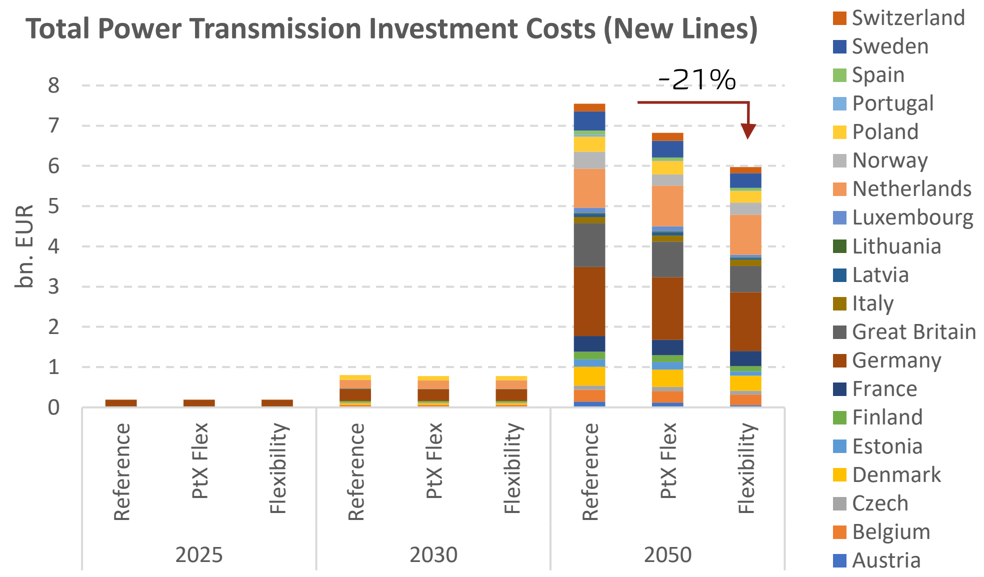
Savings in capex of generation units

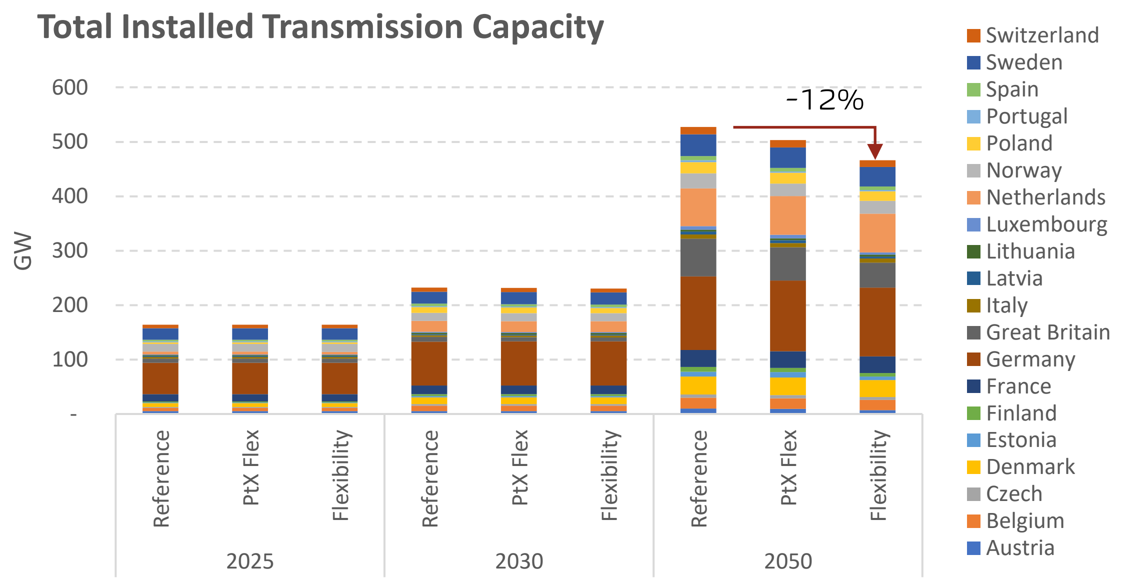


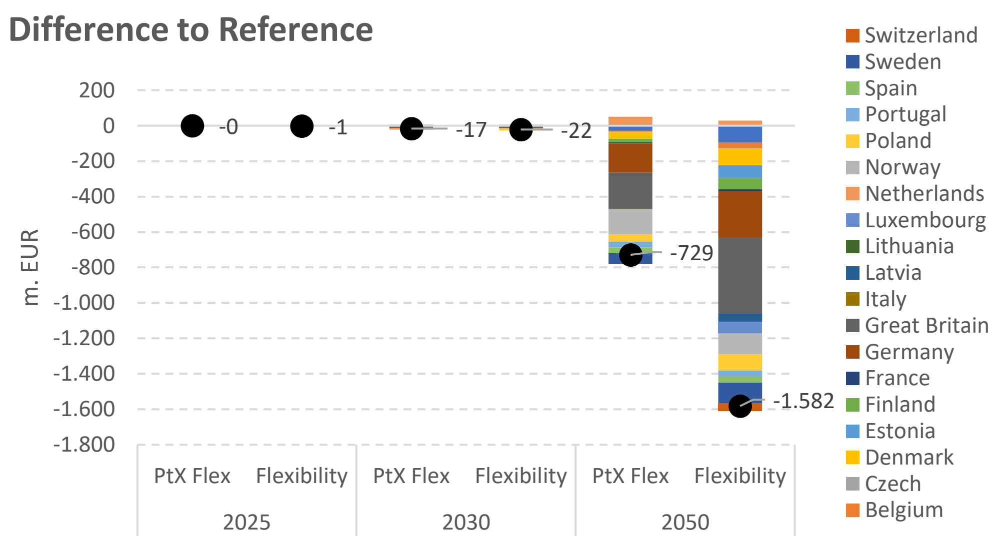


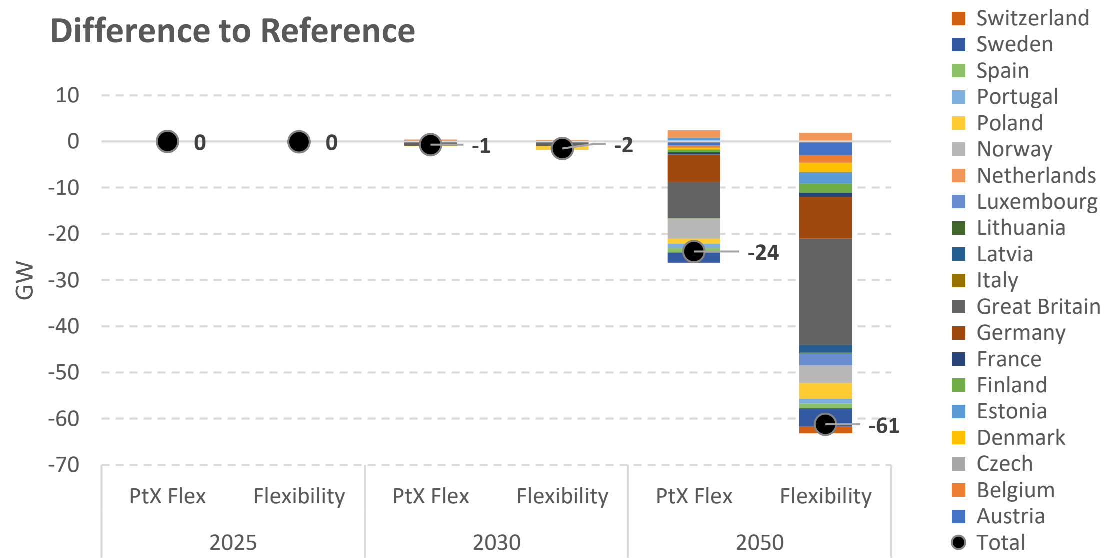
Savings in transmission capacities

Note that savings for countries with more than one bidding zones (DE, DK, NO, SE) may be attributed to decrease in national interconnections.



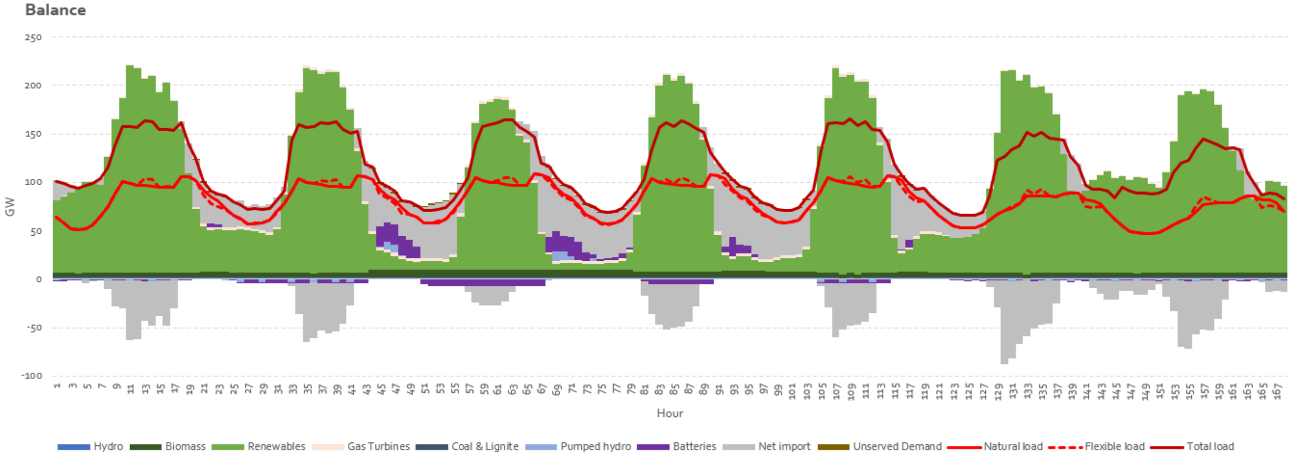


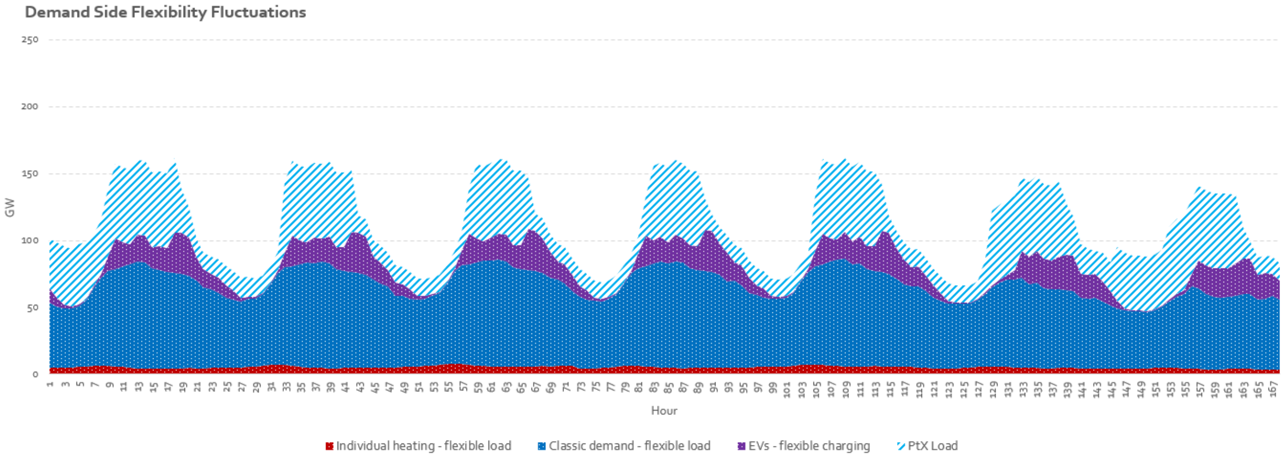




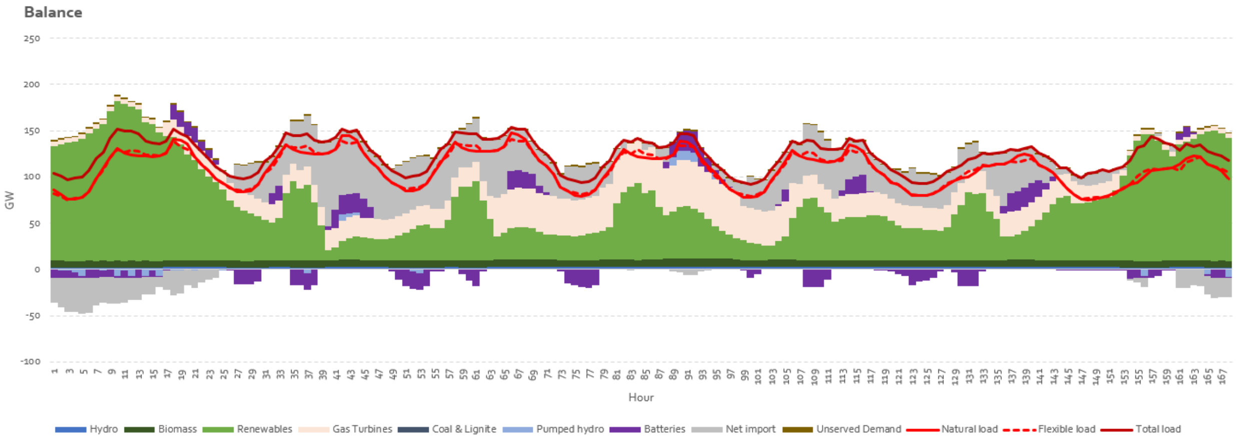
PtX flexibility and VRE correlations: *Germany, Reference, 2050*

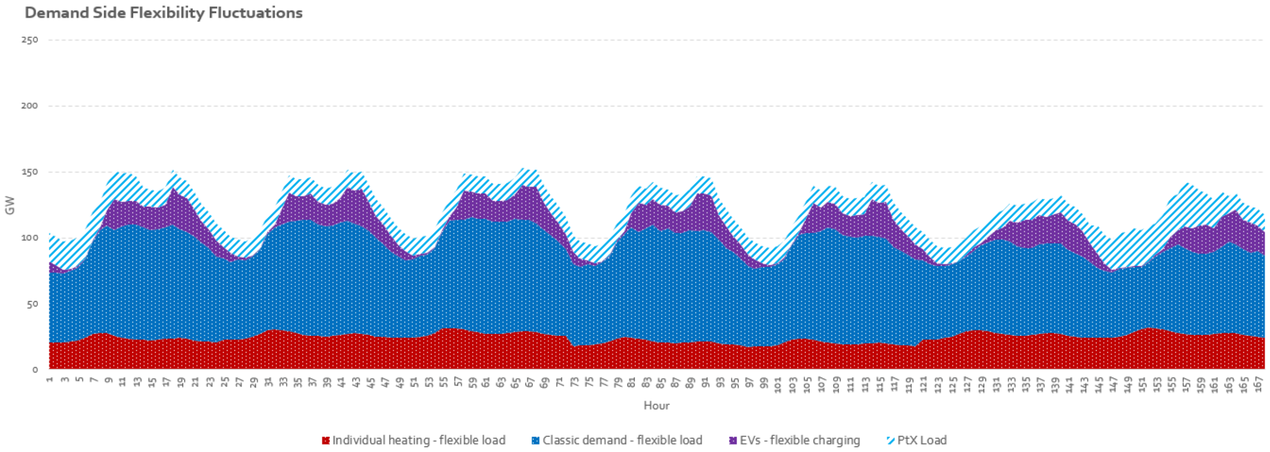
High VRE Week (Week 28)





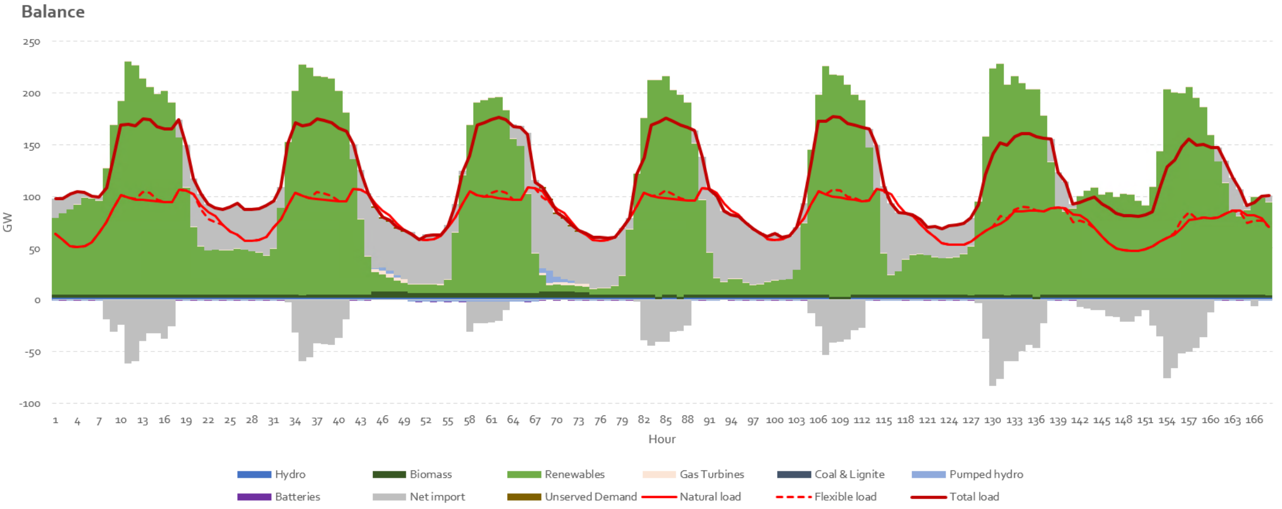
Low VRE Week (Week 48)

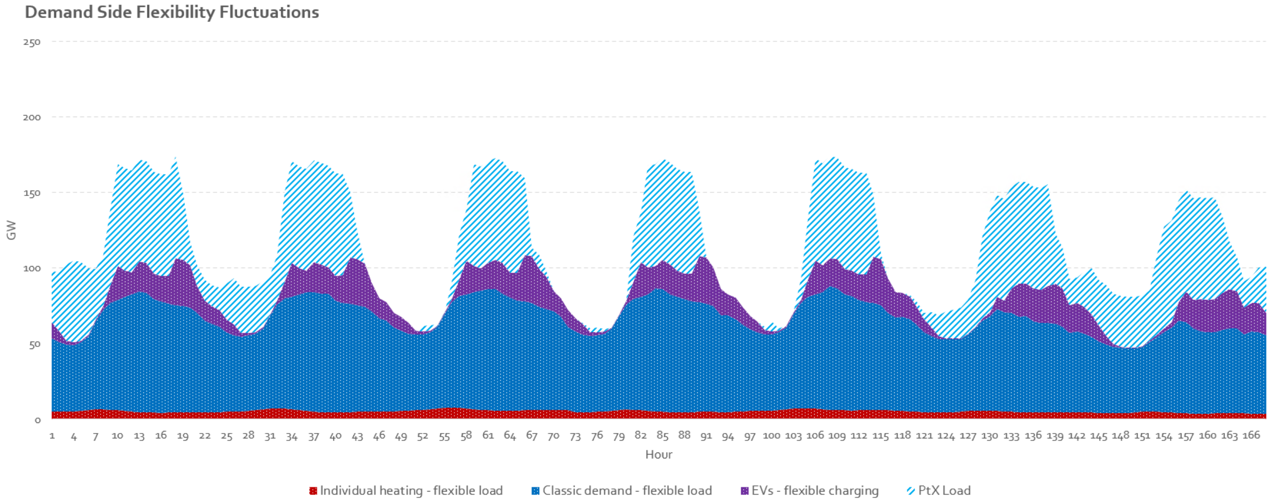




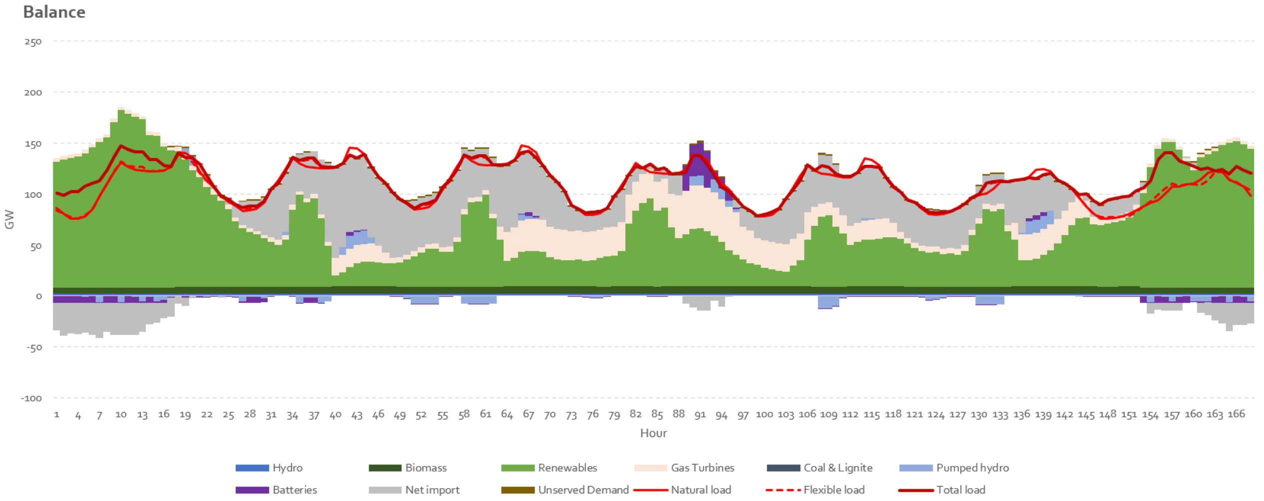
PtX flexibility and VRE correlations: *Germany, PtX Flex, 2050*

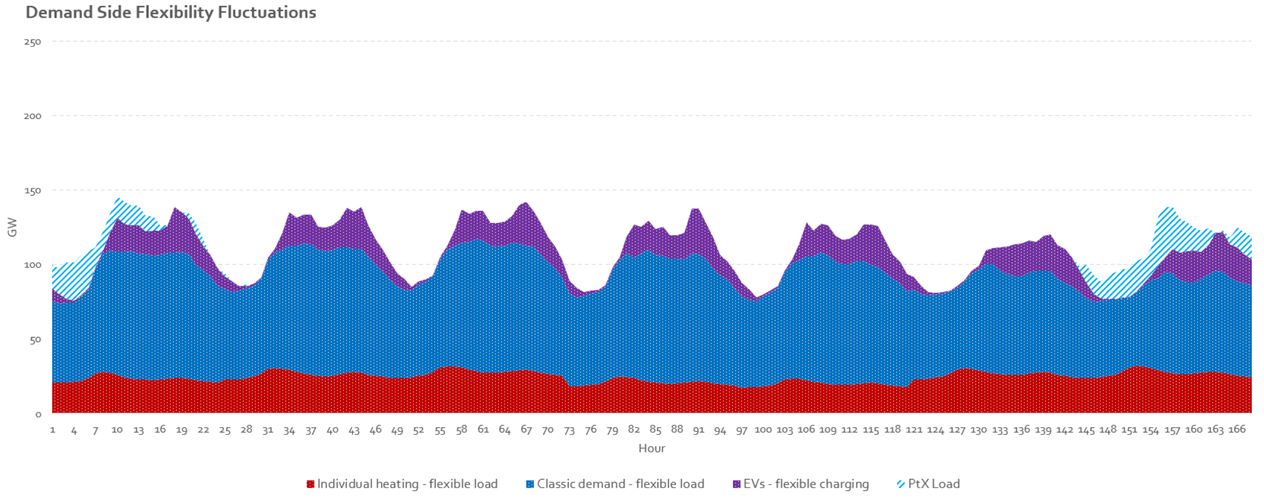
High VRE Week (Week 28)





Low VRE Week (Week 48)

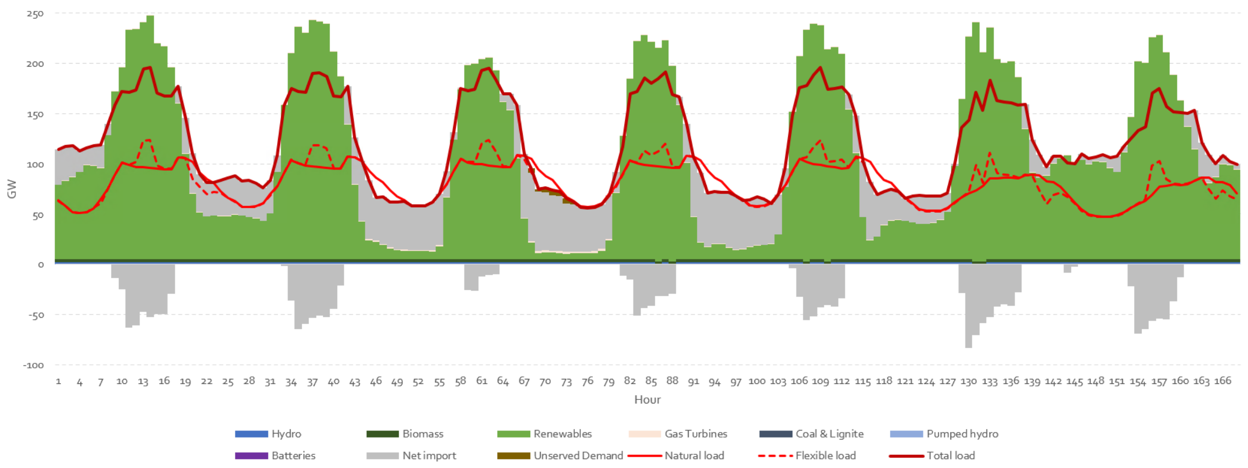




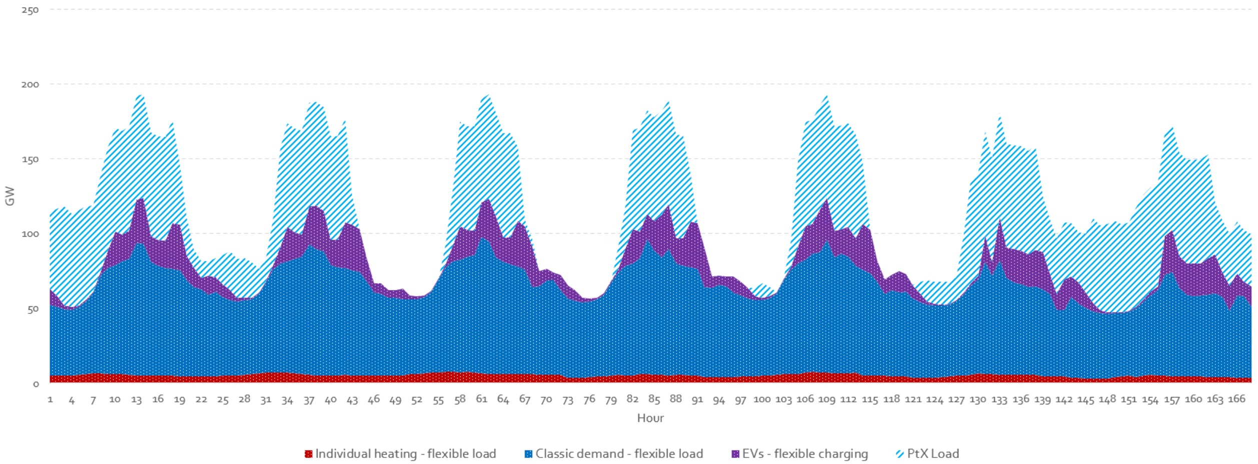
PtX flexibility and VRE correlations: *Germany, Flex, 2050*

High VRE Week (Week 28)

Balance

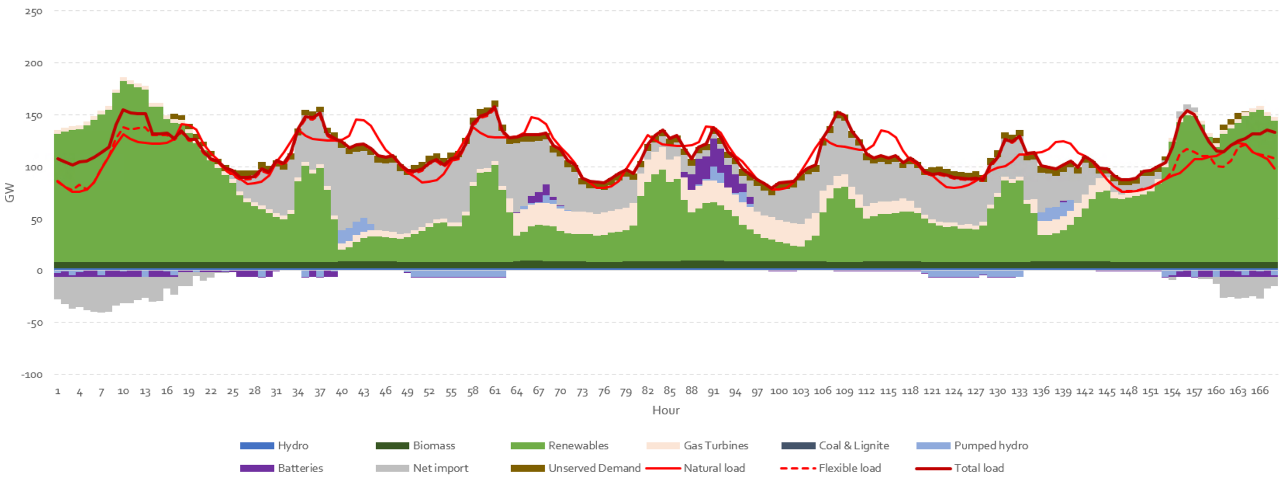


Demand Side Flexibility Fluctuations

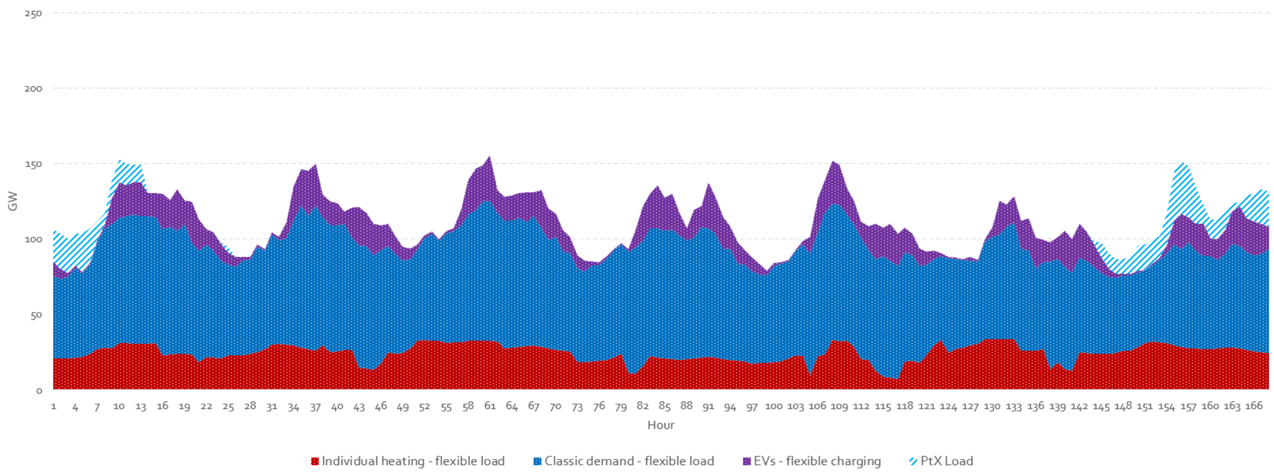


Low VRE Week (Week 48)

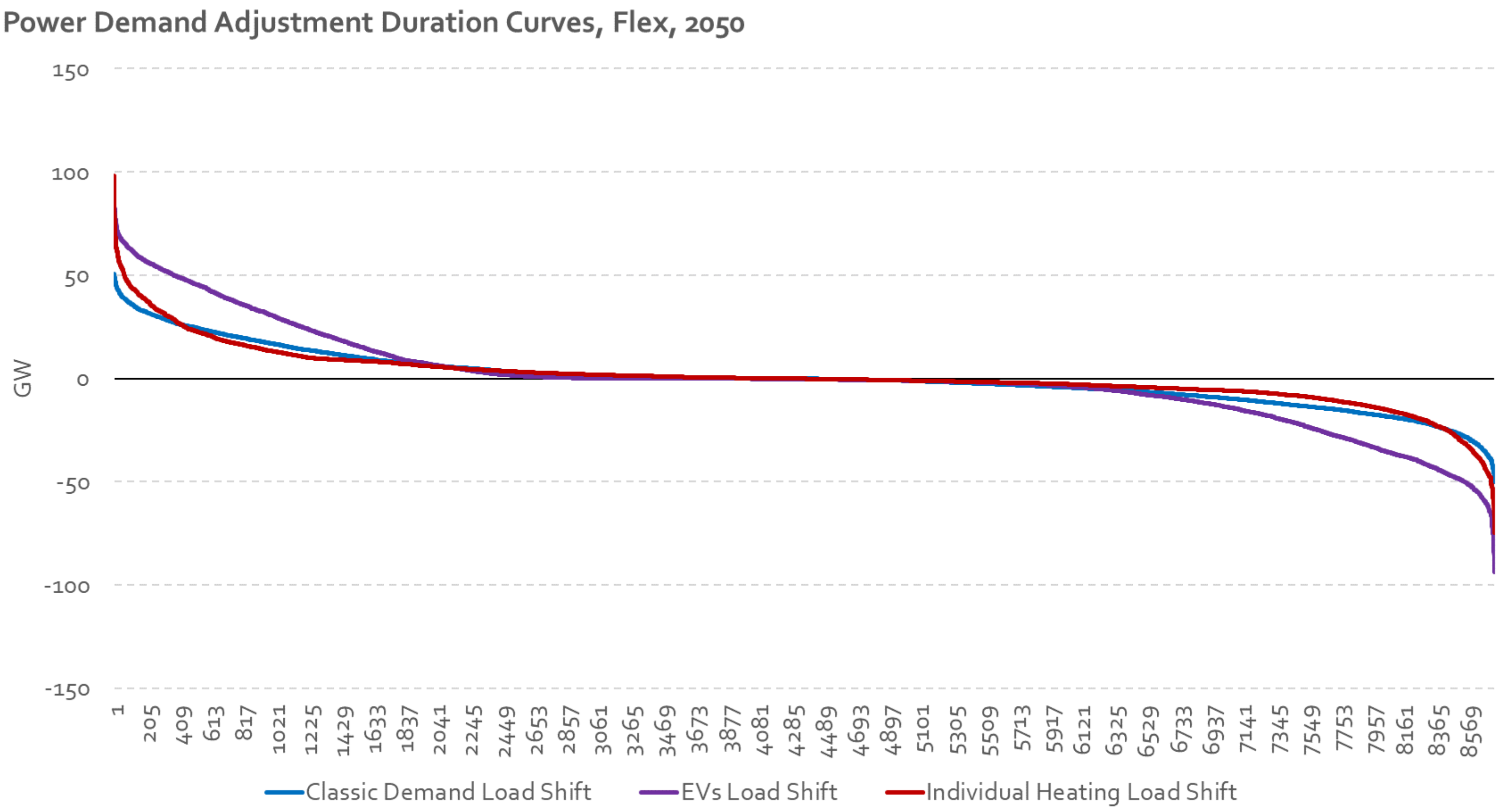
Balance



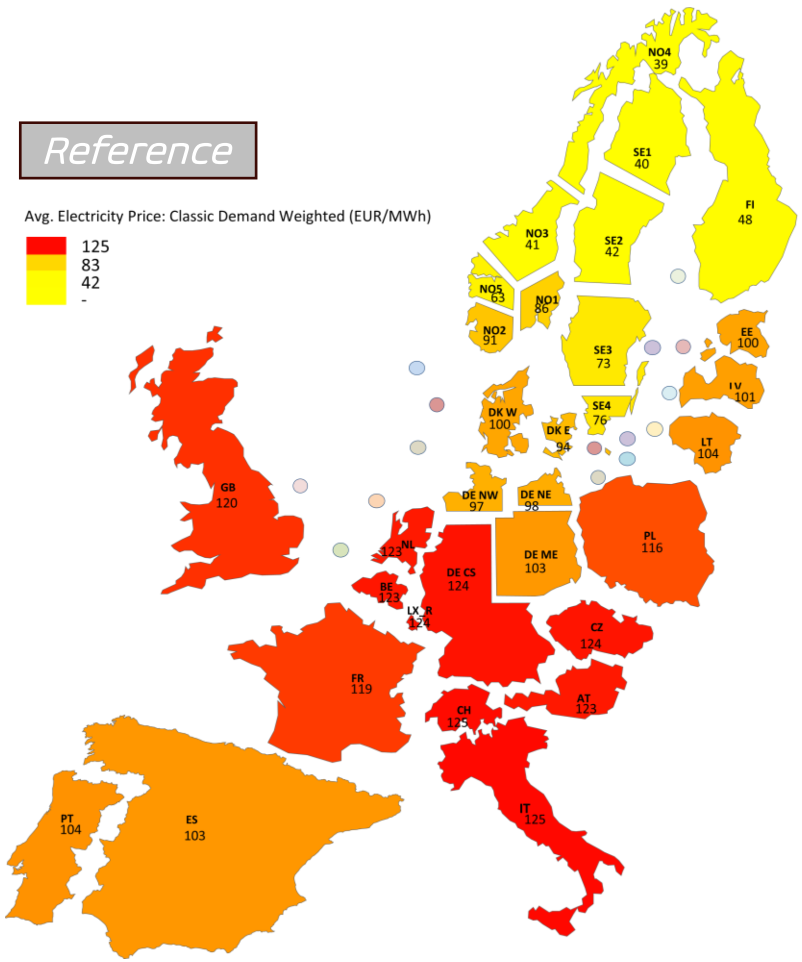
Demand Side Flexibility Fluctuations

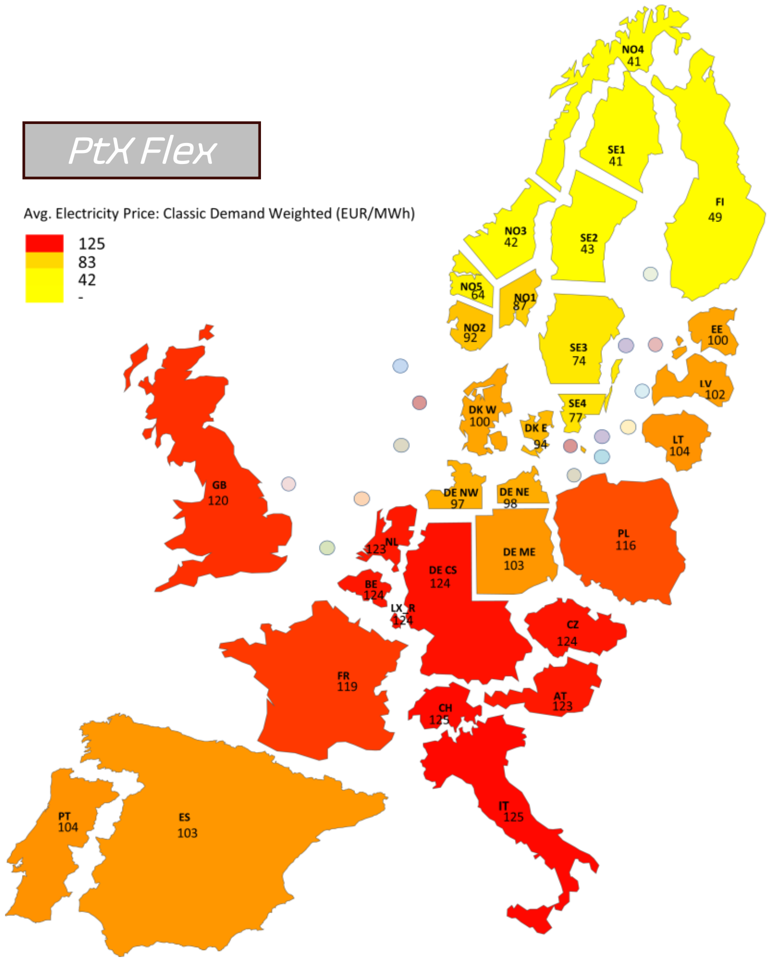


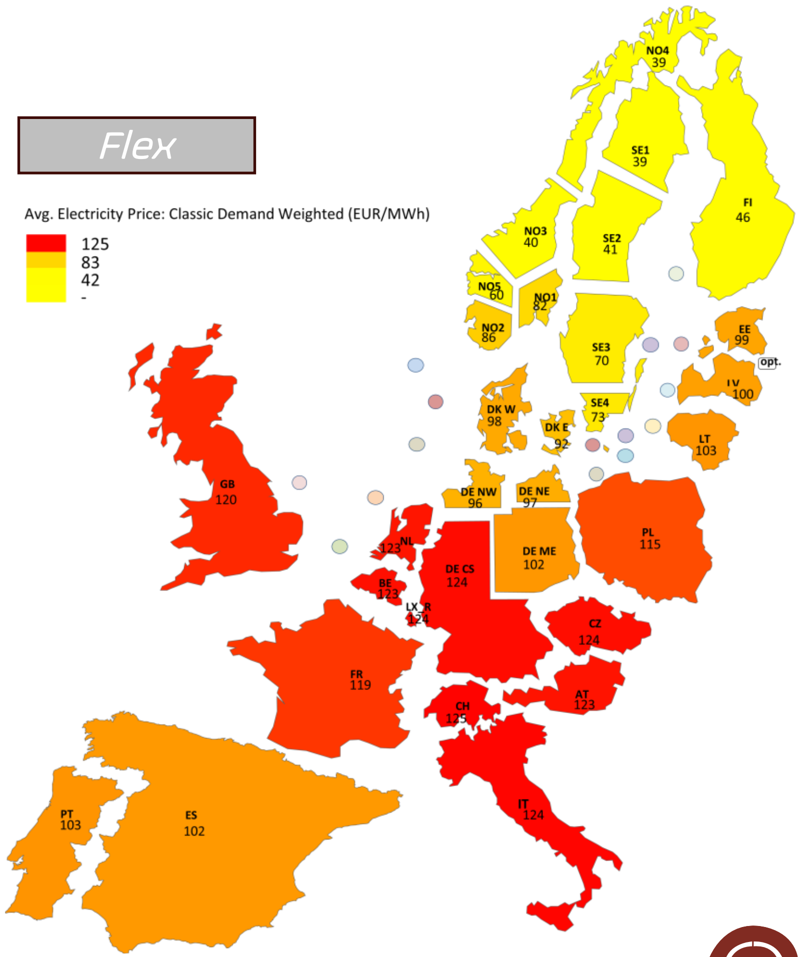
Power Demand Adjustment Duration Curves



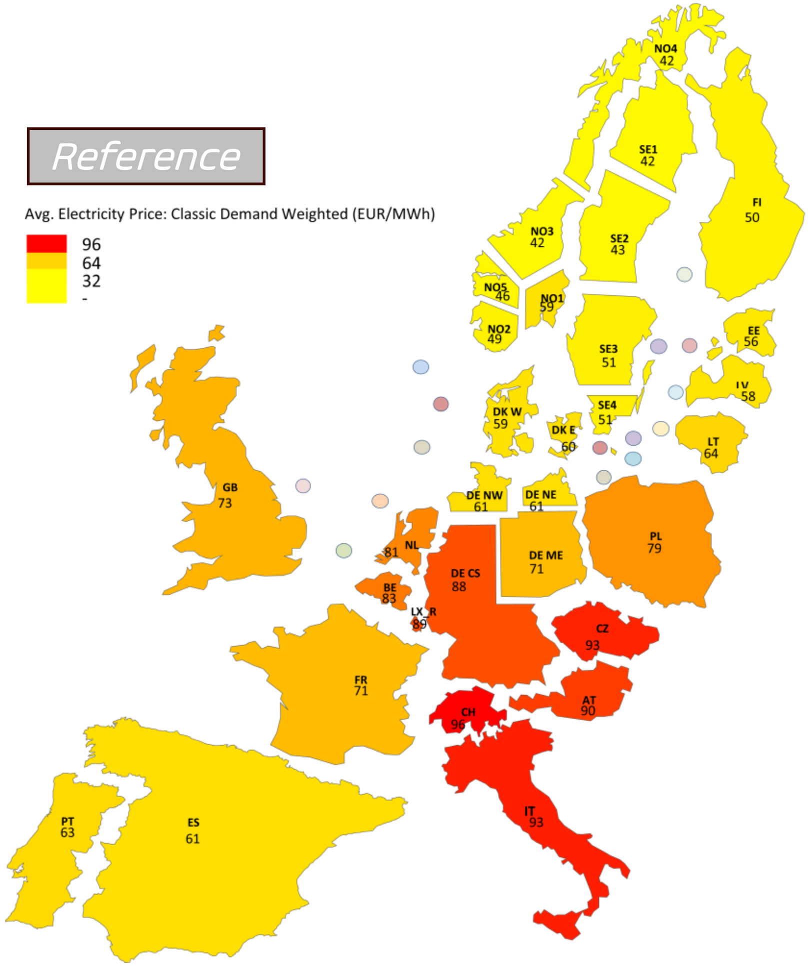
Demand Weighted Electricity Prices (2025)

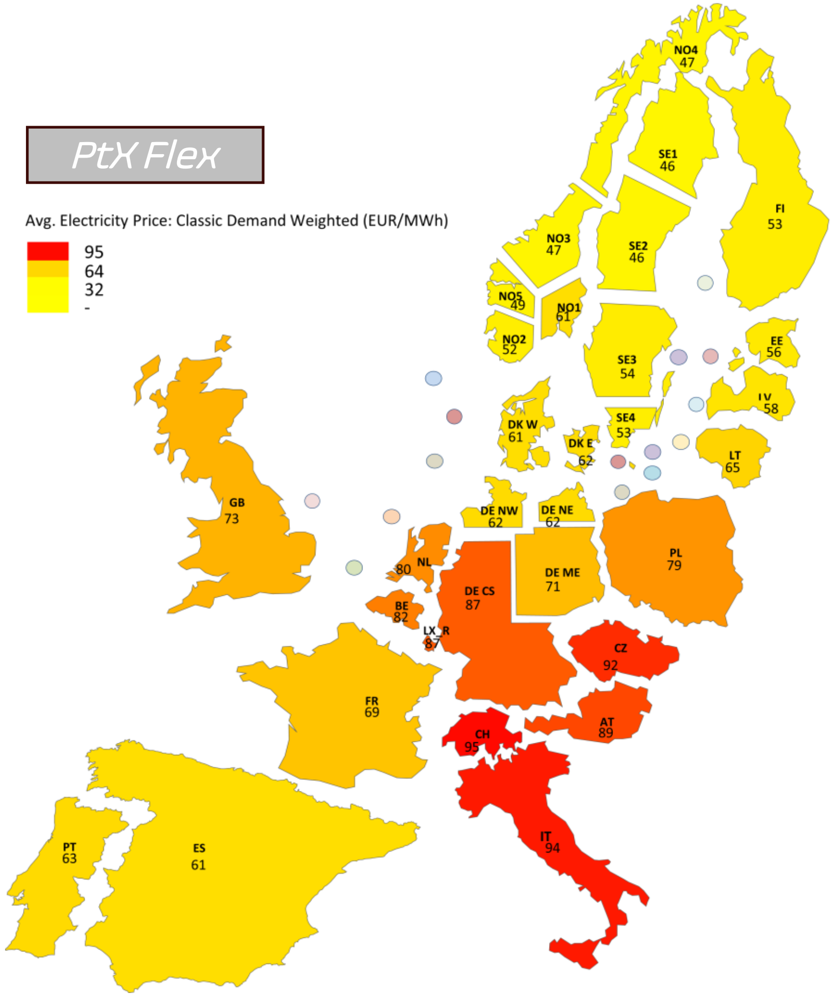


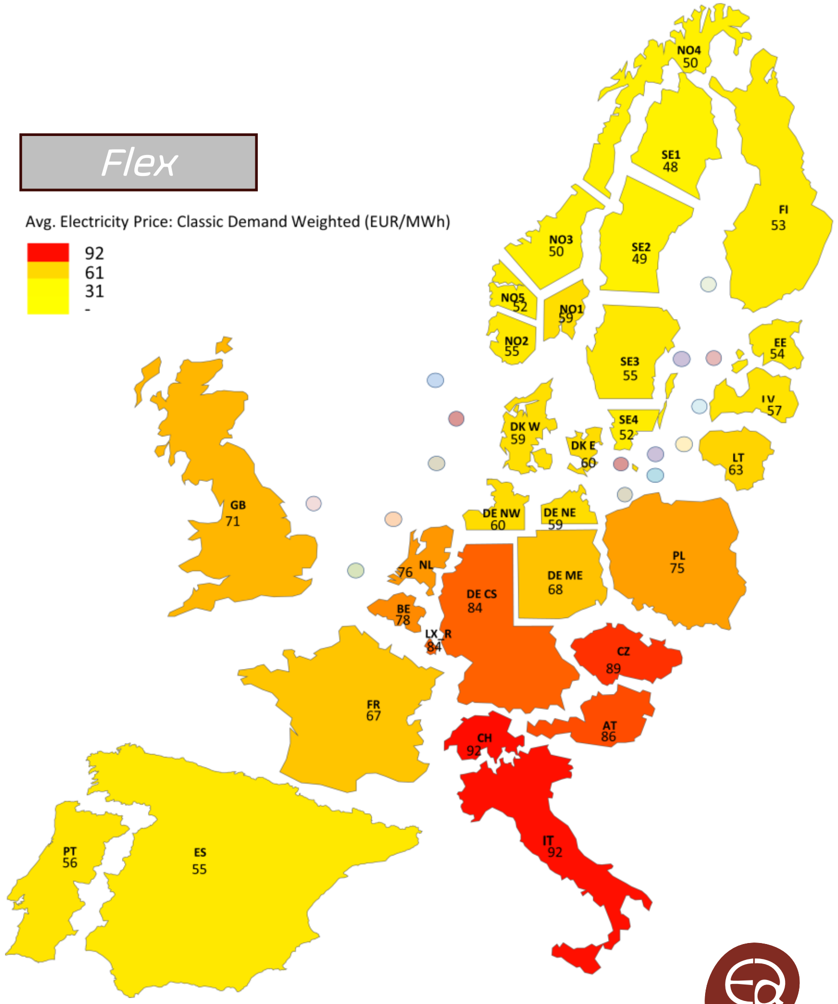




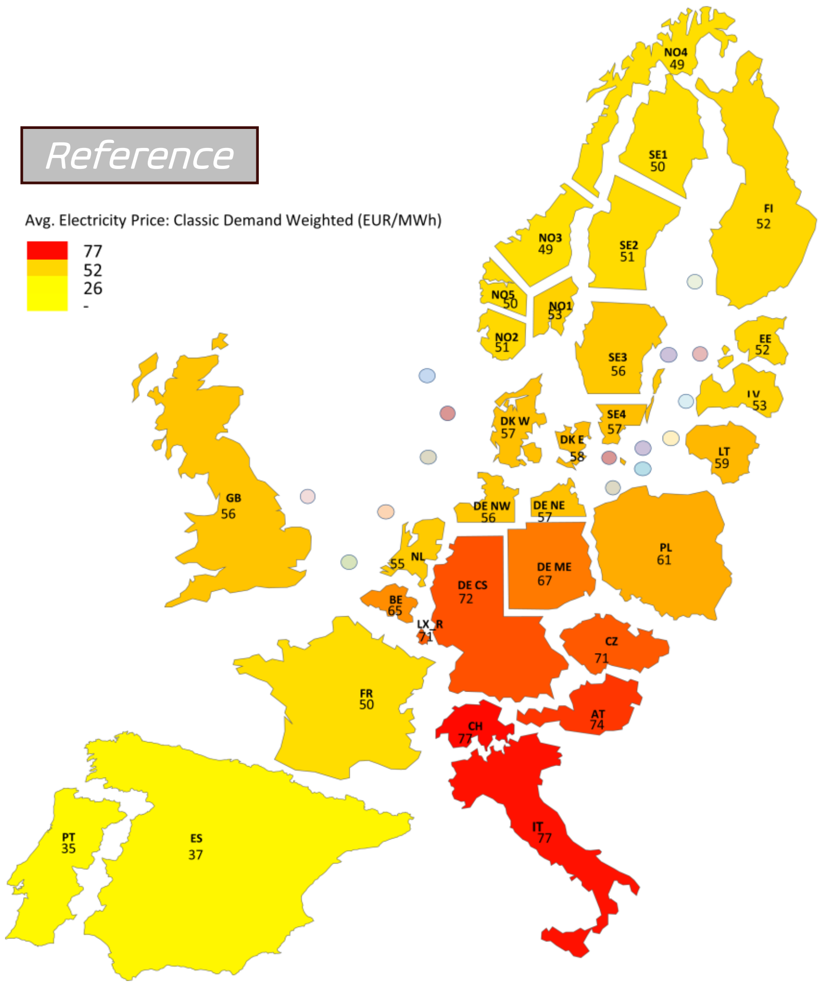
Demand Weighted Electricity Prices (2030)

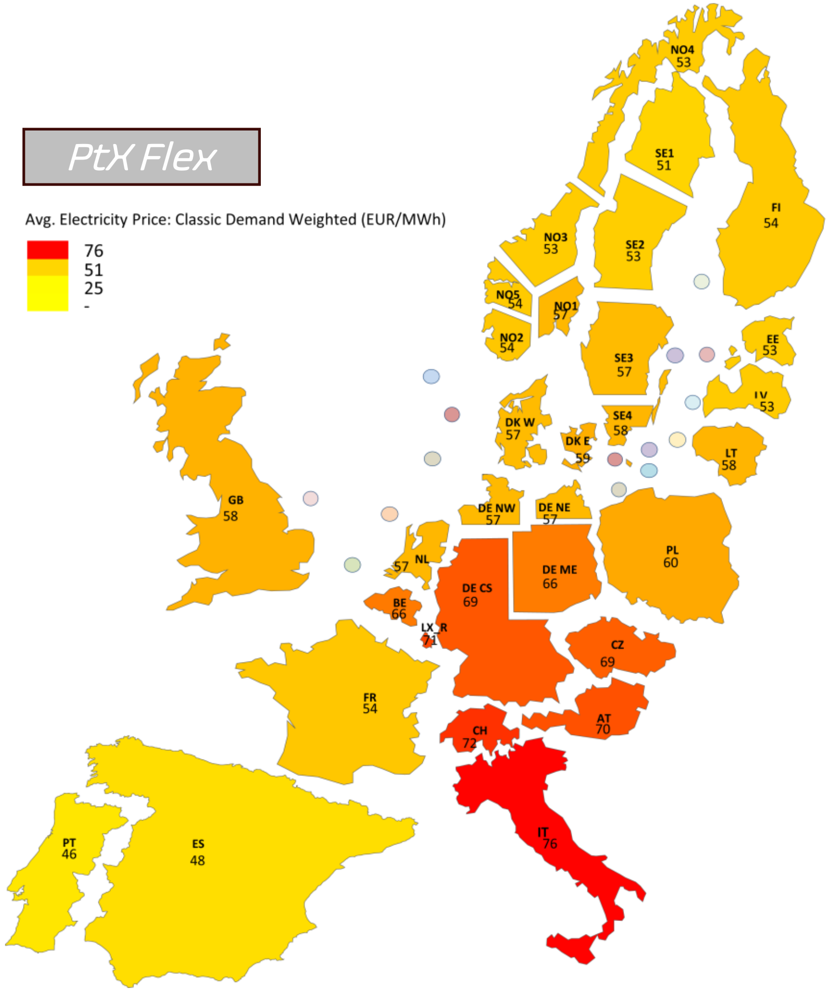


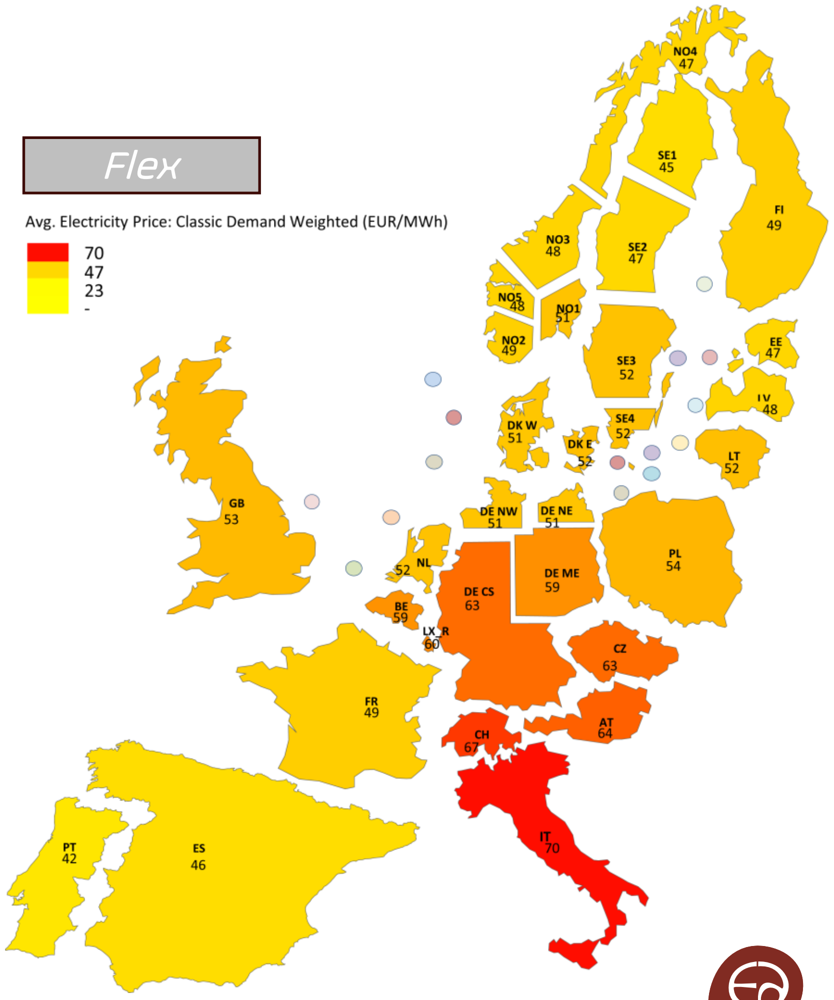




Demand Weighted Electricity Prices (2050)







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