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ENERGY RESEARCH

Prospects for Long Duration Energy Storage in Germany

05/07/2022

Agenda

Deploying LDES would reduce power system costs, increase renewable energy utilization and reduce hydrogen consumption

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Key results of modelling the use of LDES in the German power system

1	Lower power system costs	A power system with 15 GW of LDES by 2045 has a cumulated total system **cost advantage of around EUR 24 bn** (2025-2050) compared to a scenario without LDES
2	High sensitivity to H_2 price development	The study assumes rather low hydrogen prices, lifting the price assumption by 10% would **increase the economic benefit of LDES to EUR 40 bn (+ 67%)**
3	Higher utilization of renewable energy	LDES absorb renewable electricity by charging in hours in which renewables production exceeds demand; **curtailment can be reduced by up to 30%**
4	Lower natural gas use	LDES discharge in high price hours and thereby **reduce the amount of electricity generated by conventional gas plants**, and avoid CO_2 emissions
5	Less H_2 required in the power sector	LDES reduce the amount of power generated by H_2-fuelled power plants which translates to a **13% decrease of H_2 required for the power sector until 2050**
6	Increasing profitability of LDES technologies	Some technologies will already become investible under optimal market conditions before 2030, and **profitable under indicative hurdle rates for unsupported projects by 2035**

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Executive Summary

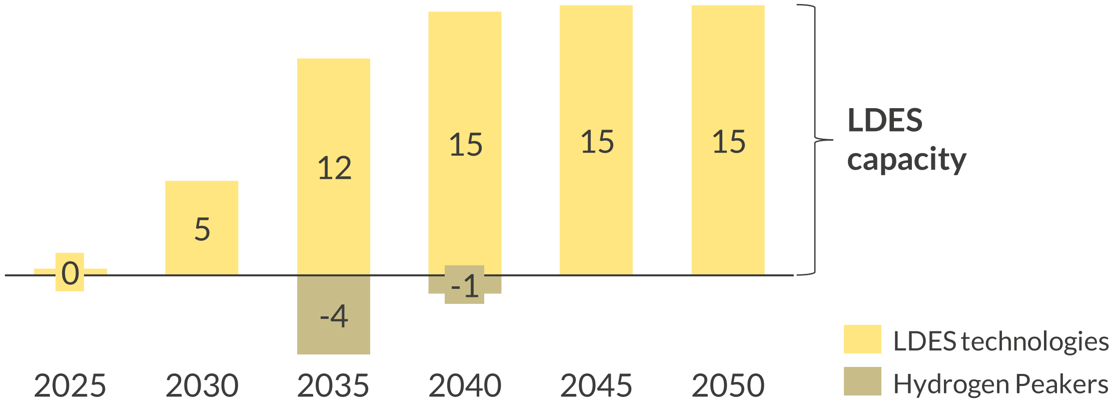
A Net Zero power system by 2035 will see larger and more frequent periods with either excess or insufficient generation from renewable energy sources

This study shows that long-duration energy storage (LDES) technologies are an effective and cost-efficient way to avoid renewables curtailment, lower the amount of hydrogen required for the power sector, and reduce wholesale prices on average

While investments in LDES won't be profitable in the short term, we expect selected technologies to become profitable in the 2030s

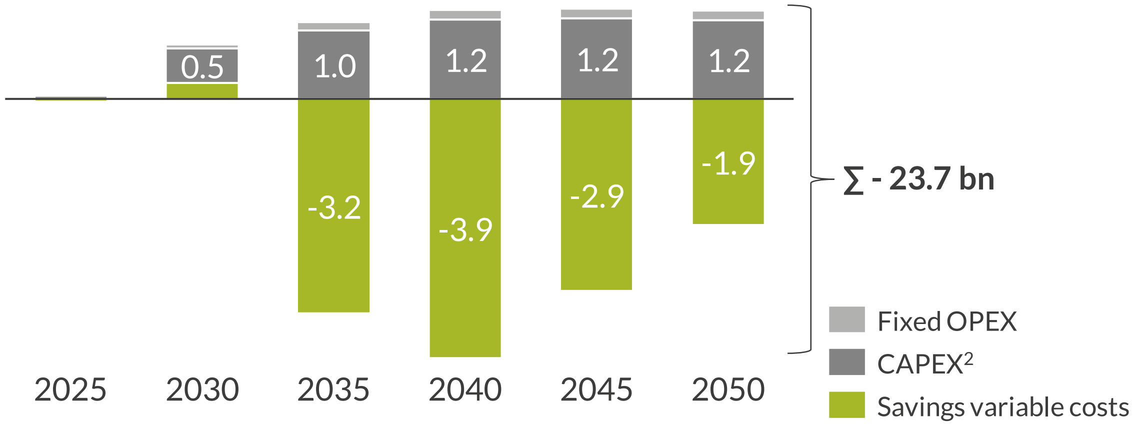
Two power market scenarios are modelled for this study. The Baseline Scenario assumes a Net Zero power system to be achieved by 2035. The LDES Scenario is built on the same assumptions but also includes an additional **LDES capacity of up to 15 GW**. In turn, hydrogen peaker capacity buildout can be backloaded while maintaining the **same level of security of supply**.

Delta of installed capacity LDES vs. Baseline Scenario
GW



The LDES Scenario has a **system cost advantage of around EUR 24 billion** compared to the Baseline Scenario. The cost reduction is mainly driven by savings in the wholesale market (50 bn) where discharging LDES substitute H_2-fuelled power plants with very high marginal costs. Additional costs related to the roll-out of LDES assets (26 bn) are priced in.

Delta of system costs LDES vs. Baseline Scenario[1]
Bn EUR (real 2021)

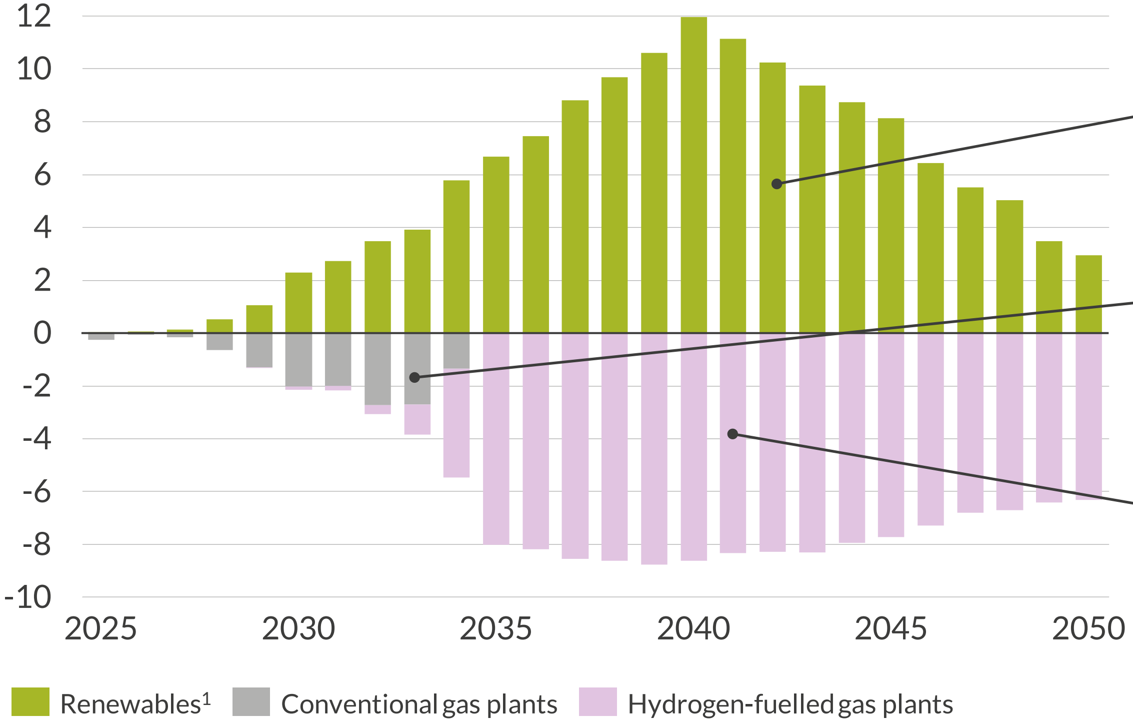


1) Savings in negative numbers, costs in positive numbers, 2) Annualised CAPEX of LDES investments with 4% interest rate

Source: Aurora Energy Research

Deploying LDES reduces power generation from gas and hydrogen power plants and limits RES curtailment

Electricity production – Difference between LDES and Baseline Scenario
TWh



Three main effects from the introduction of LDES to the power system

1. **Higher renewables utilization:** LDES absorb renewable electricity by charging in hours in which renewables production exceeds demand; **curtailment can be reduced by up to 30%**

2. **Lower natural gas use:** LDES discharge in high price hours and thereby reduce the amount of electricity generated by conventional gas plants as well as the CO_2 emissions caused in the process

3. **Lower need for hydrogen in the power sector:** After the transition from natural gas to hydrogen, LDES lower the amount of power generated by H_2-fuelled plants which translates to a **13% reduction of hydrogen use** in the power sector. This reduction **decreases Germany's H_2 import dependence and mitigates risks in case of H_2 procurement bottlenecks**

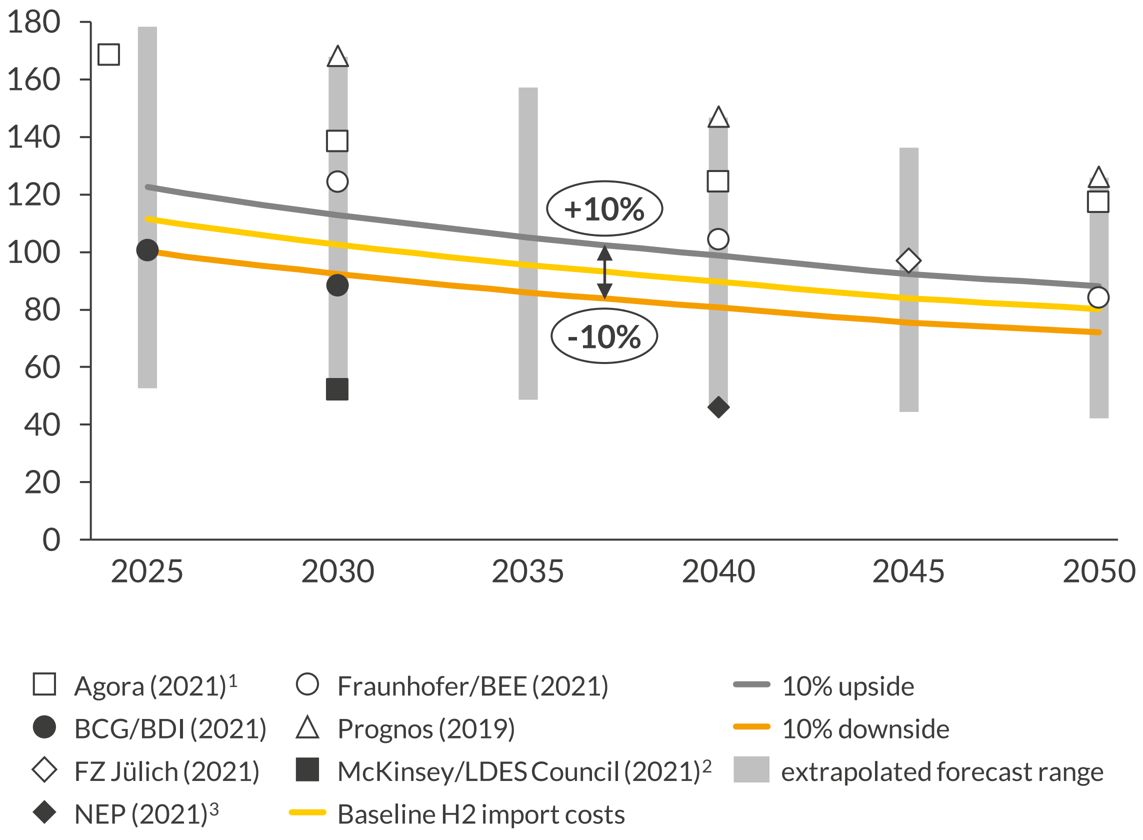
LDES discharge in high price hours and thereby reduce the amount of electricity generated by dispatchable assets, saving natural gas and hydrogen. When charging, LDES absorb renewable power generation which would otherwise be curtailed.

1) Includes wind and solar generation

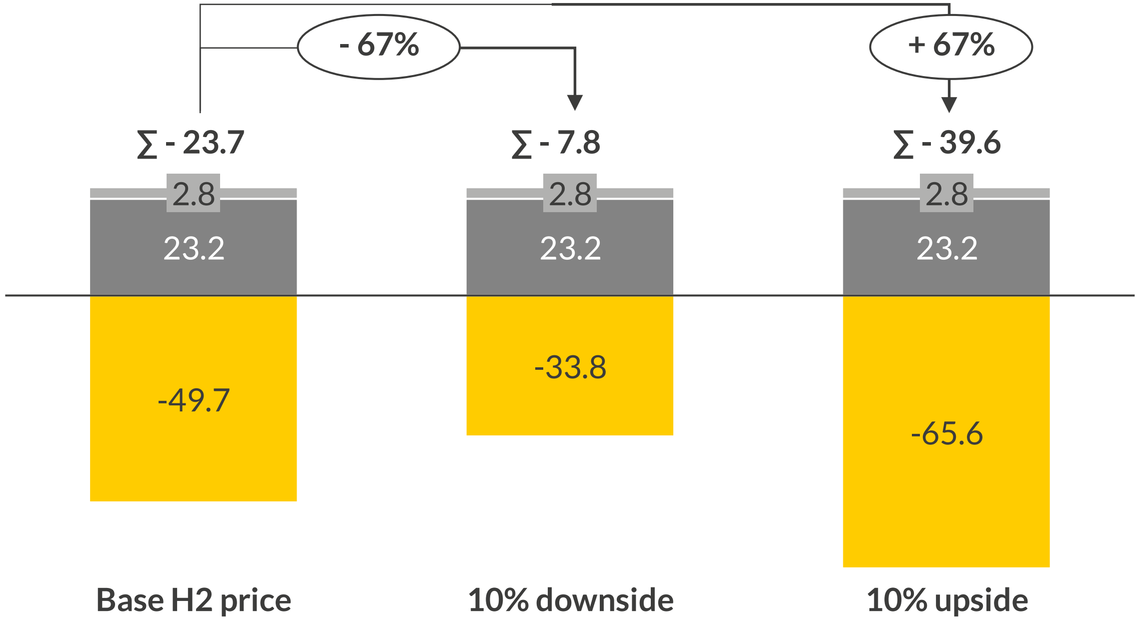
Source: Aurora Energy Research

Lifting our conservative hydrogen price assumption by only 10% increases system cost savings of LDES by 67%

Assumed cost development for imported hydrogen against benchmarks
EUR/MWh (real 2021)



Total 2025-2050 system cost delta between Baseline and LDES Scenario
Bn EUR (real 2021)



- In a sensitivity scenario with 10% higher costs for imported hydrogen, the system cost reduction would rise to EUR 39.6 bn → **LDES are an effective cushion against upward price risks on the H_2 market**
- The reverse effect can be observed when reducing the costs for hydrogen; however, a hydrogen price benchmark against external forecasts suggests that the upside sensitivity is more likely

Fixed OPEX　CAPEX　Variable costs

1) Reflects the price for a mix of domestically produced an imported green hydrogen, 2) Global cost forecast, not for the German market specifically , 3) Extrapolated based on a cost estimate for hydrogen of 46.8 EUR/MWh for 2037

Source: Aurora Energy Research

Some LDES technologies will already become investible under optimal market conditions in 2030, and be fully profitable in 2035

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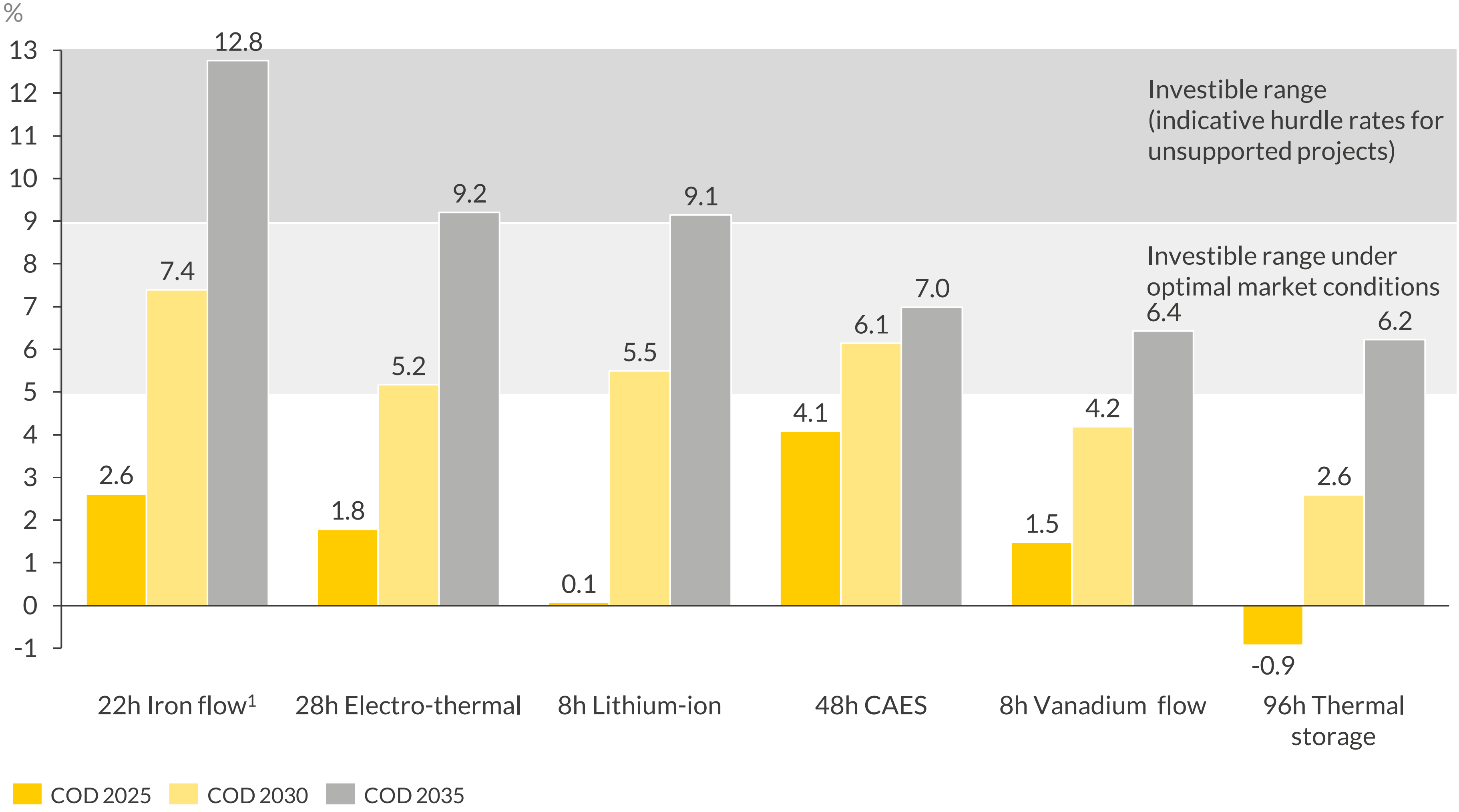
Internal rate of returns (IRR) forecast for six selected LDES technologies and three commercial operation dates (COD)



1) "22h" indicates the assumed maximum storage duration in hours

Source: Aurora Energy Research

Comments

- IRR behaviour varies between technologies and is heavily dependent on the assumed date of roll-out
- Improved IRRs in 2035 for emerging technologies such as iron flow and electro-thermal are driven by assumed CAPEX cost declines
- To fully exploit the savings potential on the system cost level, rollout of LDES capacity needs to start before IRRs reach common hurdle rates for unsupported projects
- To bridge this gap and incentivise investments in LDES projects before 2035, a more favourable market environment and policy support which recognises the value and need for LDES is required

Agenda

I. Executive Summary

II. Methodology

III. Baseline Scenario – Assumptions and Results

IV. LDES Scenario – Assumptions

V. Scenario comparison

VI. Sensitivities

VII. Profitability Analysis of LDES Technologies

1. Overview of LDES Technologies
2. Profitability Analysis

VIII. Policy considerations

Long-duration storage can be defined by its storage duration and its ability to mitigate the intermittency of renewable generation

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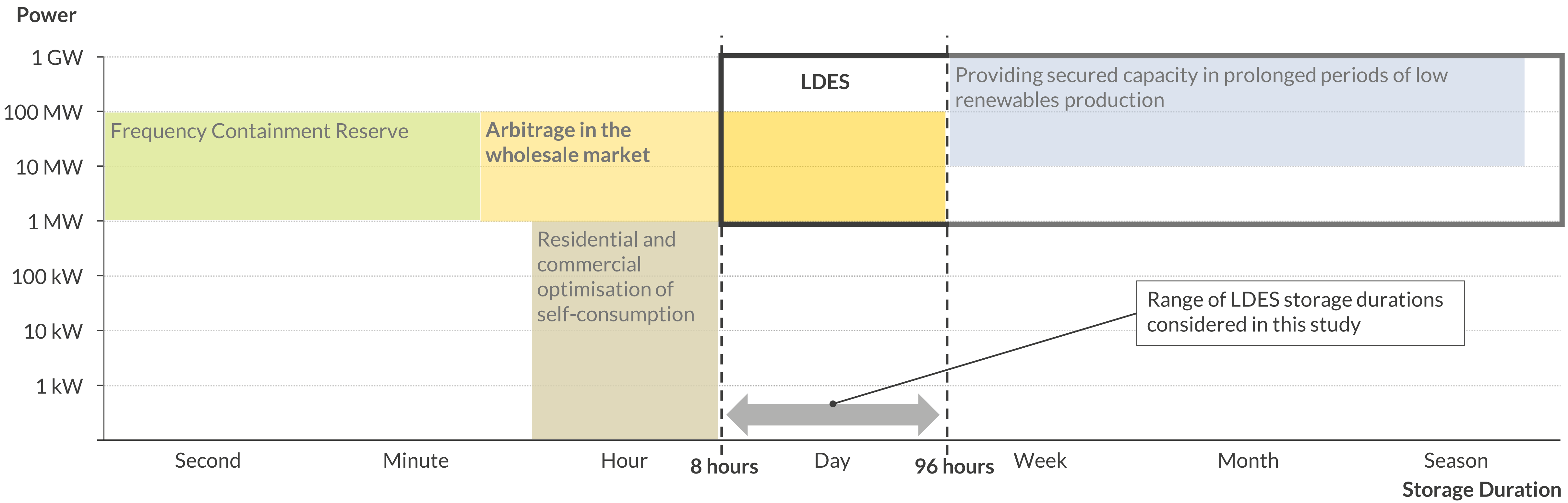
Use cases of energy storage technologies



- LDES technologies are able to respond to supply and demand variations caused by daily peaks and weather events as well as interseasonal variations in renewable electricity generation
- The focus of this study lies on storage technologies with **durations between 8 hours and 96 hours**; seasonal storage is disregarded as there is already a consensus that hydrogen-based storage will be most suitable for durations spanning across multiple weeks or months

Source: Aurora Energy Research

The study quantifies the economic benefits and business opportunities of deploying LDES in the German power system

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Technology selection

3 generic LDES technologies

- Selected representatively to cover a broad spectrum of LDES in the wholesale market
- Included in the power market scenario

6 LDES technologies

- Specified in more detail
- selected to showcase the micro economic feasibility

LDES technologies are defined as electricity and or heat storage systems which can store energy for 8 to 96 hours (energy storage capacity (MWh) divided by nominal power for discharging (MW))

Power market and financial modelling

Baseline Scenario

- Net zero power sector by 2035
- Government targets for RES buildout

LDES Scenario

- +15 GW of LDES by 2045, testing the impact on power prices, system cost and carbon emissions

Profitability of LDES

- Forecast of gross margin with dispatch model and LDES Scenario
- IRR calculation with CAPEX and OPEX

We model the power market from 2022 to 2050 with Aurora's power market model

Analysis and conclusions

Analysis of system cost difference

- Cost savings due to lower prices on the wholesales market
- Cost increases due to additional investments

Conclusions

- Benefits of LDES deployment for power consumer on the wholesales market level?
- How attractive are investments in LDES assets ?

Source: Aurora Energy Research

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Capacity installed in the Baseline Scenario increases by 161% between 2025 and 2040, driven by ambitious renewables buildout

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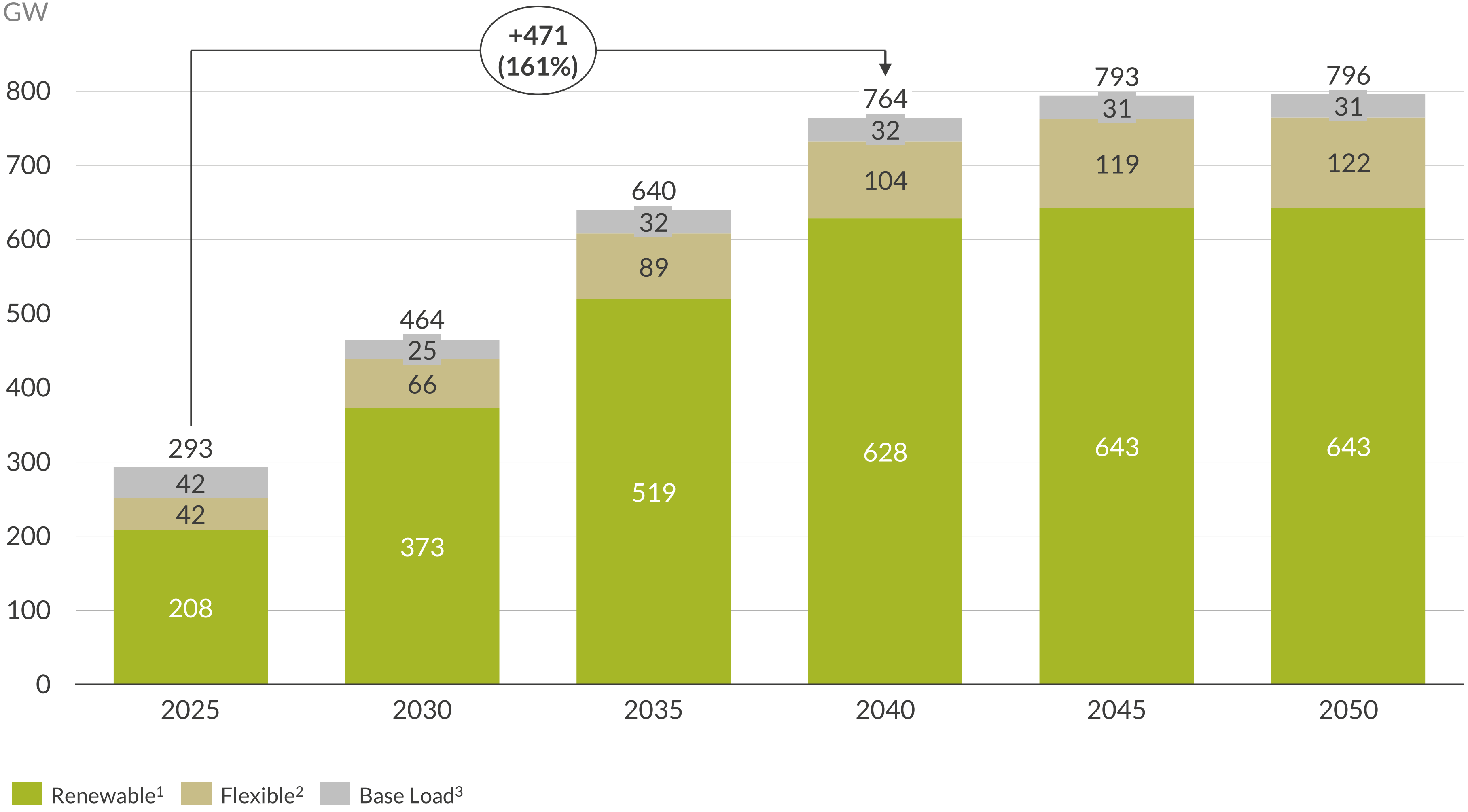
Installed capacity - Baseline Scenario

GW



1) Includes wind onshore, wind offshore, solar PV, hydropower and biomass, 2) Including gas OCGTs, oil peakers, DSR, pumped storage, and batteries 3) Coal, lignite, gas CCGTs, hydrogen CCGTs

Source: Aurora Energy Research

Outlook for the capacity mix

- Total installed capacity increases very quickly between 2025 and 2040, mainly due to ambitious government targets for renewables buildout (420 GW additional RES capacity in this period)
- Baseload capacity declines until 2030 with all of the remaining coal exiting, before rebounding to a constant level of 32 GW from 2035 onwards
- Flexible capacity is on an upwards trajectory with 80 GW being added between 2025 and 2050
- Post 2040, capacity increases at a much slower pace, given that the government targets for wind onshore and solar reach their maximum in 2040 with only wind offshore planned to grow further

The Baseline Scenario is characterised by government targets for renewables buildout and a net zero emission power sector by 2035

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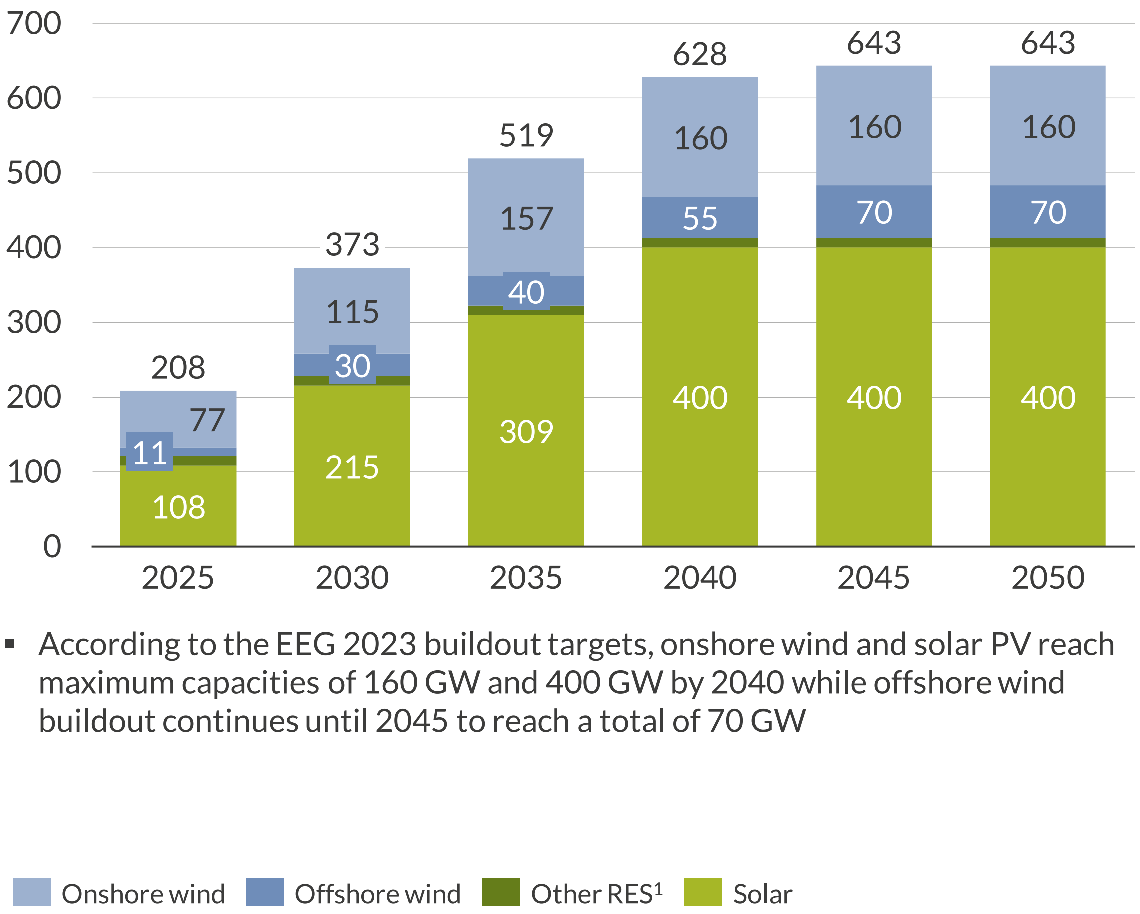
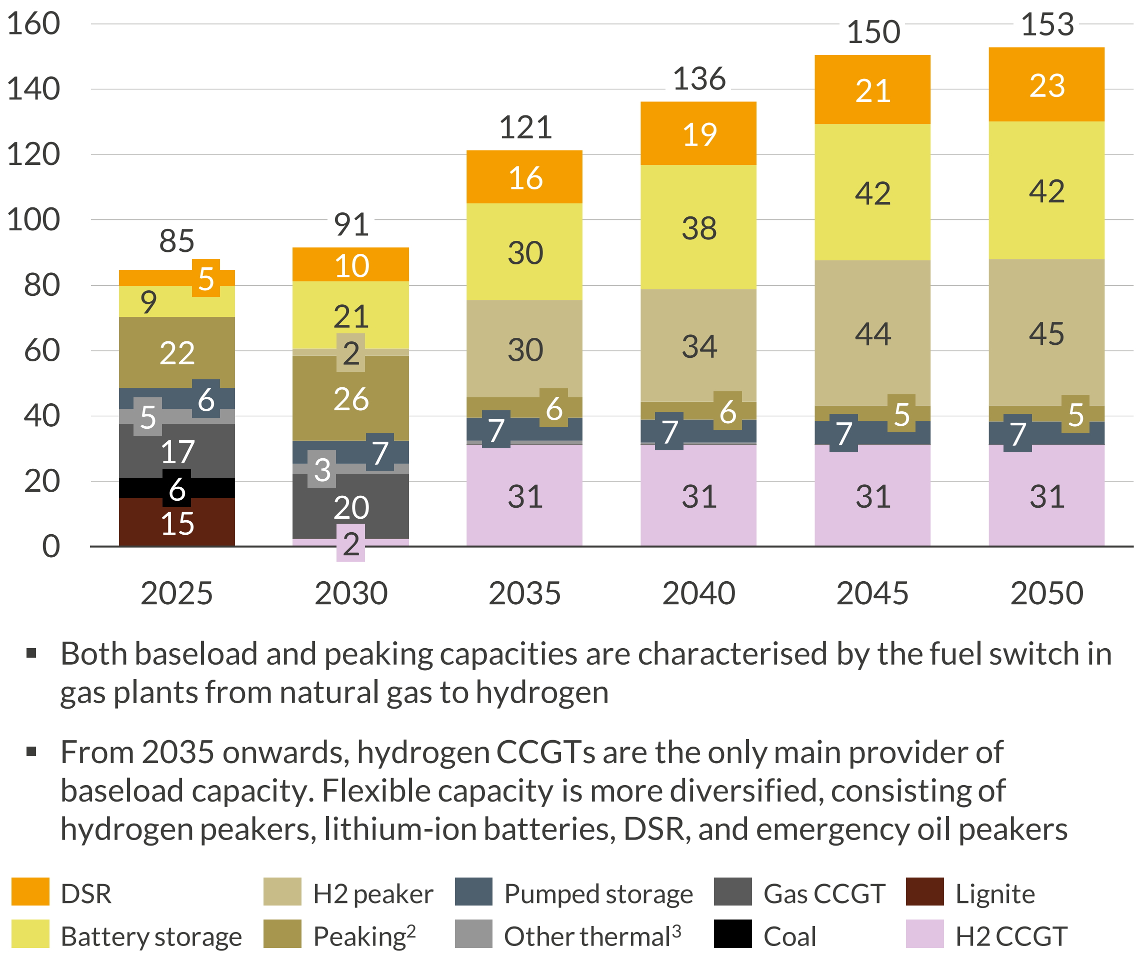
Installed renewable capacity - Baseline Scenario
GW



- According to the EEG 2023 buildout targets, onshore wind and solar PV reach maximum capacities of 160 GW and 400 GW by 2040 while offshore wind buildout continues until 2045 to reach a total of 70 GW

Installed flexible and baseload capacity - Baseline Scenario
GW



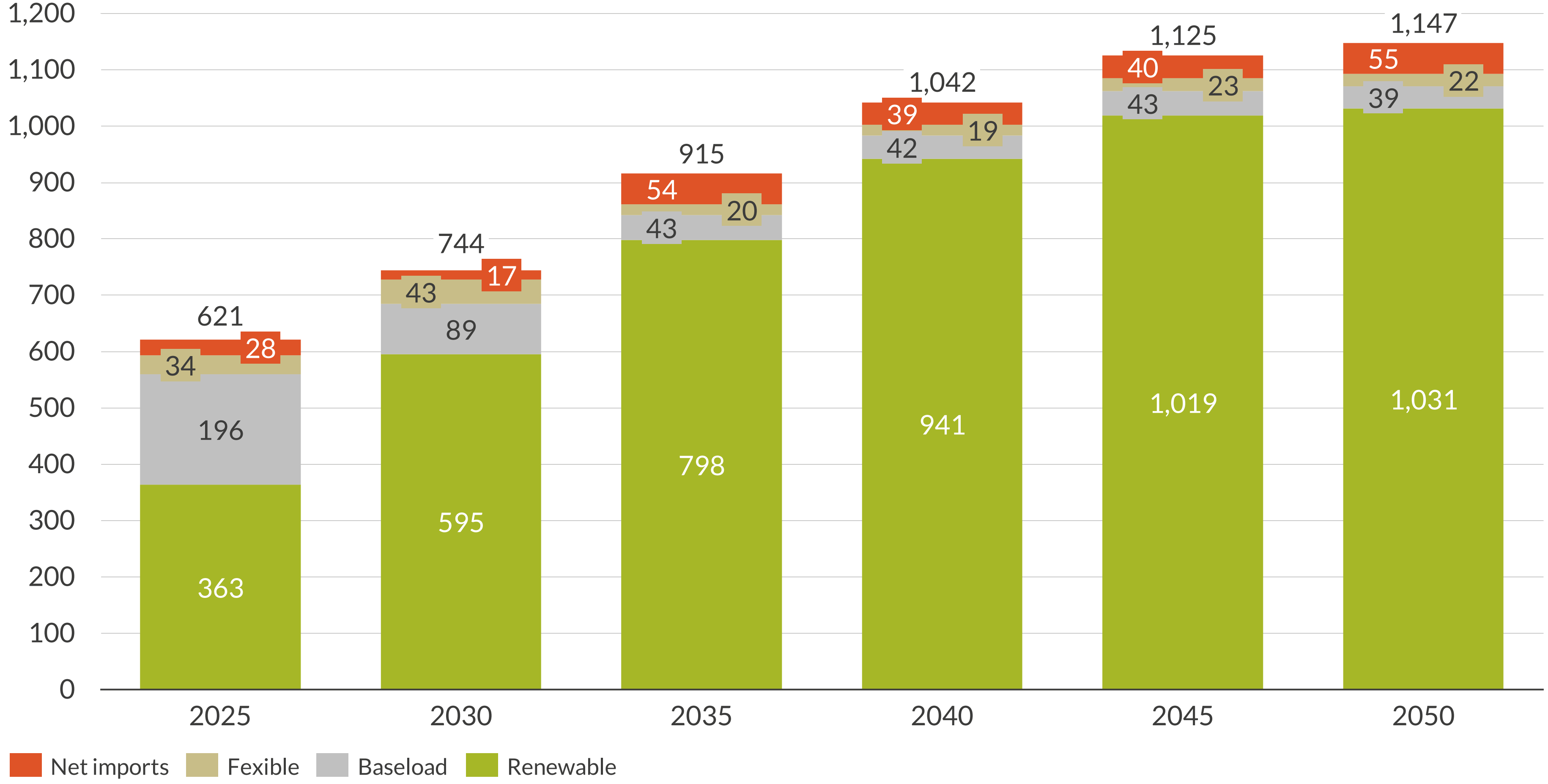
- Both baseload and peaking capacities are characterised by the fuel switch in gas plants from natural gas to hydrogen
- From 2035 onwards, hydrogen CCGTs are the only main provider of baseload capacity. Flexible capacity is more diversified, consisting of hydrogen peakers, lithium-ion batteries, DSR, and emergency oil peakers

1) Includes hydropower and biomass, 2) includes gas OCGTs and oil peakers, 3) Including waste plants and on-site industrial thermal power plants.

Source: Aurora Energy Research

Renewable power generation reaches close to 800 TWh by 2035, 93% of total domestic production

Electricity production and net imports - Baseline Scenario
TWh



Source: Aurora Energy Research

Outlook for power generation

- Driven by a fast buildout of wind and solar capacities, annual renewable generation more than doubles between 2025 and 2035, reaching almost 800 TWh in 2035
- In 2030, the share of renewables in total domestic generation is already at 82%, the government target of 600 TWh being undershot by only 5 TWh
- Flexible and baseload generation are on decline until 2035 before fluctuating around the levels of 20 TWh and 40 TWh, respectively
- Germany is a consistent net importer of electricity from neighbouring countries

Fossil power generation is phased out by 2035 and substituted by renewables and hydrogen plants

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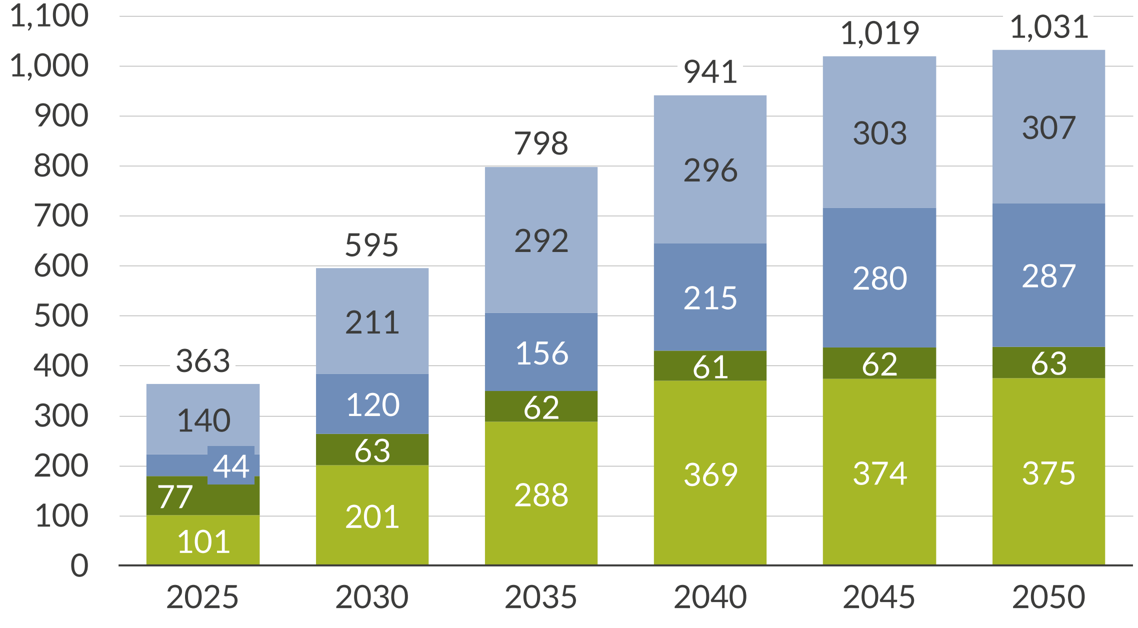
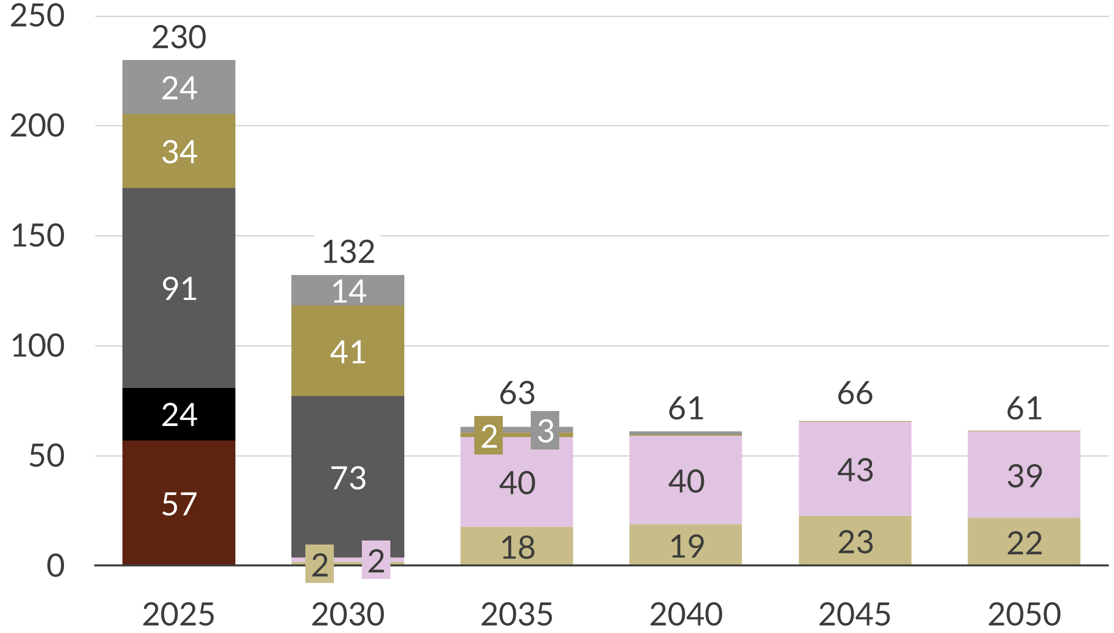
Renewable electricity production - Baseline Scenario
TWh



- Wind offshore generation sees the largest proportional growth of all RES technologies with a more than 6-fold increase between 2025 and 2050
- Driven by the ambitious capacity expansion to 400GW, solar PV replaces wind onshore as the technology with the highest generation between 2035 and 2040

Onshore wind | Offshore wind | Other RES | Solar

Flexible and baseload production - Baseline Scenario
TWh



- The sharp decline in baseload generation between 2025 and 2035 is mainly caused by the phase out of coal and lignite capacity
- The transition from gas CCGTs and OCGTs to hydrogen CCGTs and peakers contributes to the reduction as well because the high price of hydrogen compared to natural gas reduces full load hours

Other thermal | Gas CCGT | Lignite | Hydrogen peaker
Peaking | Coal | Hydrogen CCGT

While gas and coal prices are expected to fall significantly in the long run, we assume carbon prices to rise over 150EUR/ton by 2045

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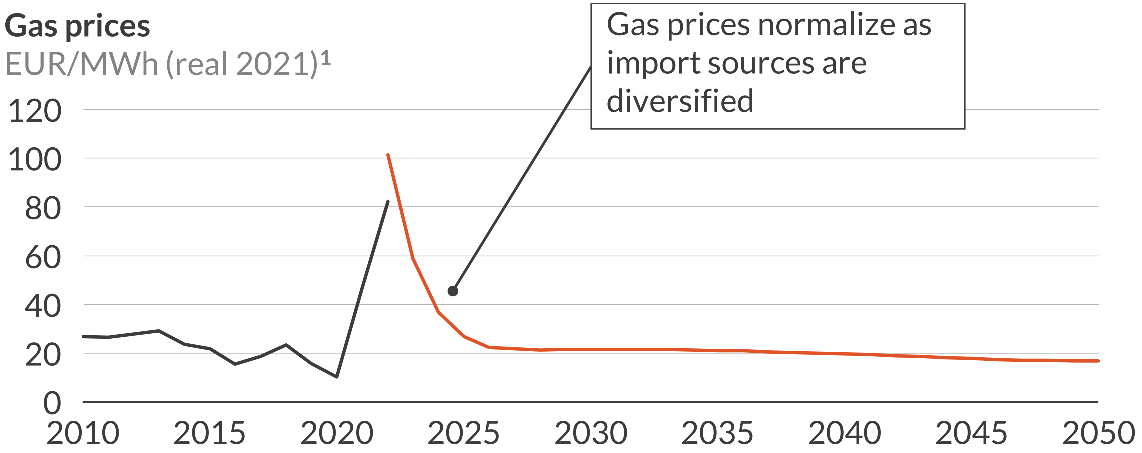
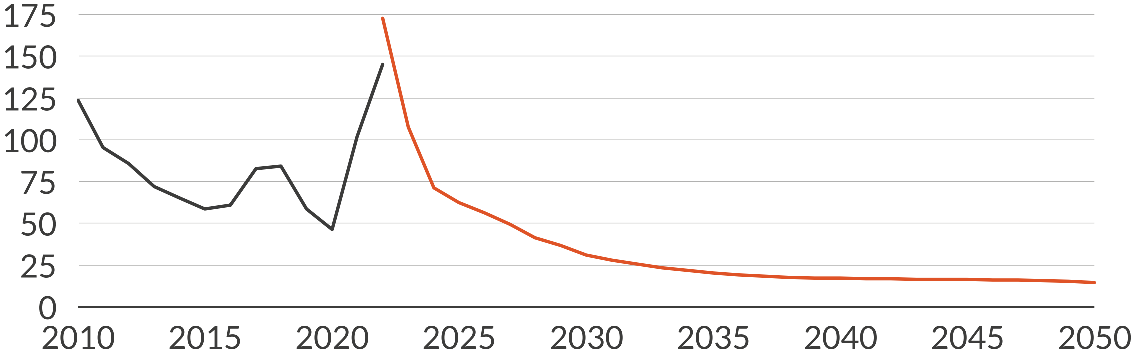
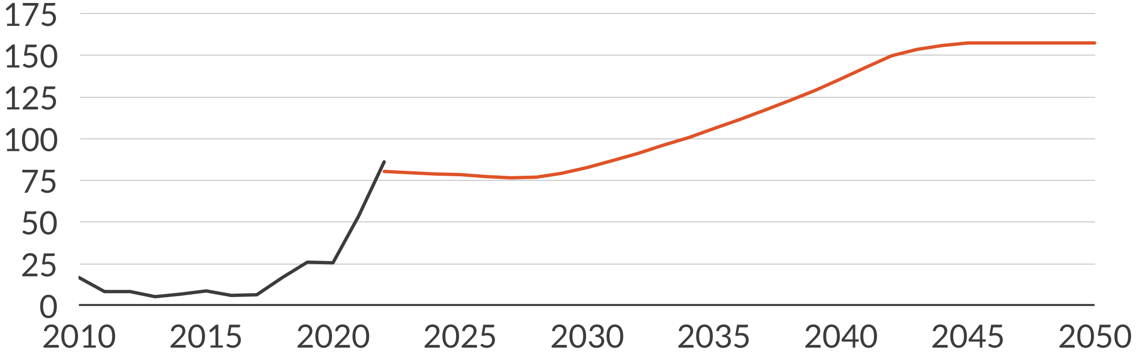
Gas prices
EUR/MWh (real 2021)[1]



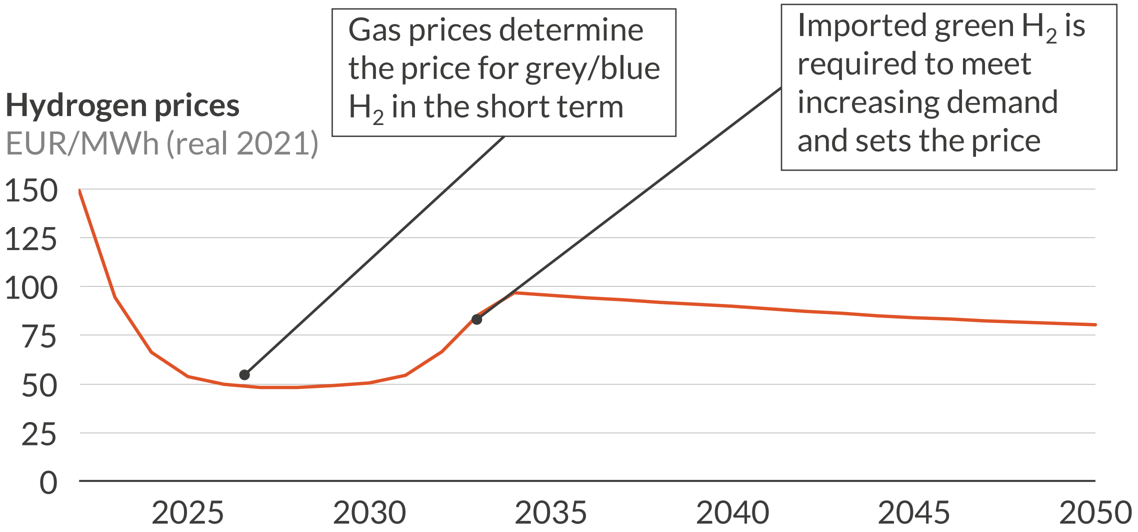
Coal prices
EUR/tonne (real 2021)[1]



Carbon prices
EUR/tCO_2 (real 2021)[1]



Hydrogen prices
EUR/MWh (real 2021)



— Historical — Baseline Scenario

1) For years 2022-2027, the prices shown take into account futures prices as of 14/03/2022 for the years in question, with declining weights.

Sources: Aurora Energy Research, EIKON

The swift decarbonisation of the power sector by 2035 causes baseload prices to climb above 80 EUR/MWh

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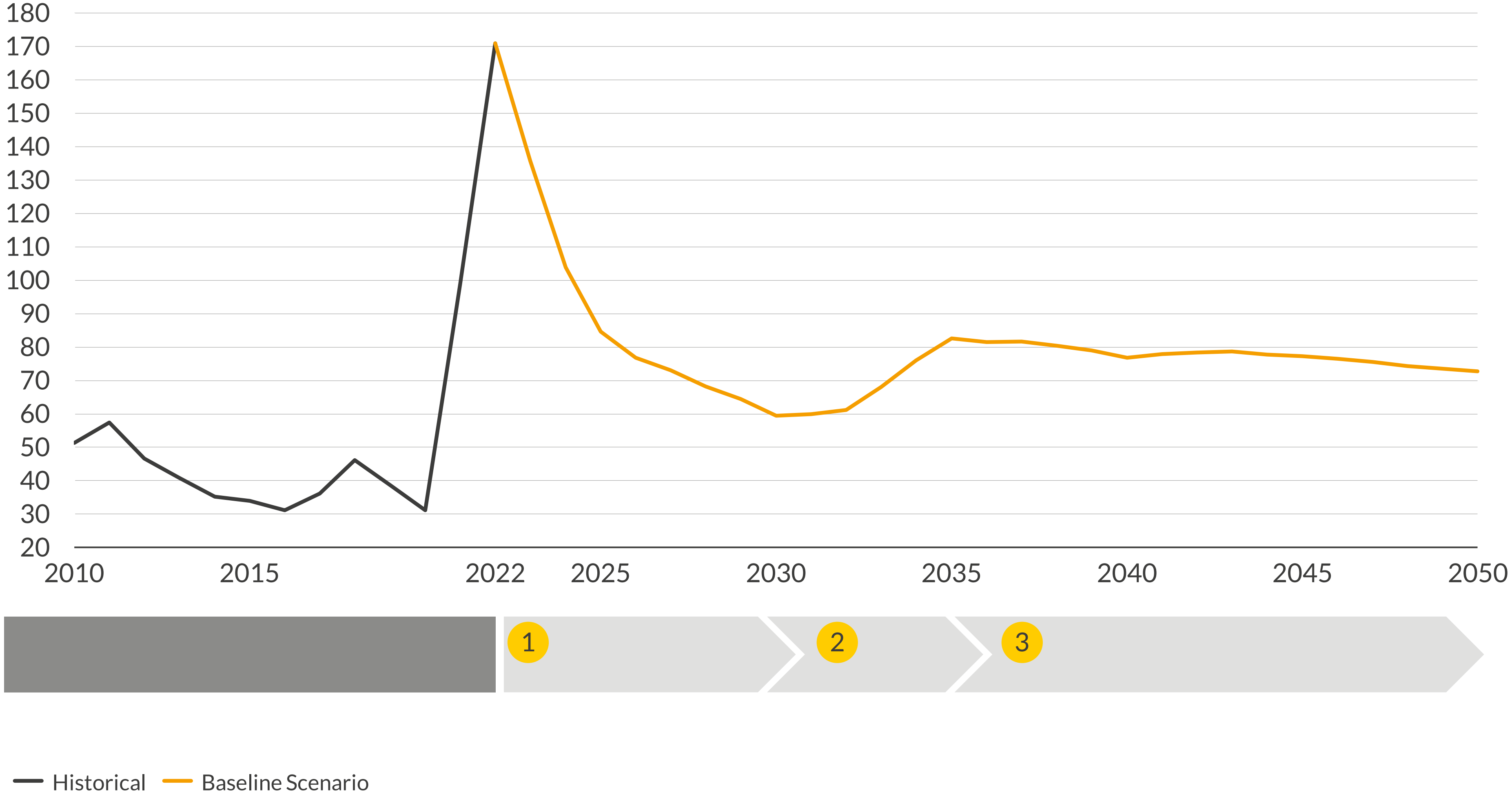
Baseload wholesale electricity price

EUR/MWh (real 2021)



Outlook for baseload prices

1. As commodity prices decline from their current high and renewables buildout accelerates, power prices fall significantly, reaching 60 EUR/MWh by 2030
2. The transition from conventional gas generation to hydrogen-fueled power plants causes baseload power prices to increase between 2030 and 2035
3. Baseload prices decrease on the long run due to continuous renewables buildout until 2045 combined with an increase in flexible capacity and declining hydrogen prices

Source: Aurora Energy Research

The combination of a high RES share and the gas to H_2 transition results in and increase of extreme prices and high price volatility

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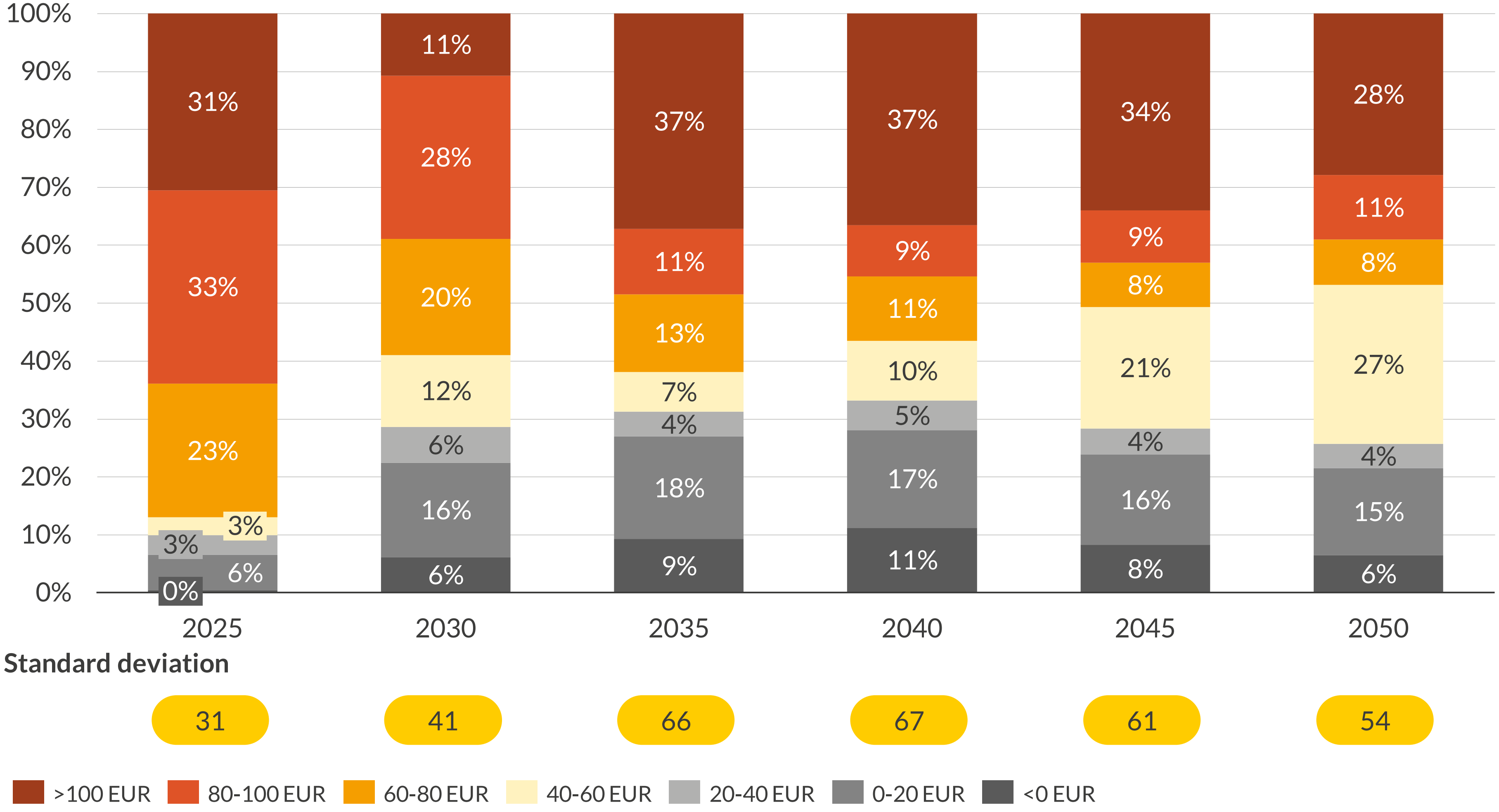
Frequency distribution of the electricity price (real 2021)
%



Outlook on the price distribution

- In 2025, power prices are still elevated due to the current peak in commodity prices which is expected to slowly decline over the next years
- The frequency of low prices (<EUR 20) increases by 21 p.p. between 2025 and 2035 as renewables set prices more frequently
- The frequency of very high prices (>EUR 100) increases by 26 p.p. between 2030 and 2035 as hydrogen replaces natural gas and increases the variable costs for dispatchable generation
- The increasing frequency of high and low prices translates to a higher price volatility – as evidenced by the increase in standard deviation

Source: Aurora Energy Research

Demand is expected to rise by 86% by 2050 due to the electrification of heat, transport and industry as well as H_2 electrolysis

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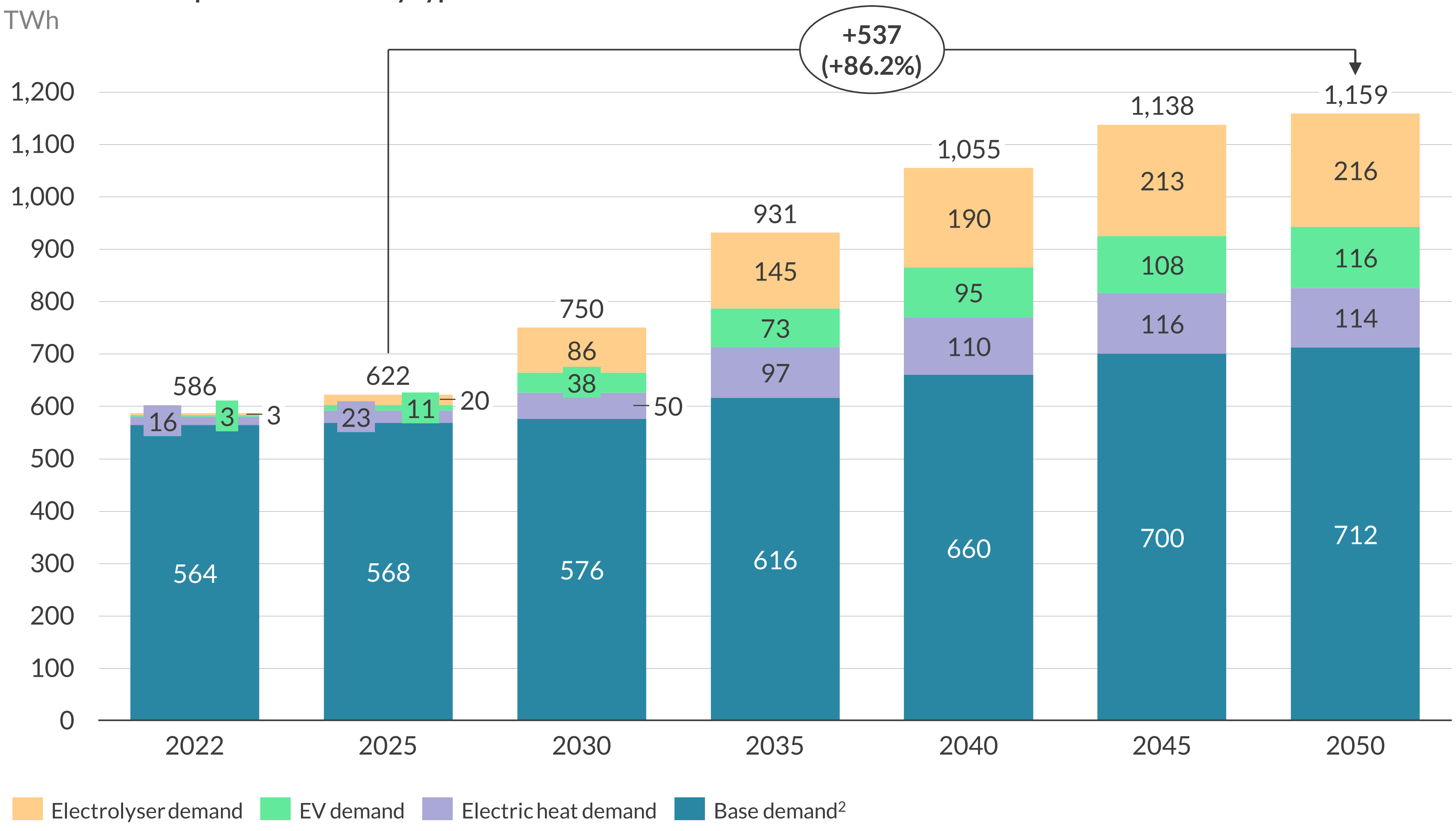
Net annual total power demand[1] by type
TWh



- Between 2025 and 2050, total power demand in the Baseline Scenario rises by 529 TWh (86%), mostly caused by sector coupling and hydrogen production
- Production of hydrogen via electrolysers is expected to pick up in the next years to meet increasing demand and support Germany's plans for lower energy import dependency.
- Power demand from electrolysis reaches 216 TWh (or 19% of total demand) by 2050
- Assuming a quick market penetration of EVs, incentivised by subsidies and decreasing costs, power demand from EVs grows by 105 TWh between 2025 and 2050

1) Total net power demand includes sectoral demand (i.e. industry, commerce, transport and households) as well as transmission losses, but excludes power plant self-consumption and demand from efficiency losses of storage. 2) Underlying base demand excluding heat pumps, EVs and electrolysis.
Source: Aurora Energy Research

In 2040, more than 4% of intermittent renewables production potential cannot be absorbed by the system and is lost to curtailment

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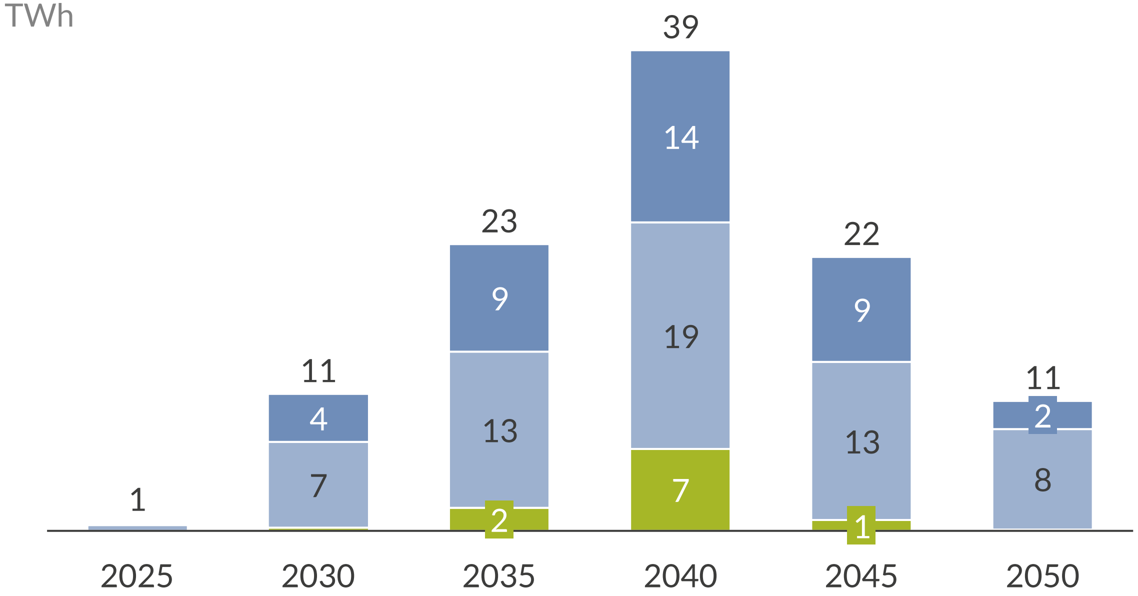
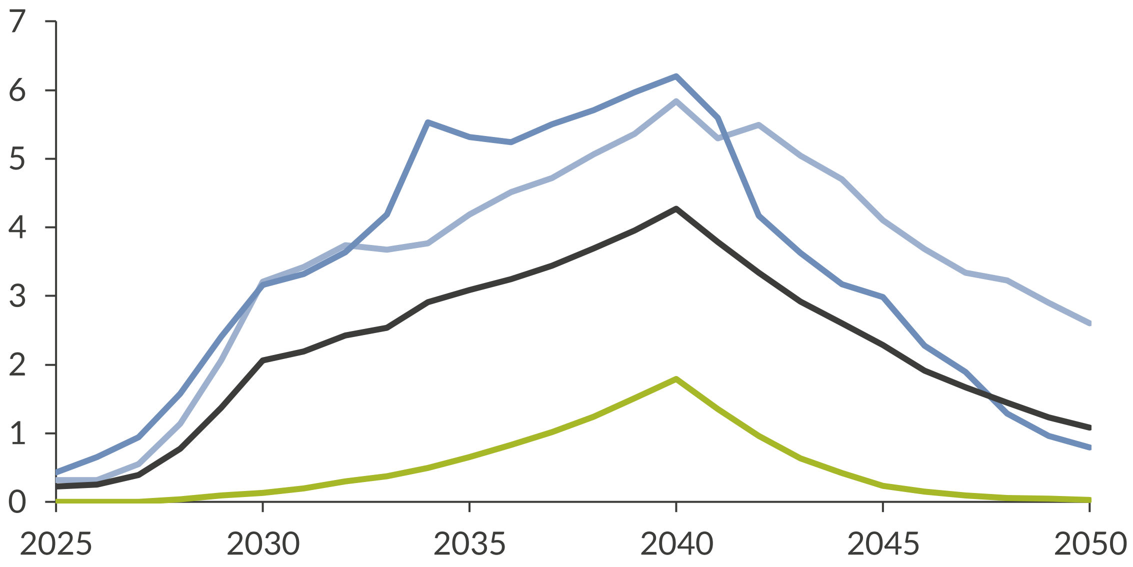
Curtailment of renewables generation
TWh



- The increasing trend of curtailed renewables generation can be explained by the rapid growth of RES capacity until 2040
- After 2040, curtailment decreases because renewable capacity is stagnating, RES assets with an optimized generation profile come online, and the power system becomes more flexible both on the supply and the demand side
- In absolute terms, wind onshore is most concerned by curtailment, followed by wind offshore and solar PV

Curtailment as percent of total renewables generation
%



- For all intermittent RES technologies on average, curtailment as a percent of total generation peaks at 4.3% in 2040
- Relative to total generation per technology, wind assets are significantly more concerned by curtailment than solar PV which is due to the different generation profiles of the technologies

Source: Aurora Energy Research

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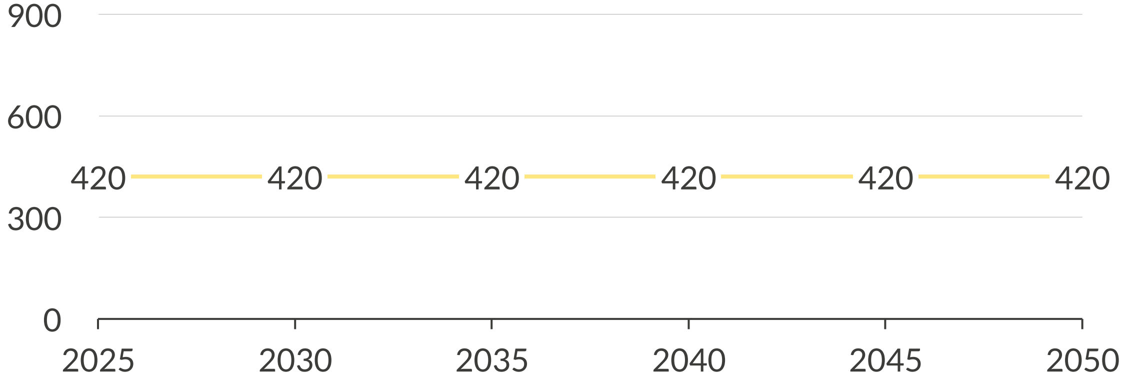
Three generic technologies are implemented in the model to simulate the system-level effect of LDES deployment

Criteria for the determiniation of generic LDES technologies

- Representation of both power and heat storage technologies
- Coverage of a wide span of storage durations: 12h, 48h, 96h
- Cost assumptions calibrated based on client input and scientific literature
    - Flow-based technology assumed for power storage
    - Water-based sensible heat storage technology assumed for heat storage

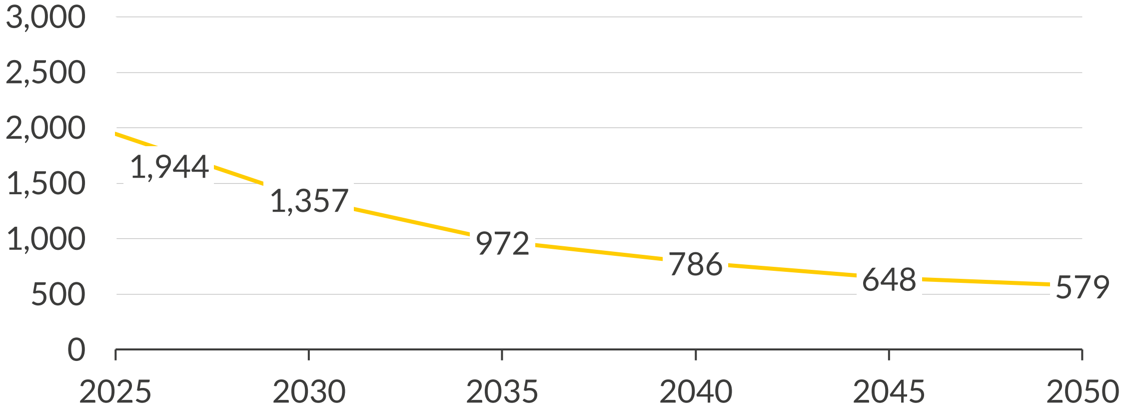
CAPEX 96h heat storage[1]

EUR/kW (real 2021)



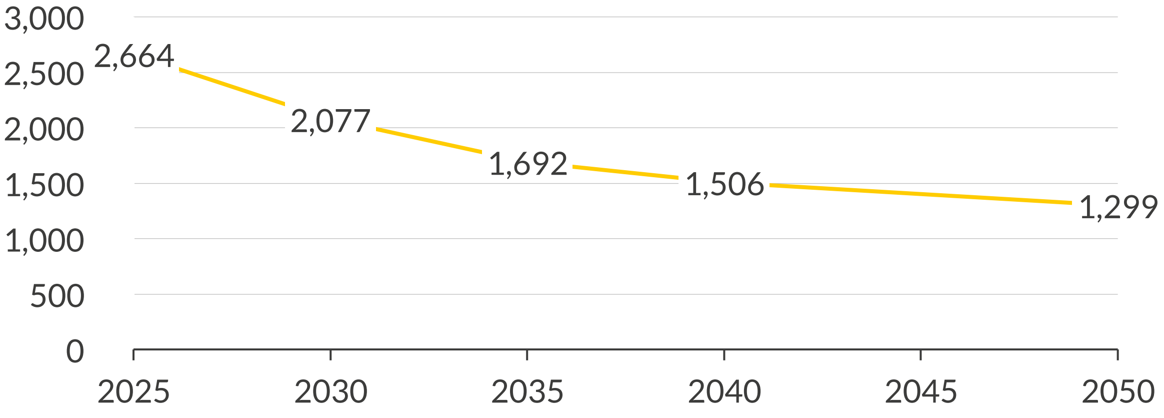
CAPEX 12h power storage

EUR/kW (real 2021)



CAPEX 48 power storage

EUR/kW (real 2021)

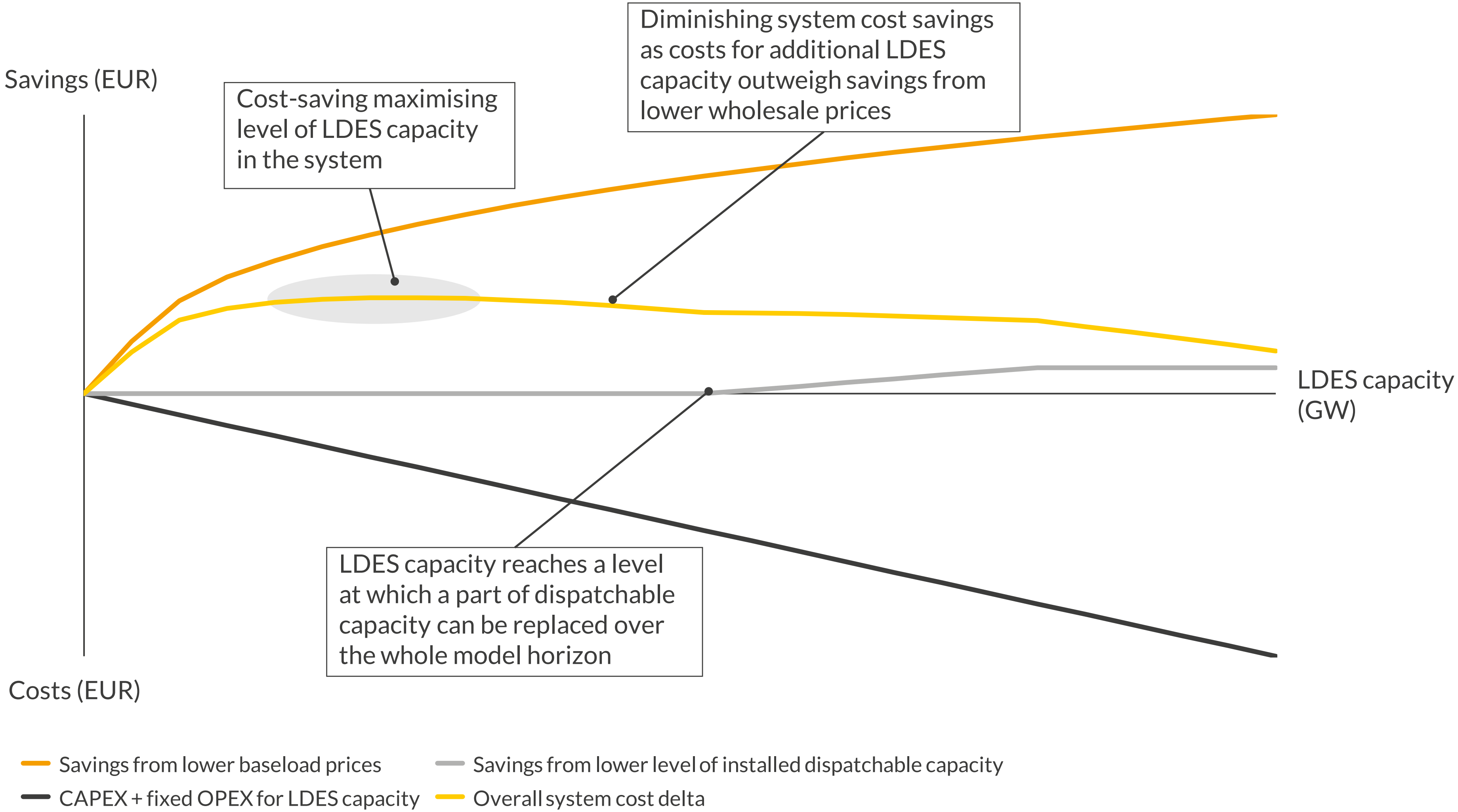


1) No cost degradation assumed as water-based sensible heat storage is already a mature technology

Sources: Aurora Energy Research , ESS Inc.

The optimal level of LDES capacity is determined by a maximisation of total system cost savings

Visualisation of LDES capacity optimisation



Source: Aurora Energy Research

LDES capacity optimisation

- The amount of LDES capacity included in the LDES Scenario is a result of an optimisation of total system cost savings
- The more LDES capacity in the system, the higher the savings from lower wholesale power prices. However, more LDES capacity also increases the required investment costs and fixed operating costs
- The optimum is reached where an additional unit of LDES capacity added to the power system does no longer yield higher overall cost savings
- Multiple scenarios with a range of LDES capacity levels are modelled to determine the optimum

To allow for a meaningful comparison of LDES and Baseline Scenario, two indicators are used to keep supply security constant

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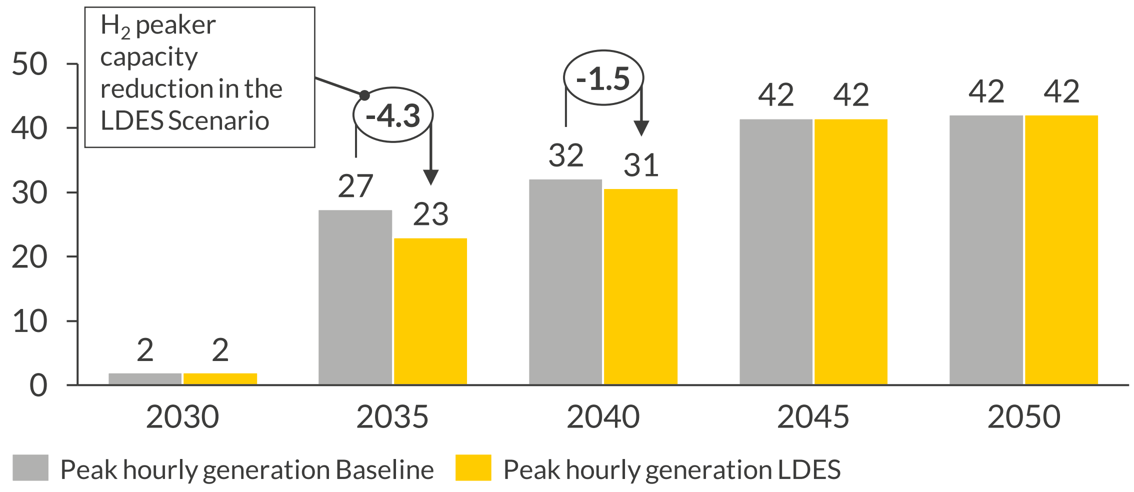
1 Constant delta between installed capacity and yearly peak generation of dispatchable technologies

- The difference between installed dispatchable capacity and peak hourly generation for a given year is the primary indicator for supply security
- For the same level of supply security, the delta between installed capacity and peak dispatch should be identical between the two scenarios
- In some years, the delta of the LDES Scenario is larger than that of the Baseline Scenario because LDES lower the peak generation of dispatchable technologies required to meet demand. In this case, the level of installed dispatchable capacity is reduced in the LDES Scenario

Peak generation analysis for hydrogen OCGTs [1]

GW

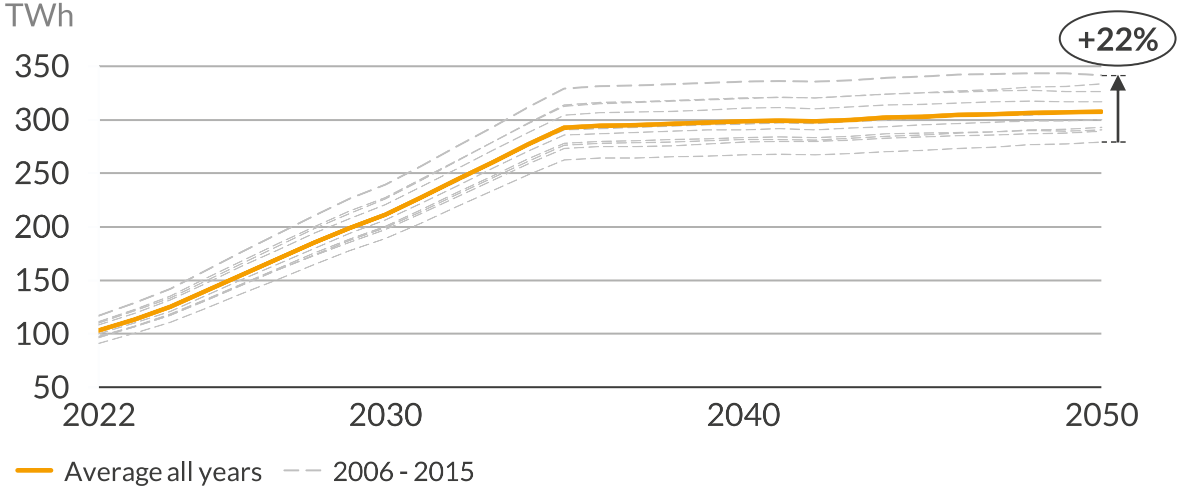


2 Weather year analysis

- The amount of dispatchable and flexible capacity required to complement intermittent renewables generation can differ quite markedly from year to year due to weather variations (see example below)
- In addition to the standard weather year used by Aurora for power market modelling, both the Baseline and the LDES Scenario were run based on the weather data of 4 historic weather years to make sure that none of the scenarios suffers from loss of load in periods with exceptionally low renewables generation

Variation in projected onshore wind production in the Baseline Scenario based on weather data for a sample of historic years

TWh

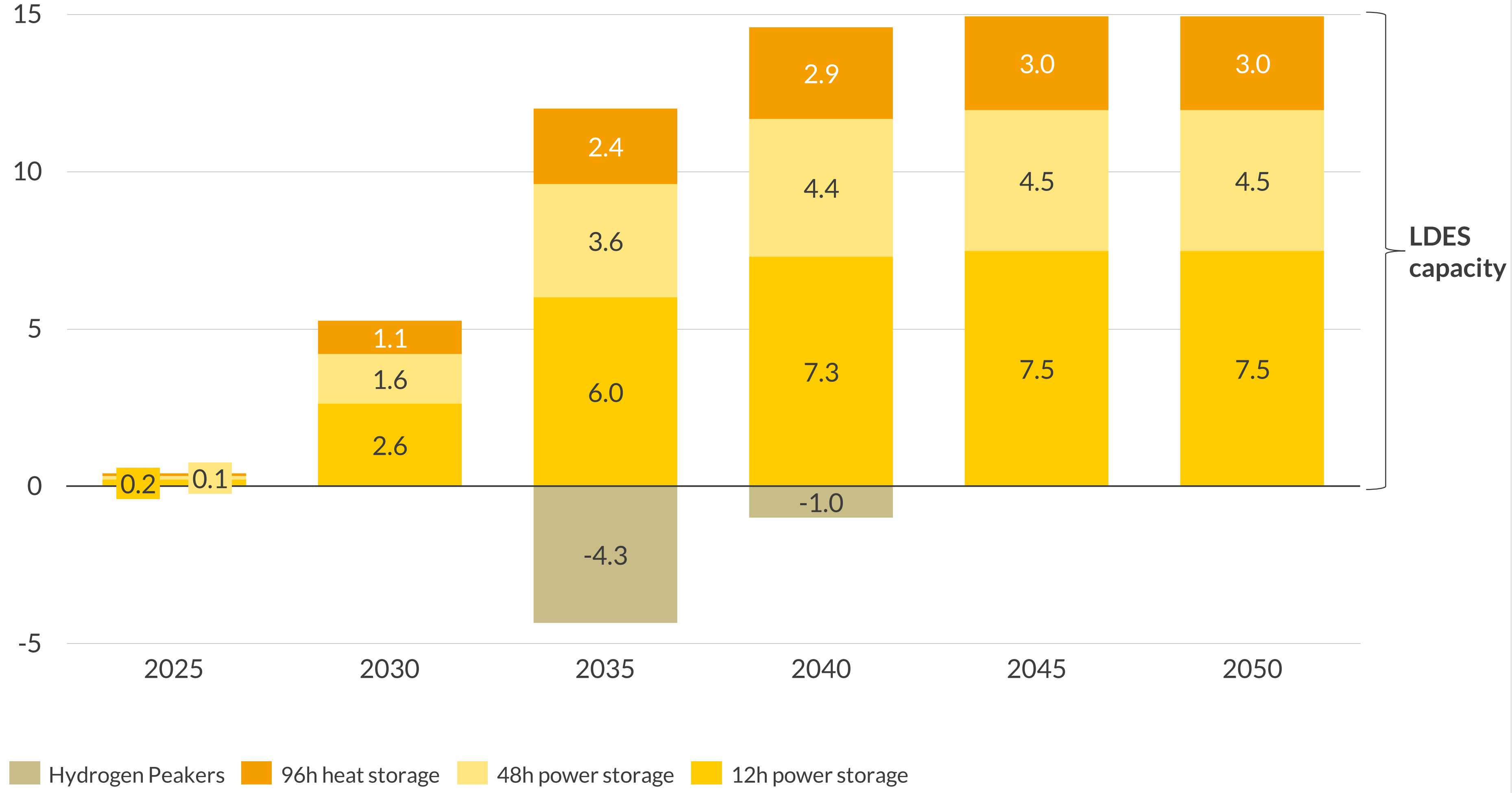


1) The same analysis was done for each of the dispatchable technologies individually (Gas OCGT, Gas CCGT, Hydrogen peakers, and Hydrogen CCGT).

Source: Aurora Energy Research

Additional LDES capacity allows to backload hydrogen peaker buildout without lowering security of supply

Installed capacity delta between LDES Scenario and Baseline Scenario
GW



Capacity changes

- To optimise the system cost savings from LDES deployment, 12 GW of capacity are installed by 2035 and 15 GW by 2045
- The deployment of LDES capacity lowers the need for hydrogen fuelled peaker plants by over 4 GW in 2035 while achieving the same level of security of supply as in the Baseline Scenario
- By 2045, the level of hydrogen peaker capacity needed for an equal level of supply security is again identical to that of the Baseline Scenario due to a continued increase of the power demand
- The level of LDES capacity required to replace dispatchable hydrogen peaker capacity over the whole model horizon would not be the most cost efficient

Source: Aurora Energy Research

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Long duration energy storage would lower wholesale power prices by 1.8 EUR per year on average between 2025 and 2050

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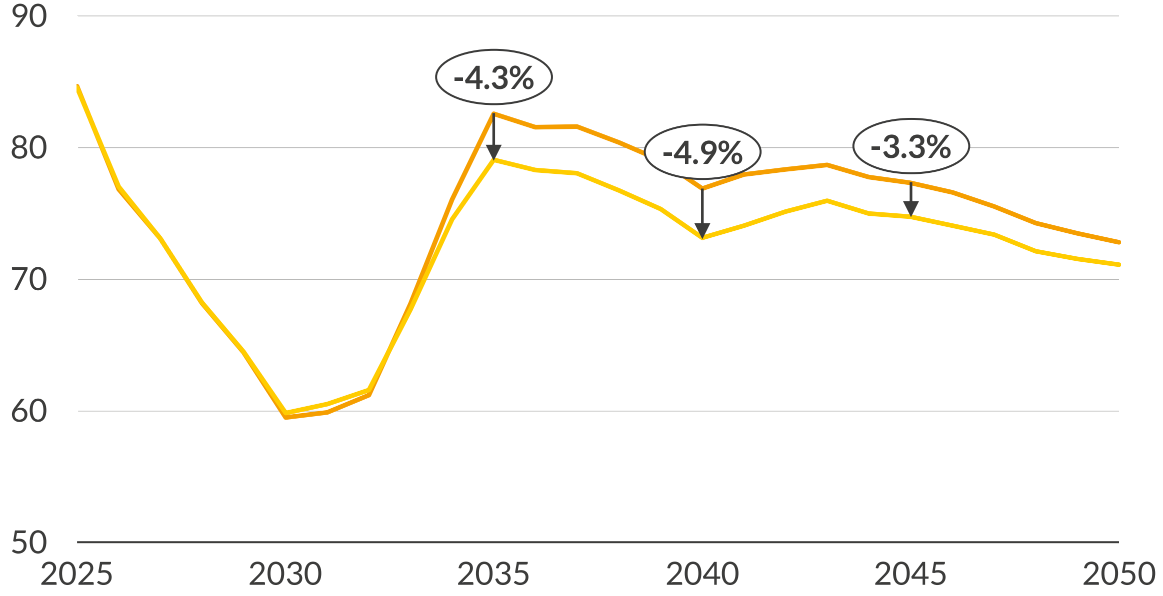
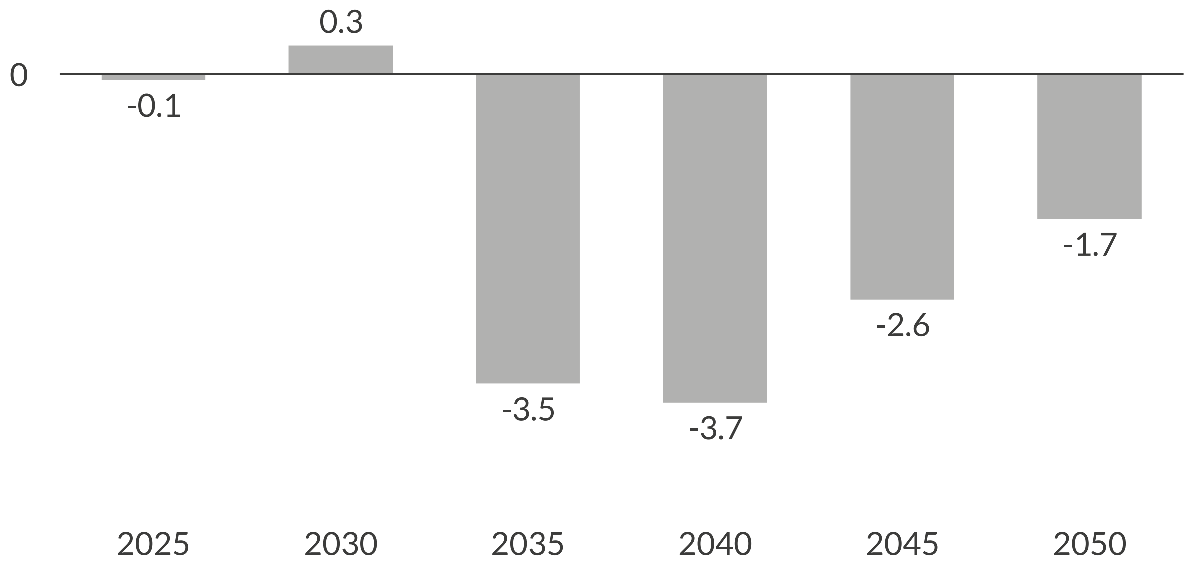
Baseload wholesale electricity price
EUR/MWh (real 2021)



Baseload wholesale electricity price delta
EUR/MWh (real 2021)



- From 2033 onwards, baseload prices in the LDES Scenario are significantly lower than in the base case
- The price delta is due to the fact that LDES discharge in high price hours and push expensive hydrogen-fuelled gas plants out of the merit order, thus lowering the wholesale price

- Contrary to the overall effect, average annual baseload prices are slightly higher in the LDES than in the Baseline Scenario between 2025 and 2032
- This is because in a system consisting of renewables and natural gas, LDES technologies decrease the magnitude of negative price hours by charging in times of excess renewables generation, but the capacity is not yet sufficient to replace the price-setting conventional gas plants in high price hours. Thus, the overall price effect is positive

Baseline Scenario — LDES Scenario

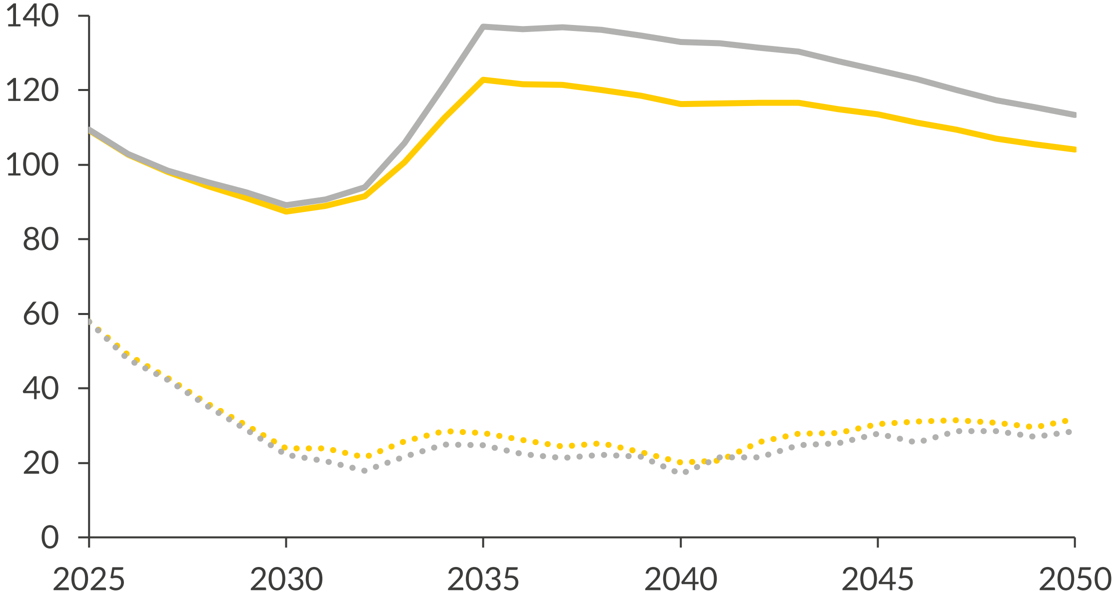
Source: Aurora Energy Research

LDES arbitrage flattens the power price curve and reduces the magnitude of extreme prices significantly

AURORA

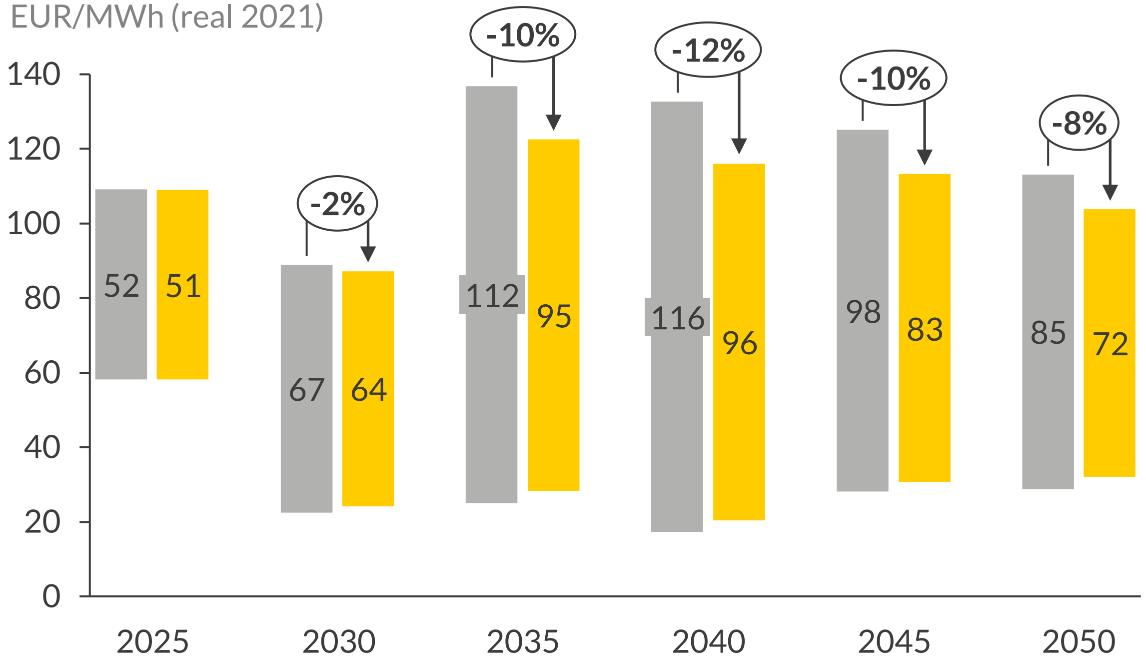
Yearly averages of daily minimum and maximum prices

EUR/MWh (real 2021)



Yearly averages of spreads between daily minimum and maximum prices

EUR/MWh (real 2021)



- The arbitrage of LDES assets on the wholesale market flattens the power price curve and reduces price peaks both at the lower and at the upper end of the spectrum, thus squeezing daily spreads
- The reducing effect on high price hours becomes more pronounced as soon as hydrogen-fuelled plants with high marginal costs set the price in the mid 30s

- Yearly averages of daily price spreads are reduced by up to 12% in 2040
- After 2040, the diminishing effect on daily price spreads becomes weaker because hydrogen prices go down and other forms of flexibility on the supply and demand side increasingly limit price peaks as well

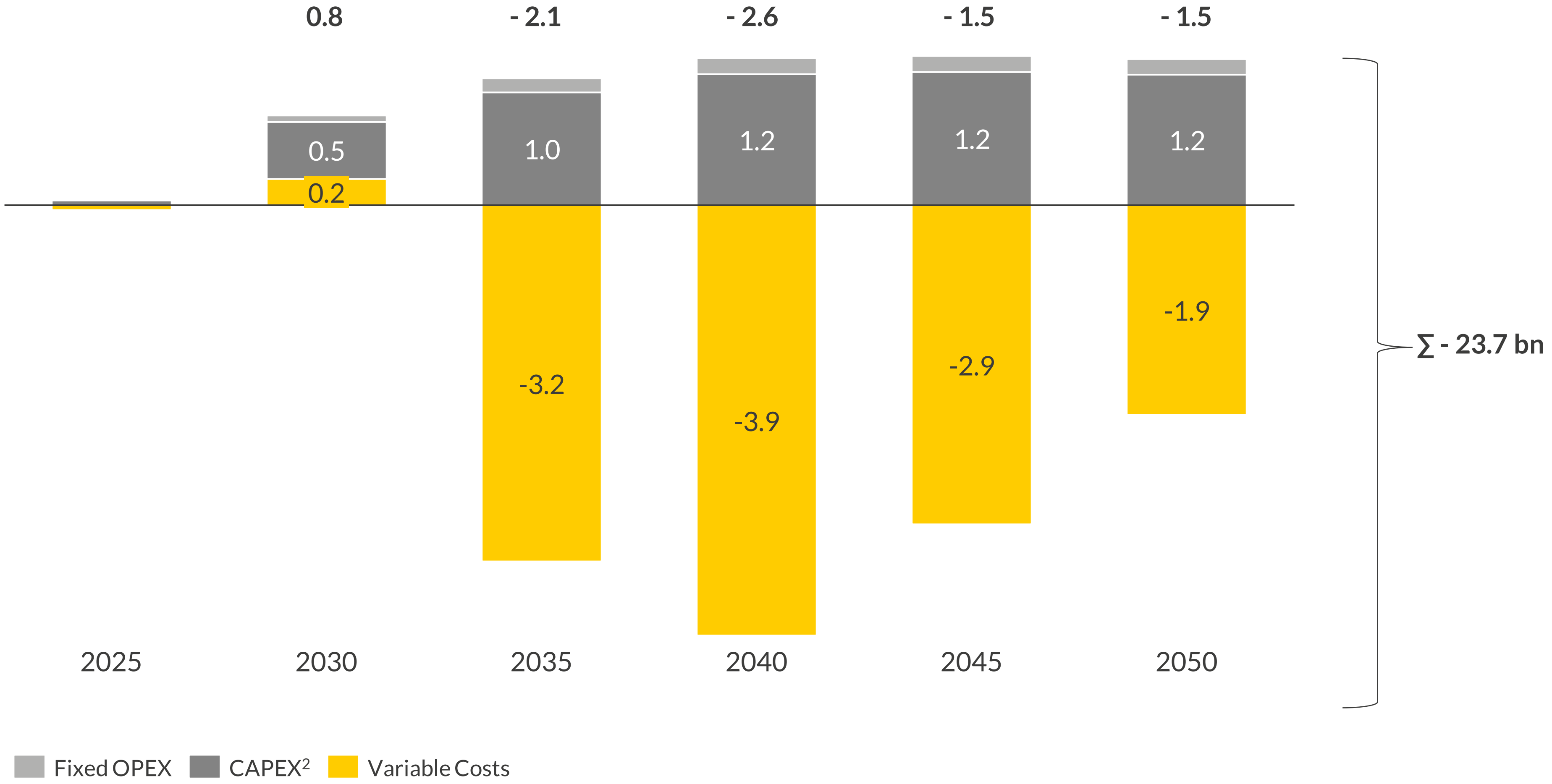
Average daily min price LDES
Average daily min price Baseline
Average daily max price LDES
Average daily max price Baseline

Spread LDES Scenario
Spread Baseline Scenario

Source: Aurora Energy Research

Integrating LDES into the power system would lower total costs by 23.7 billion Euros until 2050

System costs delta between the LDES Scenario and the Baseline Scenario[1]
Bn EUR (real 2021)



Comments

- The reduction in overall system costs is driven by the lower average wholesale power prices in the LDES Scenario compared to the Baseline Scenario
- The savings from lower power prices are partially offset by increases in investment costs related to the roll-out of LDES capacities
- Fixed OPEX for LDES have a minor contribution to the difference in system costs

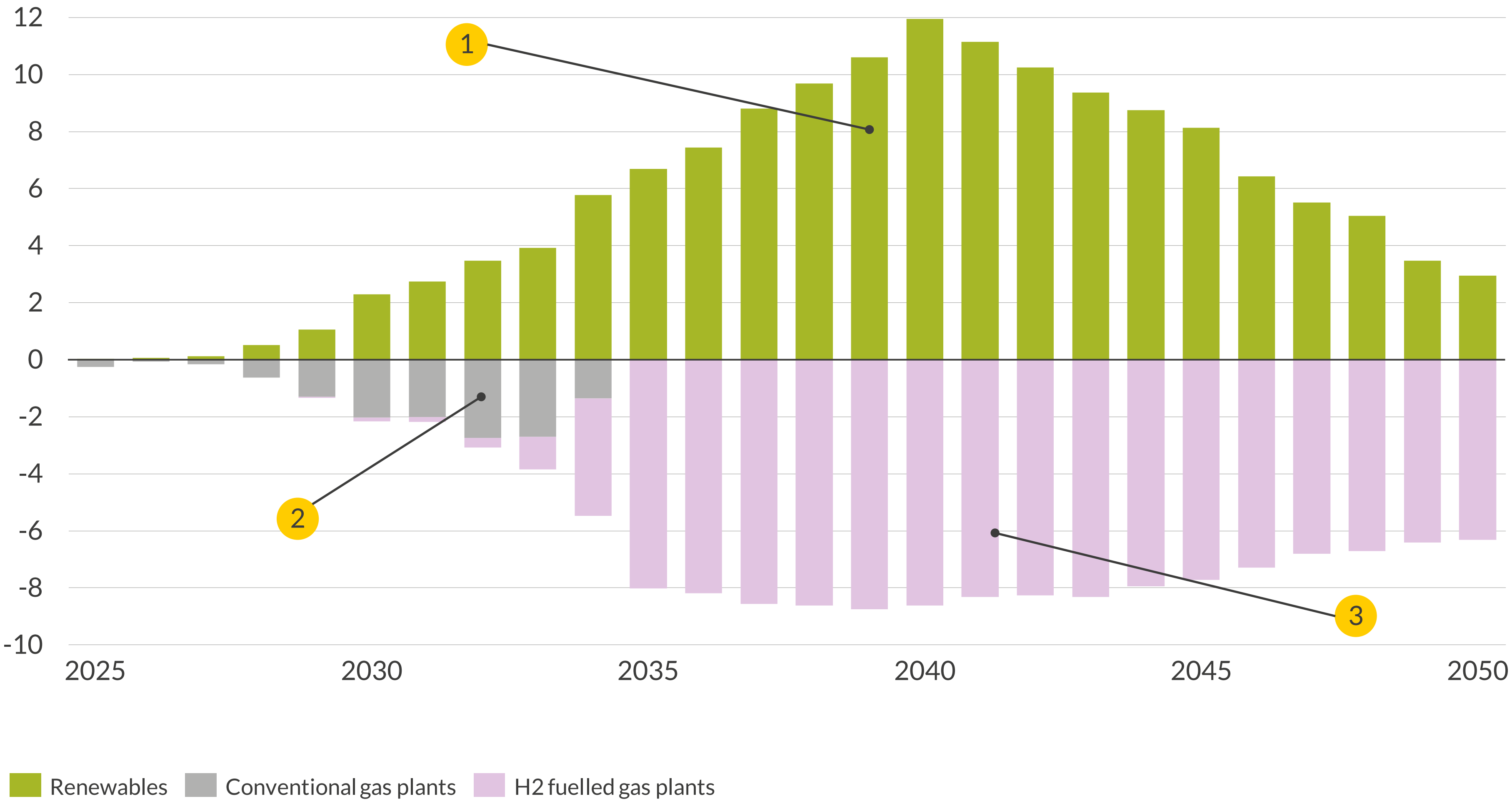
1) Savings in negative numbers, costs in positive numbers, 2) Annualised CAPEX of LDES investments with 4% interest rate

Source: Aurora Energy Research

The deployment of LDES would reduce power generation from gas and hydrogen power plants and avoid RES curtailment

AURORA

Electricity production delta between the LDES and the Baseline Scenario
TWh



Generation changes

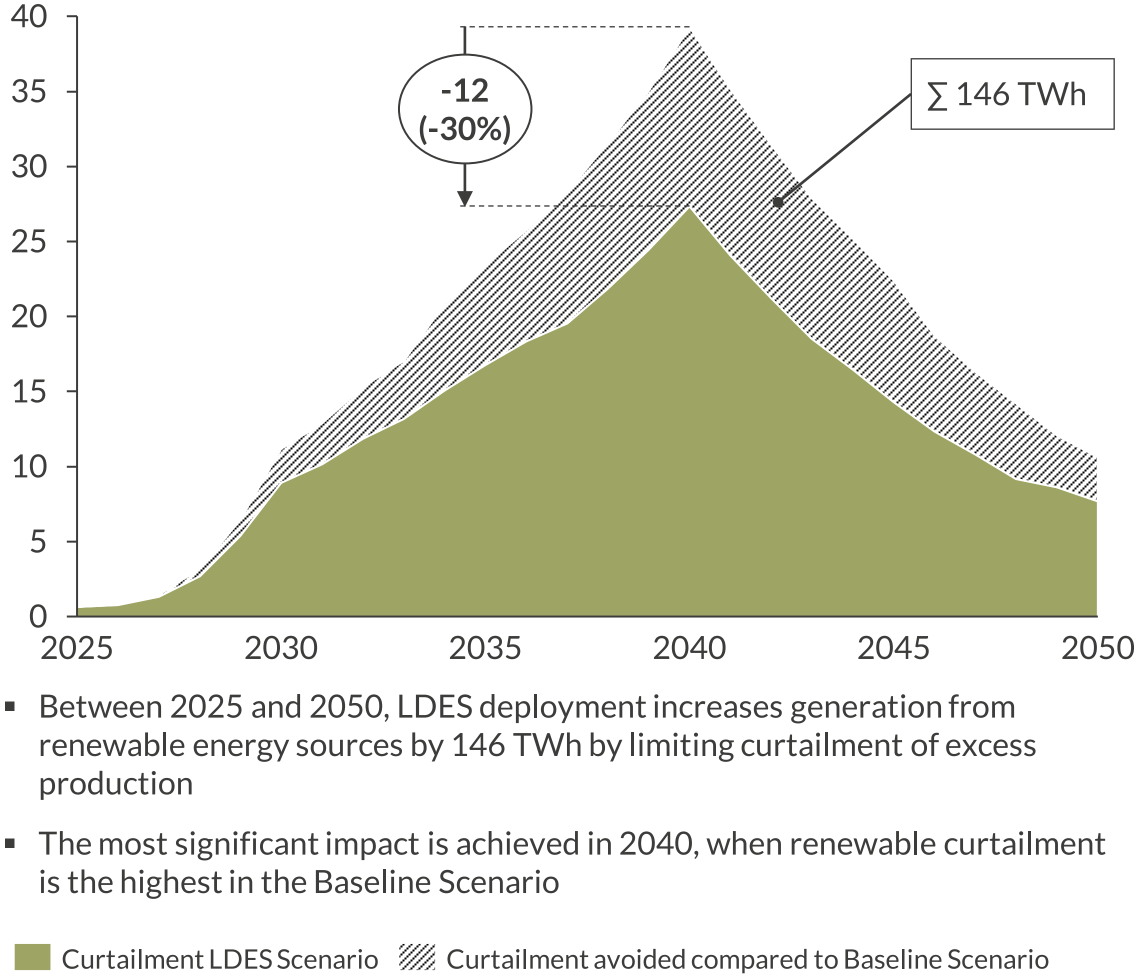
1. LDES absorb renewable electricity by charging in hours in which renewables production exceeds demand and thereby reduce curtailment (see slide 31)
2. LDES discharge in high price hours and thereby reduce the amount of electricity generated by conventional gas plants as well as CO_2 emissions (see slide 32)
3. After the transition from natural gas to hydrogen-fuelled power plants, LDES lower the amount of electricity generated by hydrogen plants which translates to a decrease in the demand for hydrogen in the power sector (see slide 33)

Source: Aurora Energy Research

Additional flexibility provided by LDES reduces RES curtailment by up to 30%

Reduction of renewables curtailment compared to Baseline Scenario

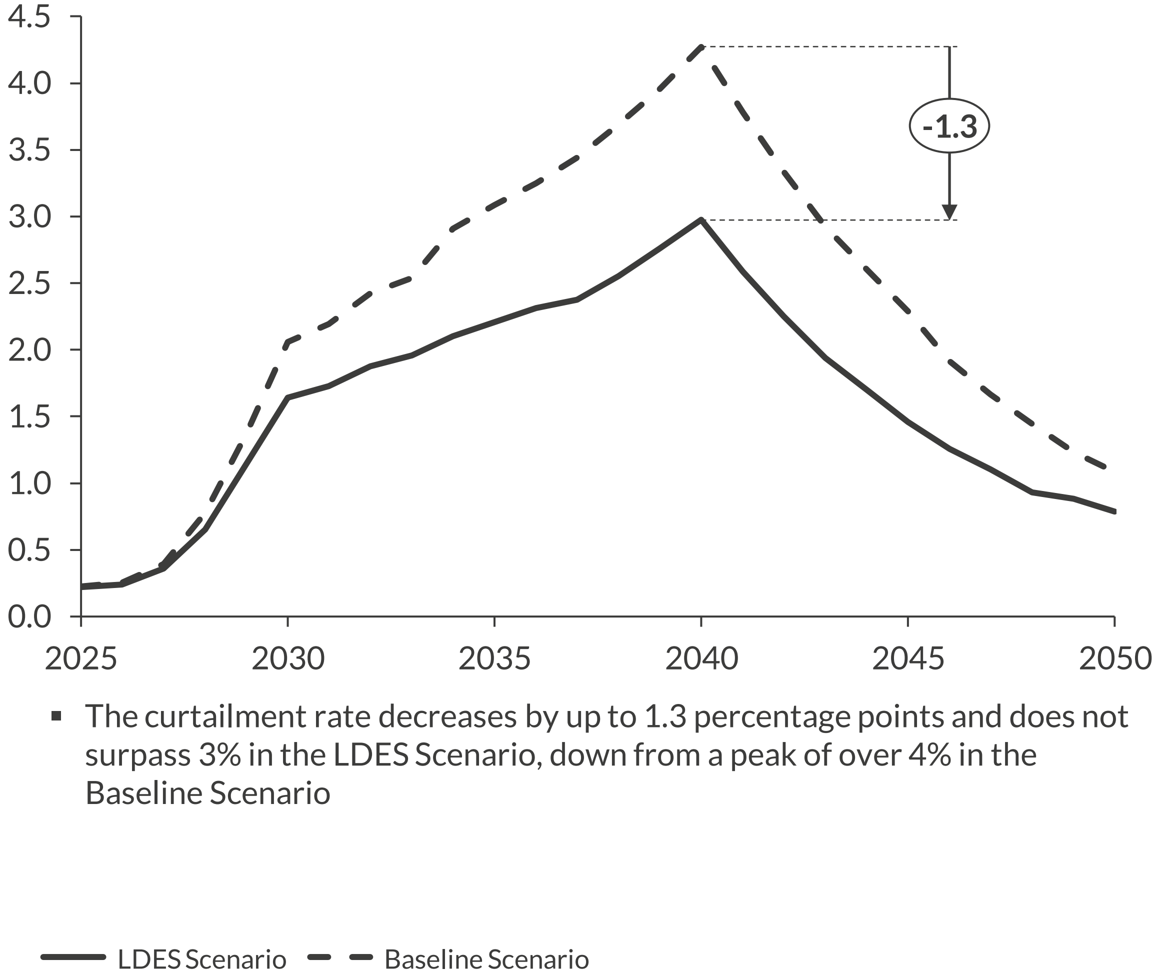
TWh



- Between 2025 and 2050, LDES deployment increases generation from renewable energy sources by 146 TWh by limiting curtailment of excess production
- The most significant impact is achieved in 2040, when renewable curtailment is the highest in the Baseline Scenario

Curtailment as percent of total renewables generation

%



- The curtailment rate decreases by up to 1.3 percentage points and does not surpass 3% in the LDES Scenario, down from a peak of over 4% in the Baseline Scenario

Source: Aurora Energy Research

The effect of LDES on fossil fuel consumption in the power sector is marginal given the already ambitious phase-out trajectory

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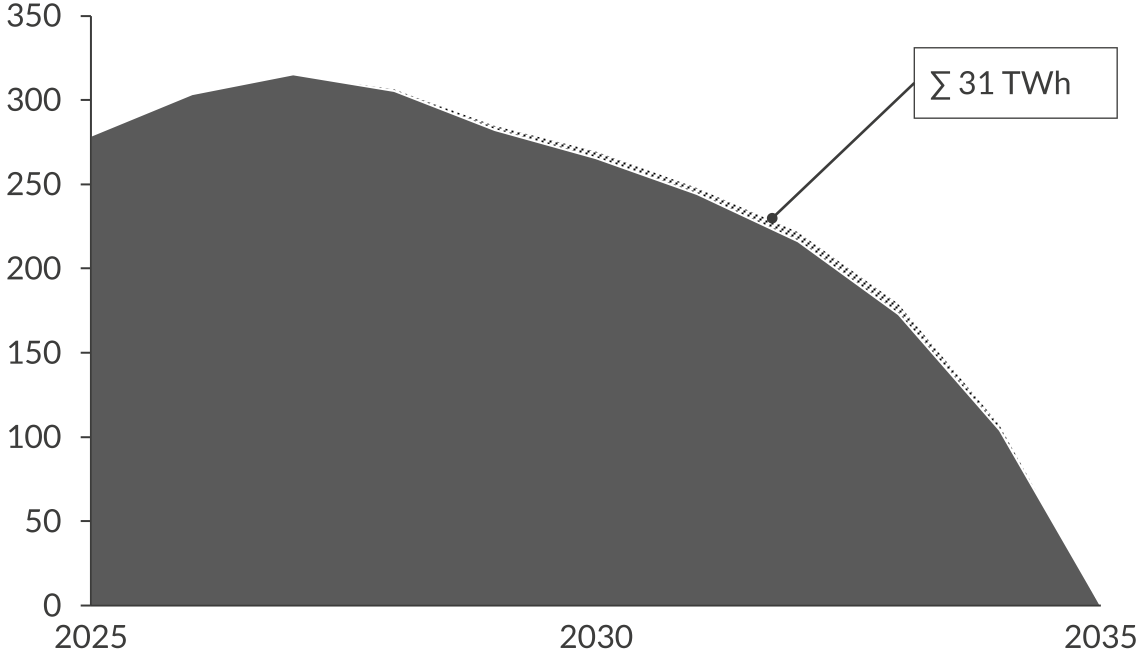
Reduction of natural gas use in the power sector compared to the Baseline

TWh

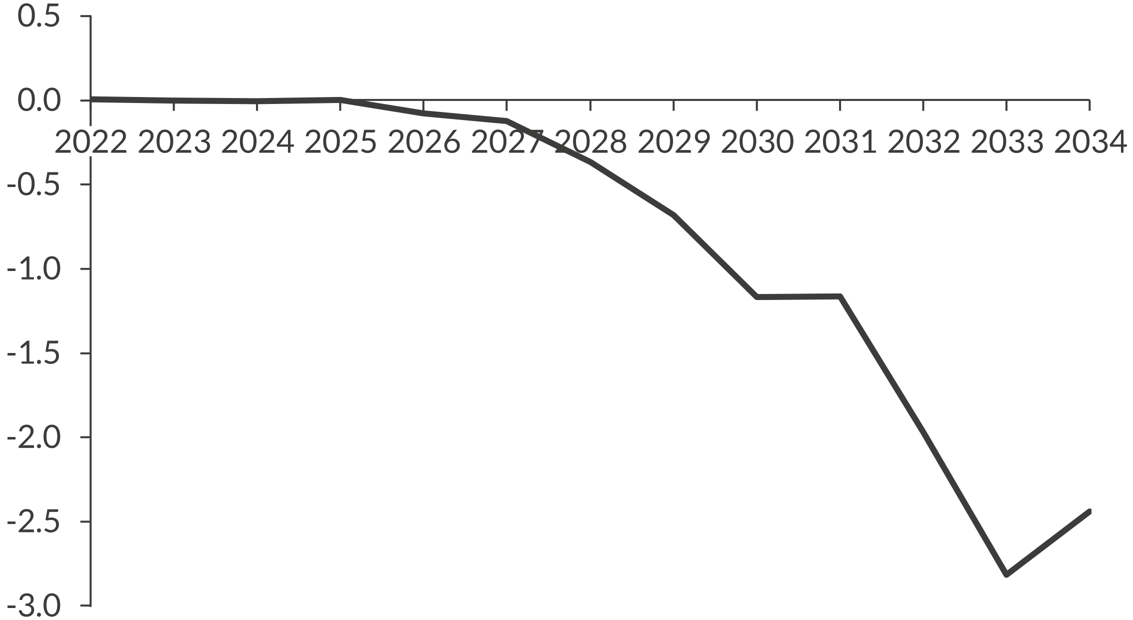


- Due to the fast capacity-driven decline of power generation from conventional gas plants until 2035, the additional diminishing effect from LDES deployment is only marginal
- The amount of natural gas saved in the power sector amounts to 31 TWh between 2025 and 2035 (1.2% of total gas burned in the Baseline Scenario)

Natural gas consumption LDES Scenario | Natural gas consumption avoided

Emission reduction as percentage of Baseline total power sector emissions

%



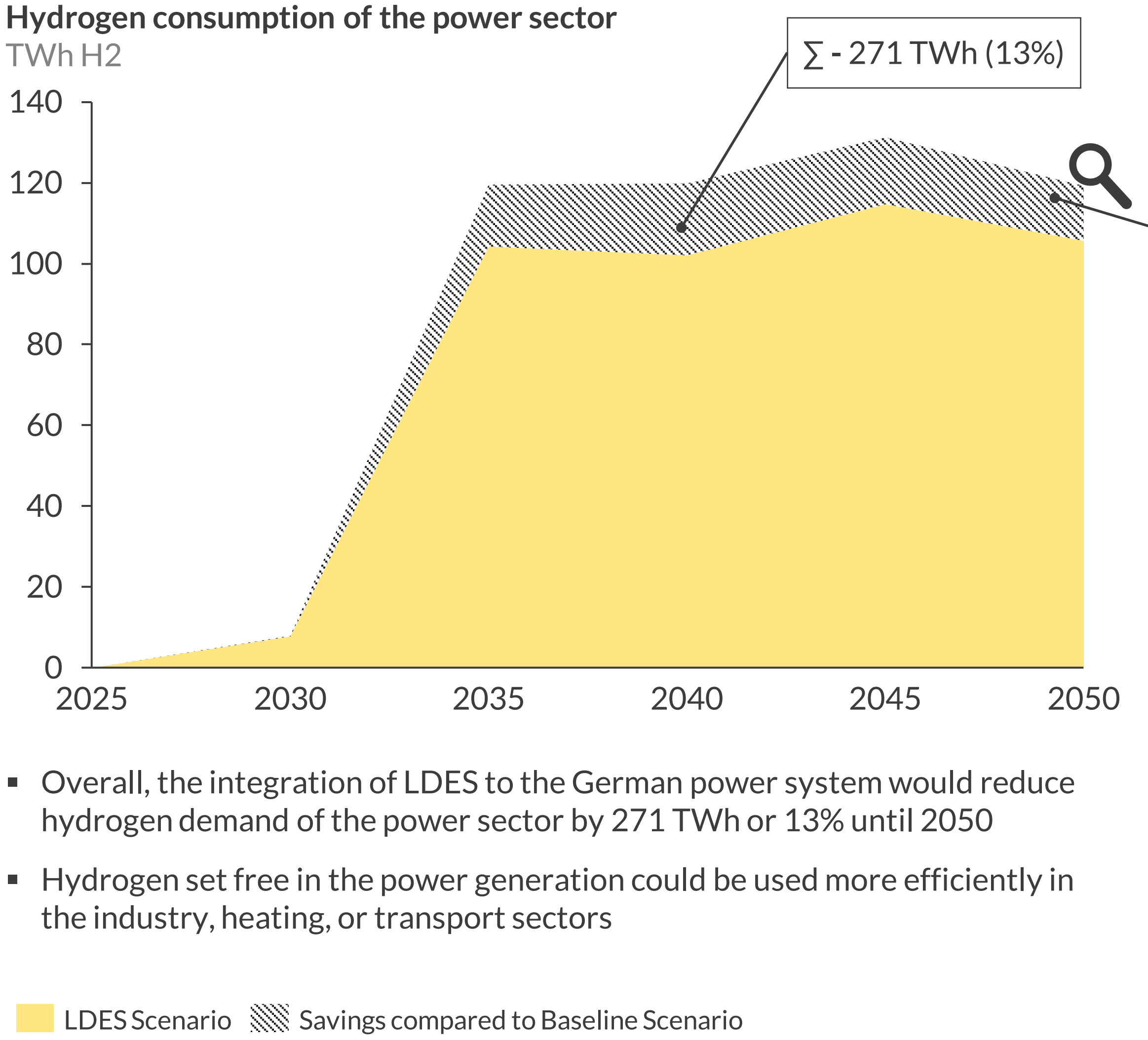
- With increasing capacities of LDES technologies, the effect on total emissions becomes more visible but stays on a low level overall
- Since Net zero is achieved in 2035, the analysis of the impact of LDES deployment on carbon emissions focuses on the period 2025-2034

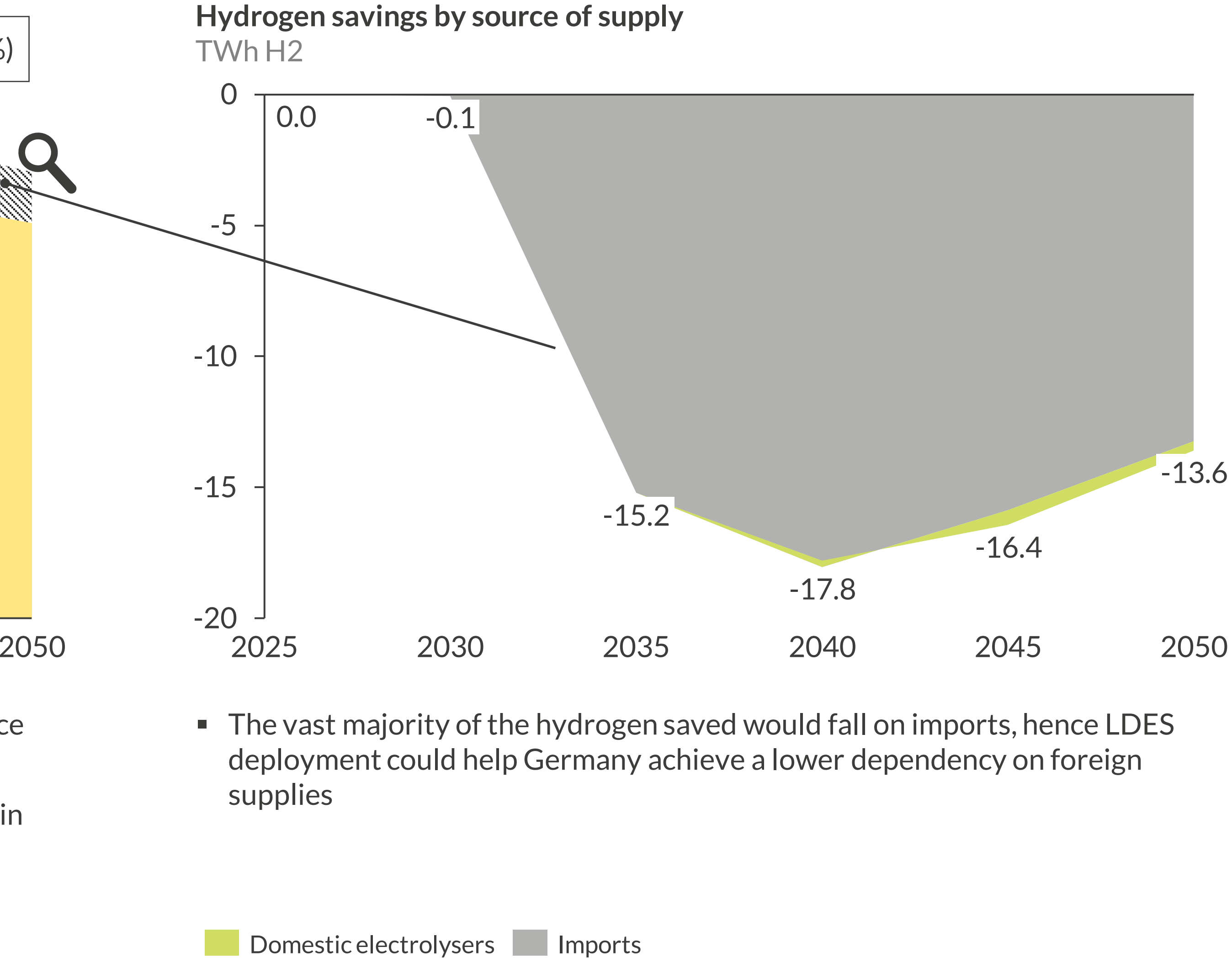
Delta CO2 emissions

Source: Aurora Energy Research

LDES would reduce the need for hydrogen in the power sector by 13% and lower Germany's reliance on hydrogen imports

AURORA





- Overall, the integration of LDES to the German power system would reduce hydrogen demand of the power sector by 271 TWh or 13% until 2050
- Hydrogen set free in the power generation could be used more efficiently in the industry, heating, or transport sectors

- The vast majority of the hydrogen saved would fall on imports, hence LDES deployment could help Germany achieve a lower dependency on foreign supplies

Source: Aurora Energy Research

Power demand from electric heat applications is slightly lower in the LDES Scenario than in the Baseline

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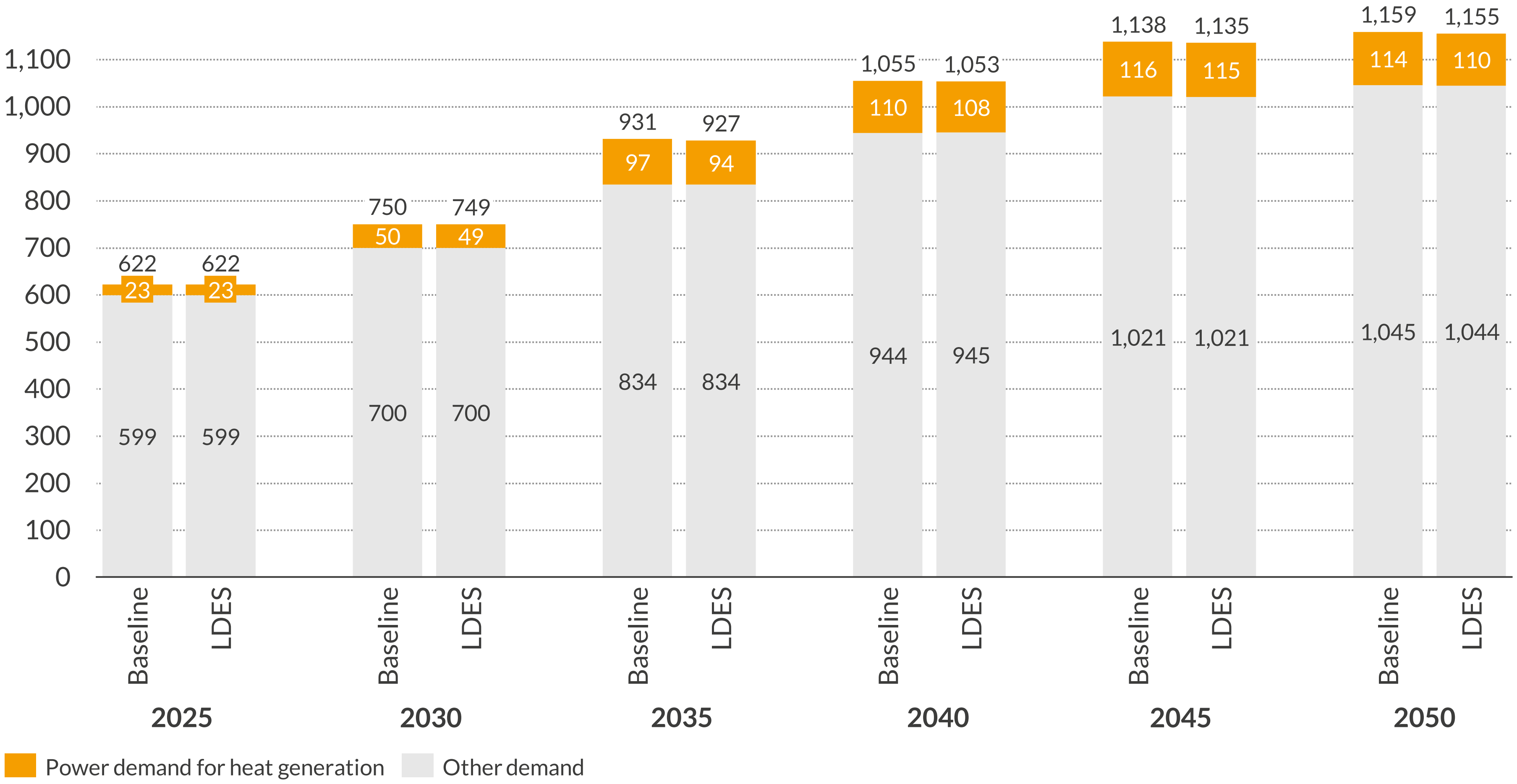
Net power demand in the Baseline and LDES Scenario

TWh



Demand changes

- Overall, the impact of LDES deployment on net power demand is only marginal
- Power demand from electric heat generation is slightly lower compared to the Baseline Scenario because the charging/discharging profile of LDES flattens the power price curve and makes power consumption for flexible electric heat generating assets less attractive

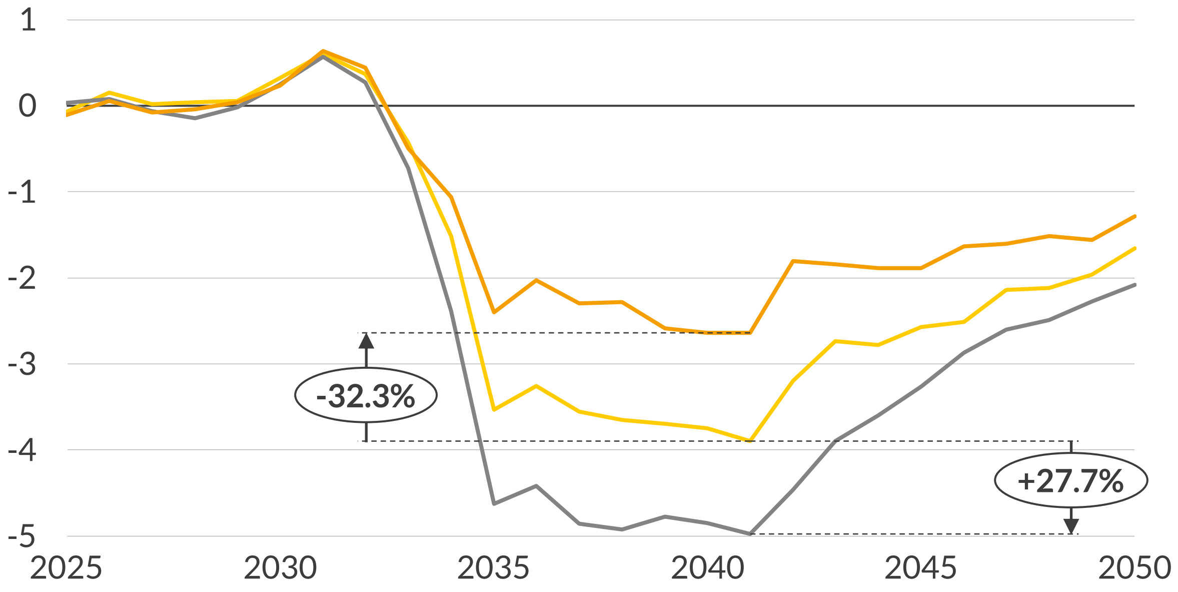
Source: Aurora Energy Research

Agenda

System cost savings are sensitive to the H_2 price: 10% higher (lower) costs for H_2 increase (decrease) total savings by 67%

AURORA

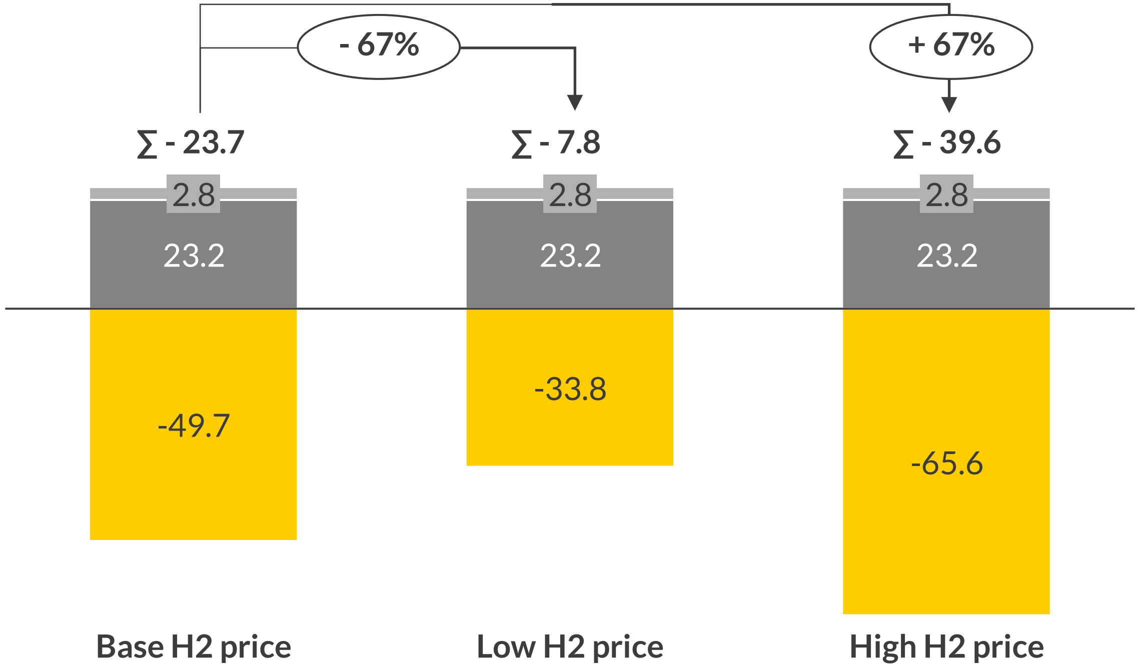
Baseload price delta between Baseline and LDES Scenario
EUR/MWh (real 2021)



- Higher (lower) H_2 prices translate to higher (lower) power prices in hours in which H_2 - fuelled gas plants set the price
- Since the baseload price delta between the Baseline and LDES Scenario is created by a substitution of H_2 plant production by LDES discharge, the hydrogen price has a direct impact on the magnitude of the price difference

Baseline H2 price | 10% higher H2 price | 10% lower H2 price

Total 2025-2050 system cost delta between Baseline and LDES Scenario
Bn EUR (real 2021)



- Because the baseload price delta determines the difference in variable costs between the Baseline and LDES Scenario, the H_2 price sensitivities impact the magnitude of variable cost savings
- Variations in the H_2 do not change the OPEX and CAPEX delta because the installed capacity of LDES stays constant

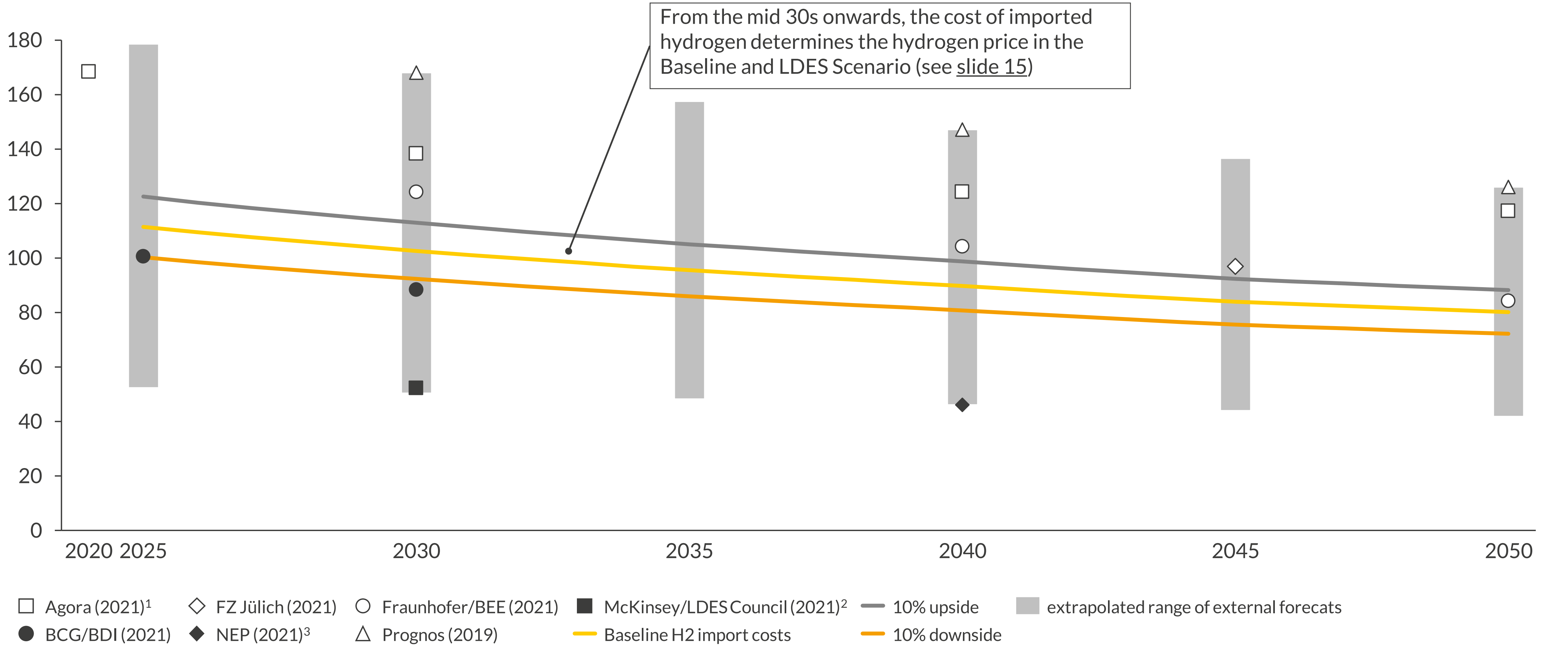
Fixed OPEX | CAPEX | Variable costs

Source: Aurora Energy Research

Cost assumptions for imported green hydrogen are within the range of forecasts made in other relevant studies

Assumed cost development for imported hydrogen against various price benchmarks

EUR/MWh (real 2021)



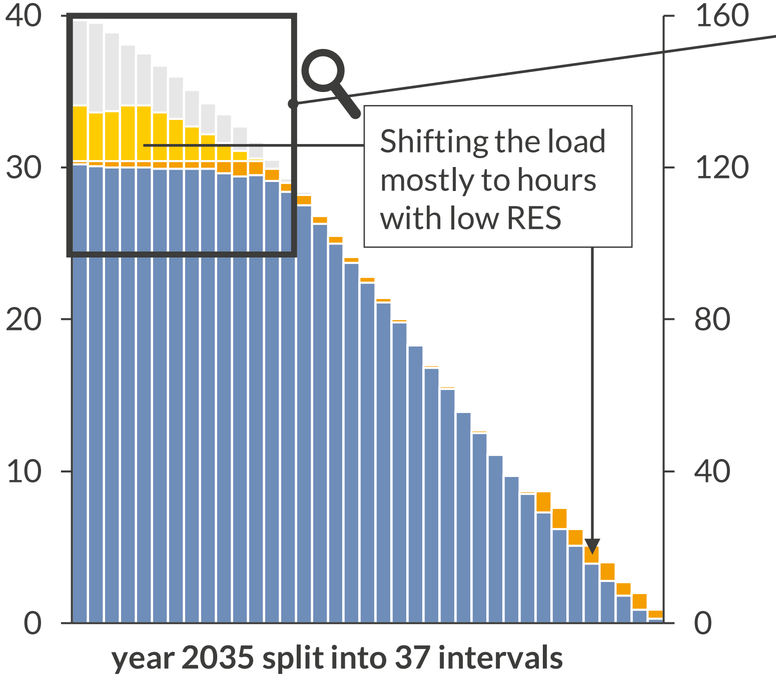
1) Reflects the price for a mix of domestically produced an imported green hydrogen, 2) Global cost prediction, not for the German market specifically , 3) Extrapolated based on a cost estimate for hydrogen of 46.8 EUR/MWh for 2037

Sources: Aurora Energy Research, Agora Energiewende, Forschungszentrum Jülich, Fraunhofer Institut, McKinsey, Boston Consulting Group, Netzentwicklungsplan 2037, Prognos

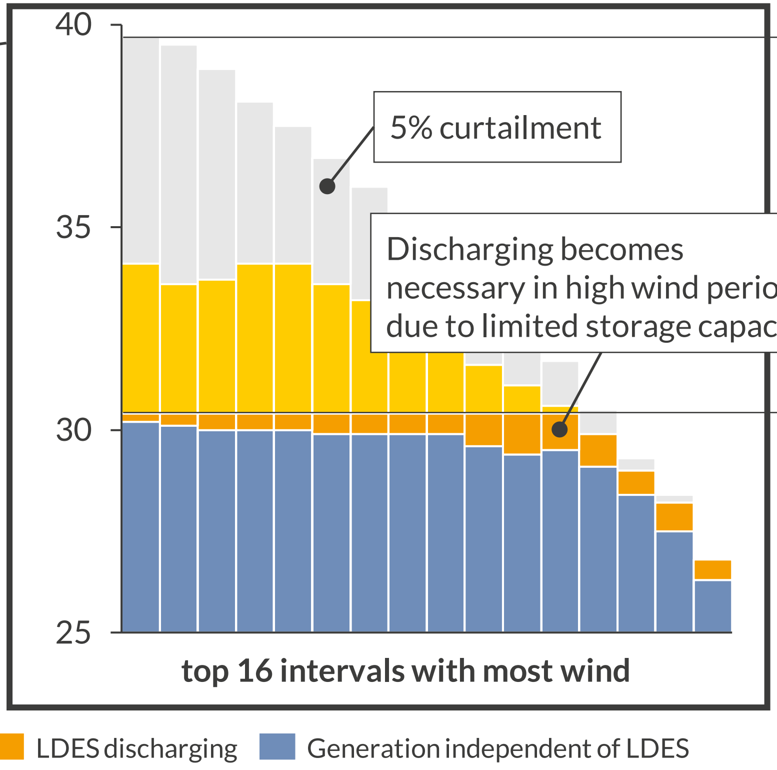
By co-locating LDES with wind offshore, EUR 1.3 billion reduction of grid connection CAPEX could be achieved in 2035

AURORA

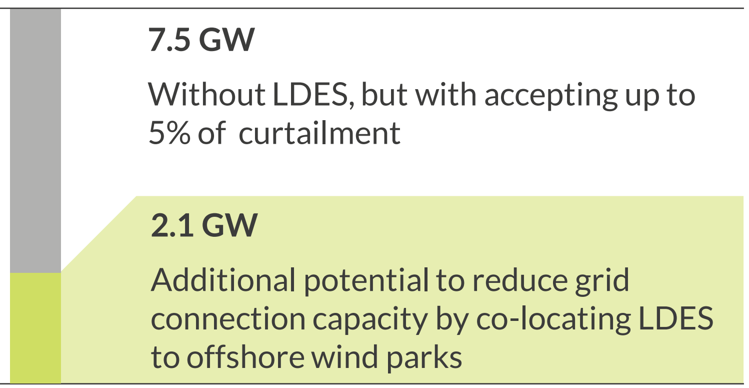
Generation of co-located offshore wind parks, LDES
GW, average in interval



Generation of co-located offshore wind parks, LDES
GW, average in interval



Potential to reduce grid connection capacity
GW



- CAPEX for grid connection of offshore wind parks: 430 €/kW
- Additionally considered CAPEX of North-South transmission system: 200 €/kW
- Total CAPEX reduction by co-locating all electric LDES and offshore capacities in 2035: **€ 1.3 billion**

Methodology

- For 2035 the wind offshore generation pattern is used to run a co-location dispatch with LDES capacities[1] and constraints in grid connection capacity
- To visualise results, hours are sorted by descending wind power output and the average for 37 intervals of the year is plotted

1) Only the power-to-power LDES capacities assumed in 2035, 3.6 GW of 24h storage, 6 GW of 12h storage

Sources: Fraunhofer ISE (2020)

Agenda

Lithium-ion batteries provide flexibility at low cost – however, costs rise strongly with duration, limiting its LDES application

AURORA

Description

- The movement of lithium ions between the anode and cathode in an electrochemical reaction results in battery charge and discharge
- Li-ion batteries have high roundtrip efficiency and are a proven technology to store power for shorter duration (industrial scale projects offer durations of up to 4h)
- Could store for longer durations, but cost increases strongly

Potential barriers for adoption

- Given the costs of Li-ion rise strongly with duration, the technology is economically limited in the numbers of hours it provides flexibility
- Contrary to other LDES technologies, it is not possible to decouple the scaling of power and energy in Li-ion batteries
- Lithium and cobalt resources may eventually prove a limiting factor to the widespread adoption of lithium-ion batteries
- High depth of discharge maximizes revenues but results in lower battery lifetime
- Thermal control issues could cause potential safety hazards

Key parameters used for the profitability analysis (COD 2030)

Currencies in real 2021

Parameter	Value	Unit
Lifetime	15	Years
Typical unit size	>100	MW
Cost – CAPEX[1]	1110[2]	€/kW
Cost – Fixed O&M[1]	8	€/kW/a
Round trip efficiency	87	%
Cycles	5,000	-
Discharge duration	8	h

Double of the common maximum storage duration in existing installations

Maturity, Buildout, Pilots

Commercial Maturity: Medium - High

- A Li-ion facility with 48 MW / 50 MWh has been built in Jardelund, Germany, by Eneco in cooperation with Mitsubishi
- Globally, the largest project with 300 MW and 4 hours of duration is the Moss Landing Energy Storage System in California
- Two Li-ion projects with 8h duration have been selected in the California long-duration storage procurement in January and March 2022

1) We assess CAPEX and Fixed O&M based on cost/kW in order to make them comparable to the other technologies and to assess need and cost for flexible capacity; 2) CAPEX assumptions are based on the power and energy related costs for 4h batteries, which were interpolated to obtain an estimate for 8h li-ion batteries. CAPEX are significantly higher compared to marketed 4h battery systems due to the higher energy storage capacity

Source: Aurora Energy Research

With increasing duration, redox-flow batteries gain in cost-effectiveness versus Li-ion but have lower roundtrip efficiency

AURORA

Description

- Redox-flow batteries are a storage technology based on electrochemical processes occurring between a positive and negative electrode
- Power output and storage depth of a redox-flow battery can be scaled independently as the energy is stored in tanks outside the energy conversion unit
- Another advantage of this type of batteries is that they do not exhibit significant degradation

Potential barriers for adoption

- Redox-flow batteries still achieve lower roundtrip efficiencies, thus they require larger spreads in the power market to achieve profitability
- The initial investment cost for the flow system is quite high – yet the additional cost for increasing storage depth is lower compared to Li-ion
- The technology is less standardized and has mostly been proven at a smaller scale
- Vanadium extraction can cause potential harmful effects on ecological systems and pose a safety hazard to animals and humans

Key parameters used for the profitability analysis (COD 2030)

Currencies in real 2021

Parameter	Iron flow	Vanadium flow	Unit
Lifetime	25	25	Years
Typical unit size	>100	>100	MW
Cost – CAPEX	1557	1487	€/kW
Cost – Fixed O&M	11	7	€/kW/a
Round trip efficiency	70	70	%
Cycles	Unlimited	Unlimited	-
Discharge duration	22	8	h

Durations of existing systems are typically in the 8-12h range, but could be scaled up

Maturity, Buildout, Pilots

Commercial Maturity: Medium

- The EU has recently awarded funds to the MELODY consortium, lead by TU Delft to develop sustainable redox-flow batteries
- In Dalian (China), a facility based on the vanadium flow technology with 200 MW / 800 MWh is currently under construction
- In the US, deliveries of iron flow batteries manufactured by ESS Inc. commenced in Q4/2021 to both utility and commercial customers
- The iron flow system of ESS Inc. has been sold to ENEL for delivery commencing 2022

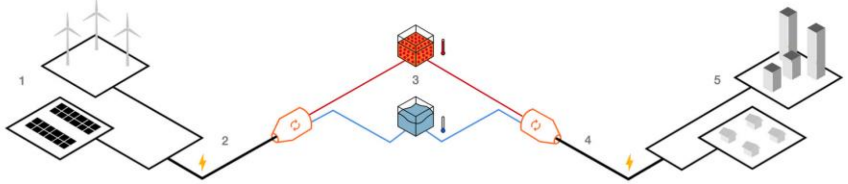
Sources: Aurora Energy Research; IRENA; European Association for Storage of Energy; Fraunhofer ICT; TU Delft; Enel

Electro-thermal storage systems are more cost intensive than redox flow batteries, but can generate both power and heat

AURORA

Description

- Reversible heat pump system[1]: In charge mode, the system operates as a heat pump, storing electricity as heat in molten salt. In discharge mode, the system operates as a heat engine, using the stored heat to produce electricity
- The required components are typically standard industrial equipment with only minor customization and R&D needed



Depiction of a reversible high temperature heat pump electro-thermal storage system

Potential barriers for adoption

- The technology is still in the development phase, major industrial-scale applications are yet to be built
- Compared to flow batteries, the technology requires higher CAPEX and fixed OPEX expenditures and achieves a lower round-trip efficiency

Key parameters used for the profitability analysis (COD 2030)

Currencies in real 2021

Parameter	Value	Unit
Lifetime	30	Years
Typical unit size	>100	MW
Cost – CAPEX[1]	2667	€/kW
Cost – Fixed O&M[1]	21	€/kW/a
Round trip efficiency	52-60 (power), 35 (heat)[2]	%
Cycles	Unlimited	-
Discharge duration	28	h

Durations of existing systems are typically in the 8-24h range, but could reach up to 100-200h potentially

Maturity, Buildout, Pilots

Commercial Maturity: Low-Medium

- MALTA Iberia to build a 100 MW electro-thermal energy storage facility with 1 GWh capacity in Spain

1) The reversible heat pump system is only one of many available types of electro-thermal LDES system, it was chosen for this study on the grounds of high availability of technical parameters 2) We assess CAPEX and Fixed O&M based on cost/kW in order to make them comparable to the other technologies and to assess need and cost for flexible capacity, 3)Round-trip efficiency of heat discharge, on top of the electric round-trip efficiency

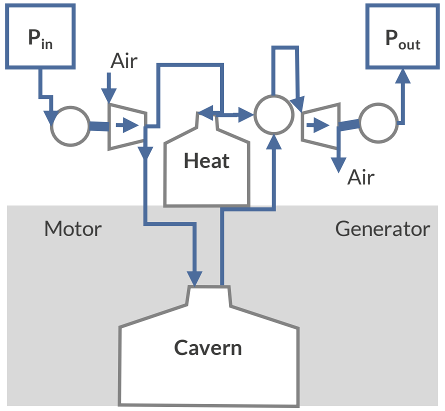
Source: MALTA Inc., Aurora Energy Research

Pilots for adiabatic compressed air storage systems are ongoing but the large-scale commercial use has yet to be proven

AURORA

Description

- A compressed air energy storage system (CAES) is based on air compression and storage in an underground cavern
- Electricity is used to compress air, for an adiabatic plant (A-CAES) the heat of compression is stored separately
- To retrieve the energy, the compressed air is used to generate power in a turbine
- The technology uses standard industrial components



Depiction of A-CAES plant

Potential barriers for adoption

- Integration at large scale has never been proven so far[1]
- Site dependency as large cavities (mostly underground caverns) are required
- Reliance on thermal energy storage systems to store the heat of air compression efficiently, making A-CAES a de-facto thermal – mechanical hybrid storage system
- To achieve a high depth of discharge, a complex water displacement system is required which increases CAPEX costs

Key parameters used for the profitability analysis (COD 2030)

Currencies in real 2021

Parameter	Value	Unit
Lifetime	30	Years
Typical unit size	>100	MW
Cost – CAPEX	2000	€/kW
Cost – Fixed O&M	15	€/kW/a
Round trip efficiency	65	%
Cycles	Unlimited	-
Discharge duration	48	h

Typical durations of existing systems are 8-12h

Maturity, Buildout, Pilots

Commercial Maturity: Low

- Most major experimental projects and commercial ventures have so far failed to yield viable prototypes
- In 2019, Hydrostor built the world's first commercially contracted A-CAES facility for Ontario's Independent Electricity System Operator in Goderich, CA
- Two 500 MW / 5 GWh projects have been announced in California, USA by Hydrostor, offering ~10 h of duration

1) A-CAES systems are not to be confused with diabatic compressed air systems (D-CAES) which is a technology with a high commercial maturity (Two D-CAES systems are operational in Germany and the US for over 40 years) . Although the concept is similar, D-CAES systems require additional fuel to release power and achieve lower efficiencies of only up to 45%

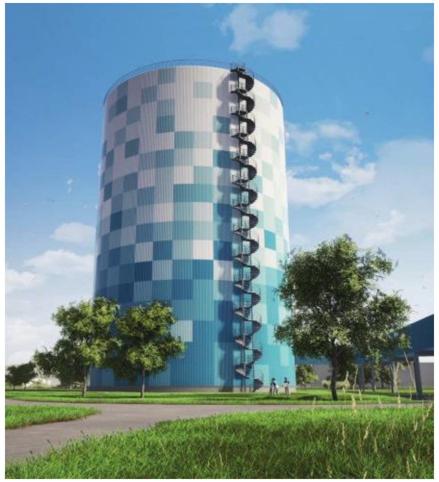
Sources: Aurora Energy Research; European Association for Storage of Energy; TNO; Energeia; Recharge News

Water-based sensible thermal storage systems are widely used for heat storage

AURORA

Description

- Electrodes are used to convert electrical energy to heat. The heat is stored in insulated water tanks, pits or caverns and released to the heating grid when needed
- Due to low costs, simple implementation and abundant availability, water storage technology is widely used with applications in the solar thermal engineering field among others



Key parameters used for the profitability analysis (COD 2030)

Currencies in real 2021

Parameter	Value	Unit
Lifetime	30	Years
Typical unit size	>100	MW
Cost – CAPEX	420	€/kW
Cost – Fixed O&M	10	€/kW/a
Round trip efficiency	90 (heat)	%
Cycles	Unlimited	-
Discharge duration	96	h

Potential barriers for adoption

- Low barriers for adoption but limitations due to the relatively low energy density and the requirement for insulation to prevent large heat losses over longer storage durations

Maturity, Buildout, Pilots

Commercial Maturity: High

- Hot water tank energy storage systems are used as part of district heating networks in Germany, for instance in Hamburg, Hannover, Rostock or Friedrichshafen
- Built in 2020, A pilot project in Kiel combines an electrode boiler and a hot water tank to generate and store heat

Source: Aurora Energy Research, Stadtwerke Rostock, Stadtwerke Kiel, University Stuttgart

Overview of key technical parameters used for each LDES technology for the profitability analysis

AURORA

Parameters of long duration storage technologies used for the profitability analysis

	Storage duration, hours[1]	Capital cost, EUR (real 2021)[2]	Fixed operation cost, EUR (real 2021)[2]	Lifetime	Efficiency, %	Degradation of usable storage capacity, % per year
Iron flow batteries	22	1557/kW	11/kW	25 years	70	Negligeable (<0.2)
Li-ion batteries	8	1110/kW	8/kW	~5000 cycles before repowering due to significant degradation	87	2
Adiabatic compressed air (CAES)	48	2000/kW	15/kW	30 years	65	Negligeable (<0.2)
Vanadium flow batteries	8	1487/kW	7/kW	25 years	70	Negligeable (<0.2)
Electro-thermal energy storage	28	2667/kW	21/kW	30 years	52-60 (electric) 35 (thermal)	Negligeable (<0.2)
Water-based sensible heat storage	96	420/kW	10/kW	30 years	90 (thermal)	Negligeable (<0.2)

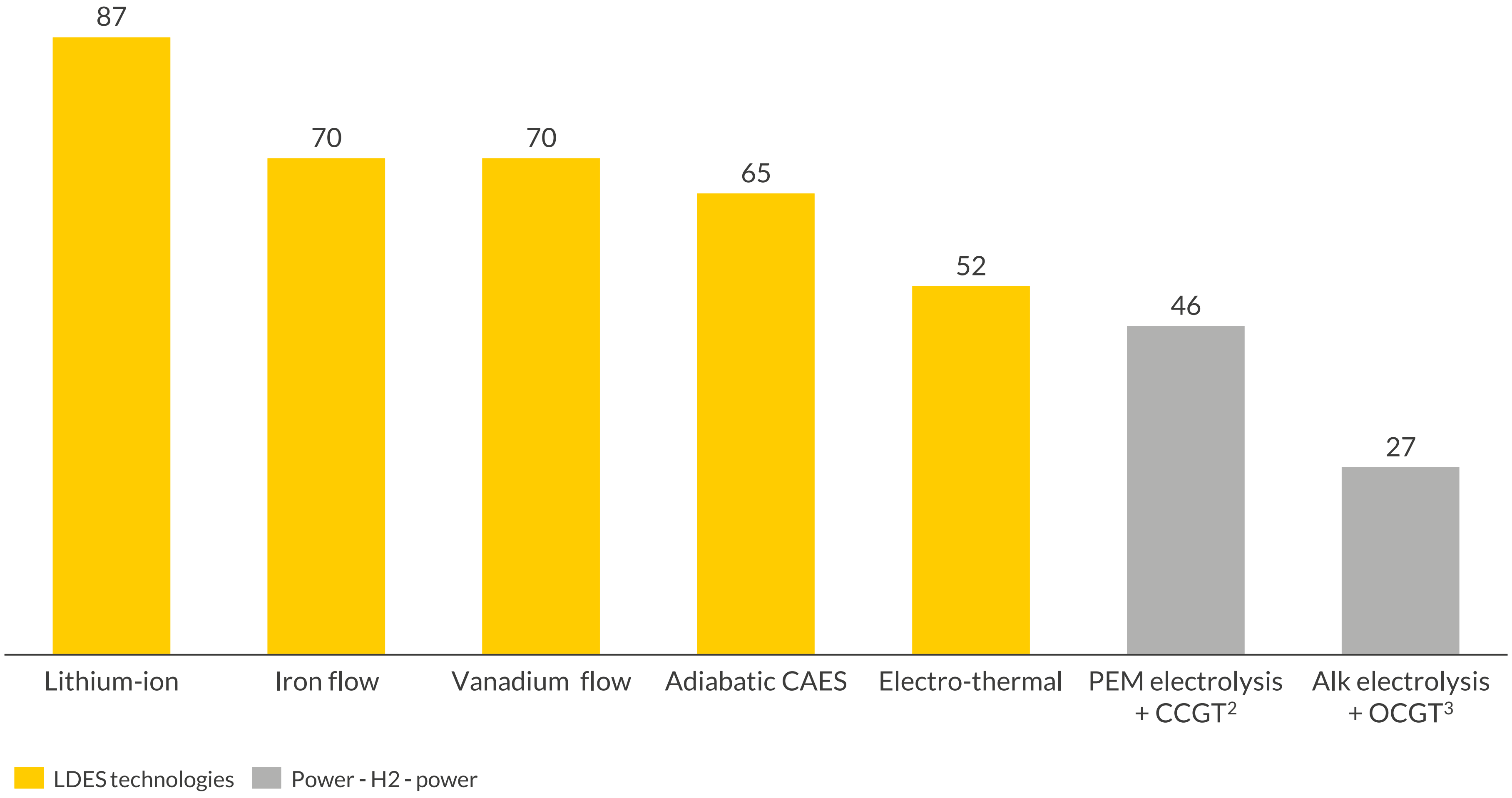
1) For some technologies, assumed storage durations are longer than those of actual products which are currently on the market; however, longer storage durations are technically feasible 2) For commercial operation date 2030

Sources: Aurora Energy Research, ESS inc. MALTA inc. , Invinity, Invinity, EASE, IRENA

AURORA

The energy efficiency of LDES is superior to that of a power-H_2-power cycle, even when disregarding H_2 leakage

Comparison of LDES roundtrip efficiencies with the efficiency of using H_2 as a power storage medium
%



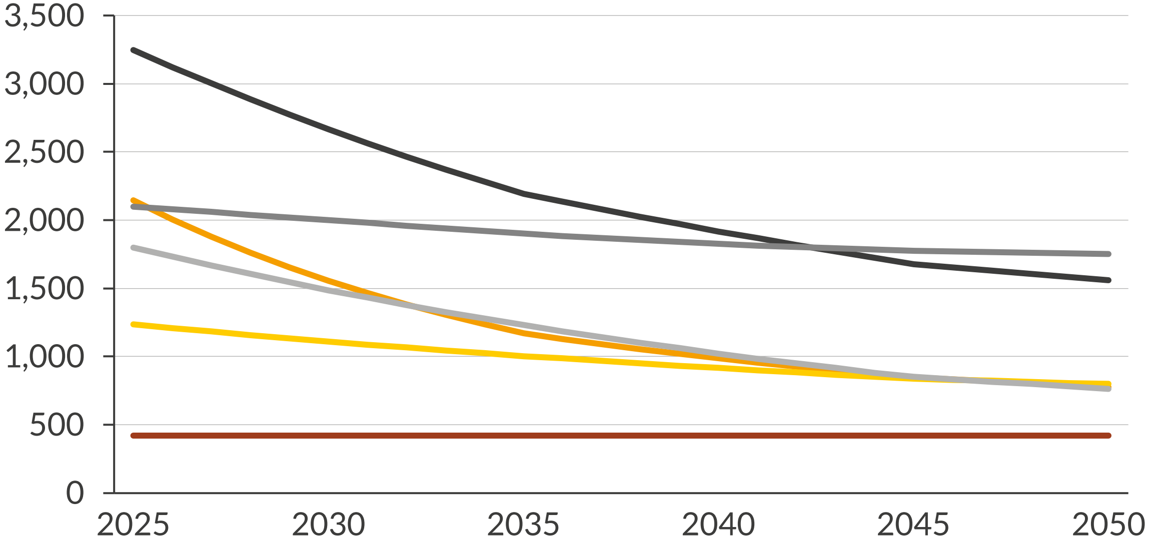
- All LDES technologies considered in this study provide a more energy efficient solution for power storage than a power - H_2 – power cycle[1]
- In practical application, the efficiency of the power-H_2-power cycle could be even lower because hydrogen is prone to leakage losses due to the very small size of the molecule
- Only the electric output is considered for the electro-thermal system, overall energy efficiency of the technology is higher when including heat output as well

1) Renewable electricity is used to generate hydrogen via electrolysis; the hydrogen is then used in power plants to generate electricity; 2) PEM electrolysis with 80% , CCGT with 58% efficiency; 3) Alkaline electrolysis with 68% efficiency, OCGT with 38% efficiency

Sources: Aurora Energy Research, ESS inc. MALTA inc. , Invinity, Invinity, EASE, IRENA

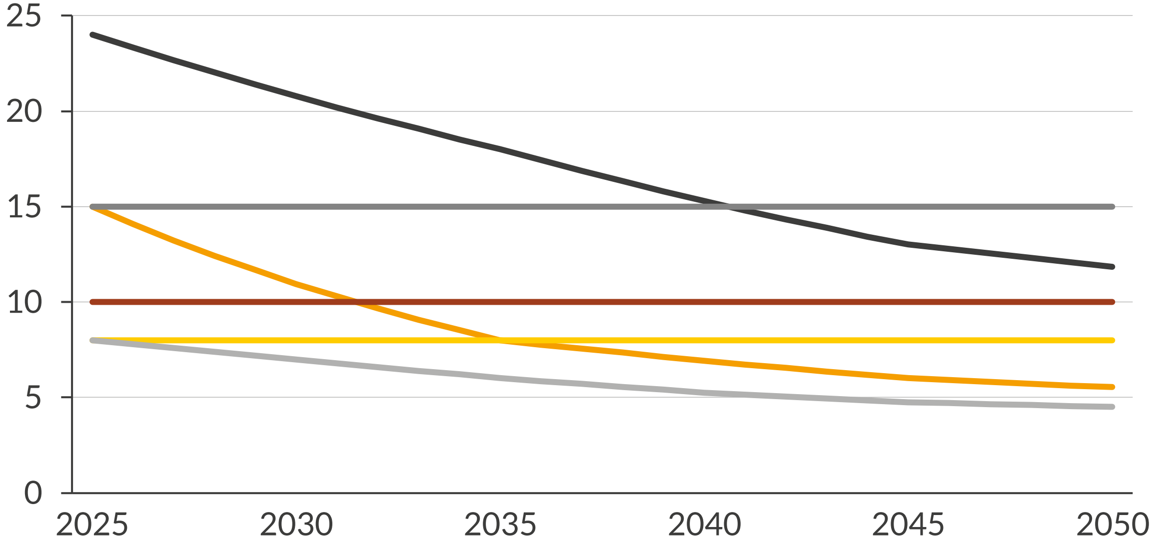
The costs of deploying and operating LDES assets is anticipated to fall over time for most technologies

CAPEX assumptions for the selected LDES technologies
EUR/kW (real 2021)



- Investment costs are dependent on the storage duration which varies between the technologies considered in this study; therefore the CAPEX assumptions cannot be used for a cost effectiveness benchmarking
- CAPEX decline is higher for emerging than for established technologies
- CAPEX of the adiabatic CAES are assumed to decline only marginally because many of the required components are similar to those used in the diabatic CAES, a technology which has already been deployed at commercial scale

Fixed OPEX assumptions for the selected LDES technologies
EUR/kW (real 2021)



- Similar to investment costs, fixed OPEX costs are assumed to decline for emerging LDES technologies as operation and maintenance can benefit from economies of scale

22h Iron flow — 8h Lithium-ion — 28h Electro-thermal — 48h CAES — 8h Vanadium flow — 96h Thermal storage

Sources: Aurora Energy Research, ESS inc. MALTA inc. , Invinity, Invinity, EASE, IRENA

Agenda

The economic prospects for LDES technologies are quantified on the basis of gross margins and internal rates of return (IRRs)

AURORA

1 Dispatch modelling with input from the LDES Scenario

- A dispatch model for storage technologies uses an hourly price forecast as most important input
- With assumptions on power to power efficiency and variable OPEX the model optimises the hourly dispatch to reach the maximum for the yearly gross margin (revenues with discharging minus costs of charging)
- Heat revenues are considered (see deep dive on the right)
- For technologies with scalable storage capacity, the hourly dispatch optimisation is iterated with varying storage durations to identify the storage duration which maximises yearly gross margins

2 Calculation of IRRs

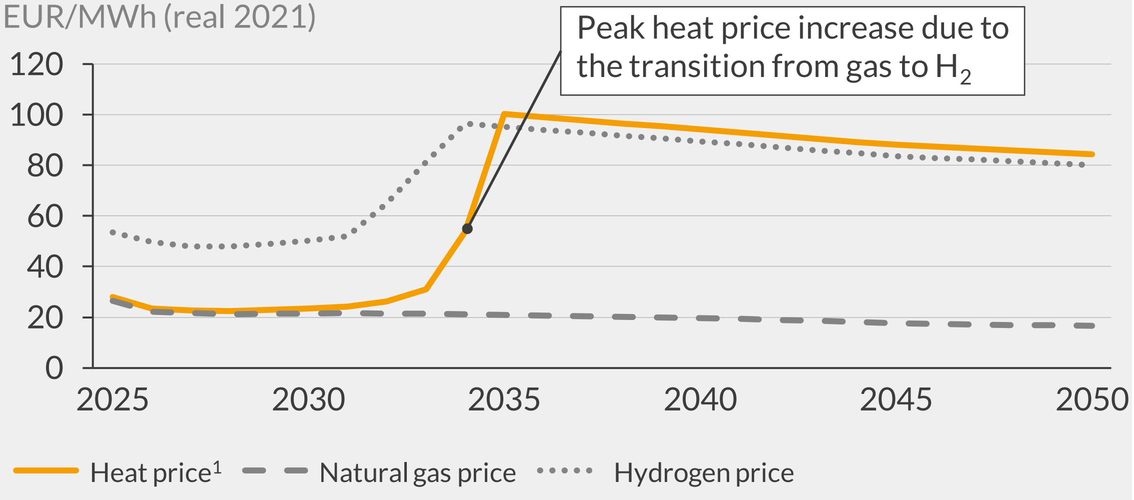
- To calculate the internal rate of return (IRR) the forecasted gross margins are combined with CAPEX and fixed OPEX assumptions for the LDES technologies
- The IRR is calculated over up to 25 years, shorter if lifetime constraints exits (e.g. lithium ion batteries)
- Different years for the investment are considered in view of the expected CAPEX decline for LDES technologies

Deep dive: Heat revenue assumptions

- The heat price captured by heat-dispatching LDES technologies is an average of the costs for natural gas and hydrogen, weighted by the share of natural gas and H_2-fuelled plants in total dispatchable generation
- This reflects the assumption that LDES would dispatch in hours with low availability of renewable generation where gas boilers (fuelled by natural gas or H_2) set the price on the heat market due to the unavailability of renewable heat sources
- Hence, long-duration heat storage technologies would be able to capture peak heat prices

Peak heat price captured by heat dispatching LDES technologies

EUR/MWh (real 2021)



1) An efficiency of 95% is assumed for gas boilers, thus the heat price lies slightly above the weighted average of the gas and hydrogen prices

Source: Aurora Energy Research

Gross margins are expected to rise until 2040, the decline is a result of lower hydrogen prices

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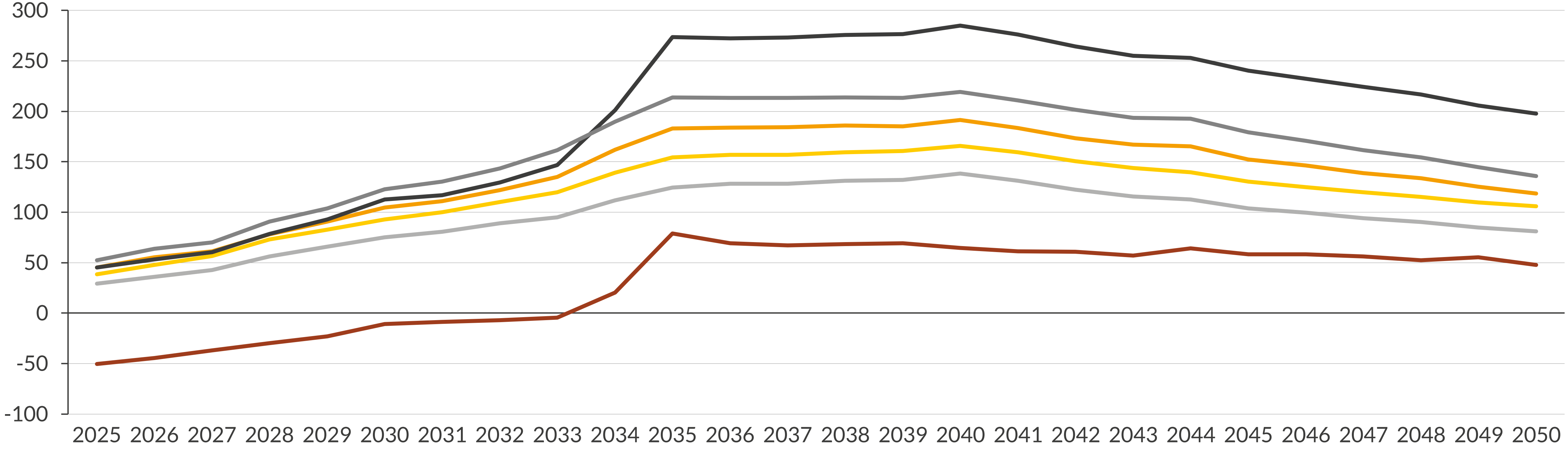
Gross wholesale margins of selected LDES technologies
EUR/kW of capacity installed (real 2021)



Phase 1 – The capacity addition of new renewables is larger than for LDES

Phase 2 – The ratio of renewables and LDES is at a reasonable level, thus gross margins increase at a slower rate

Phase 3 – Declining hydrogen prices reduce gross margins

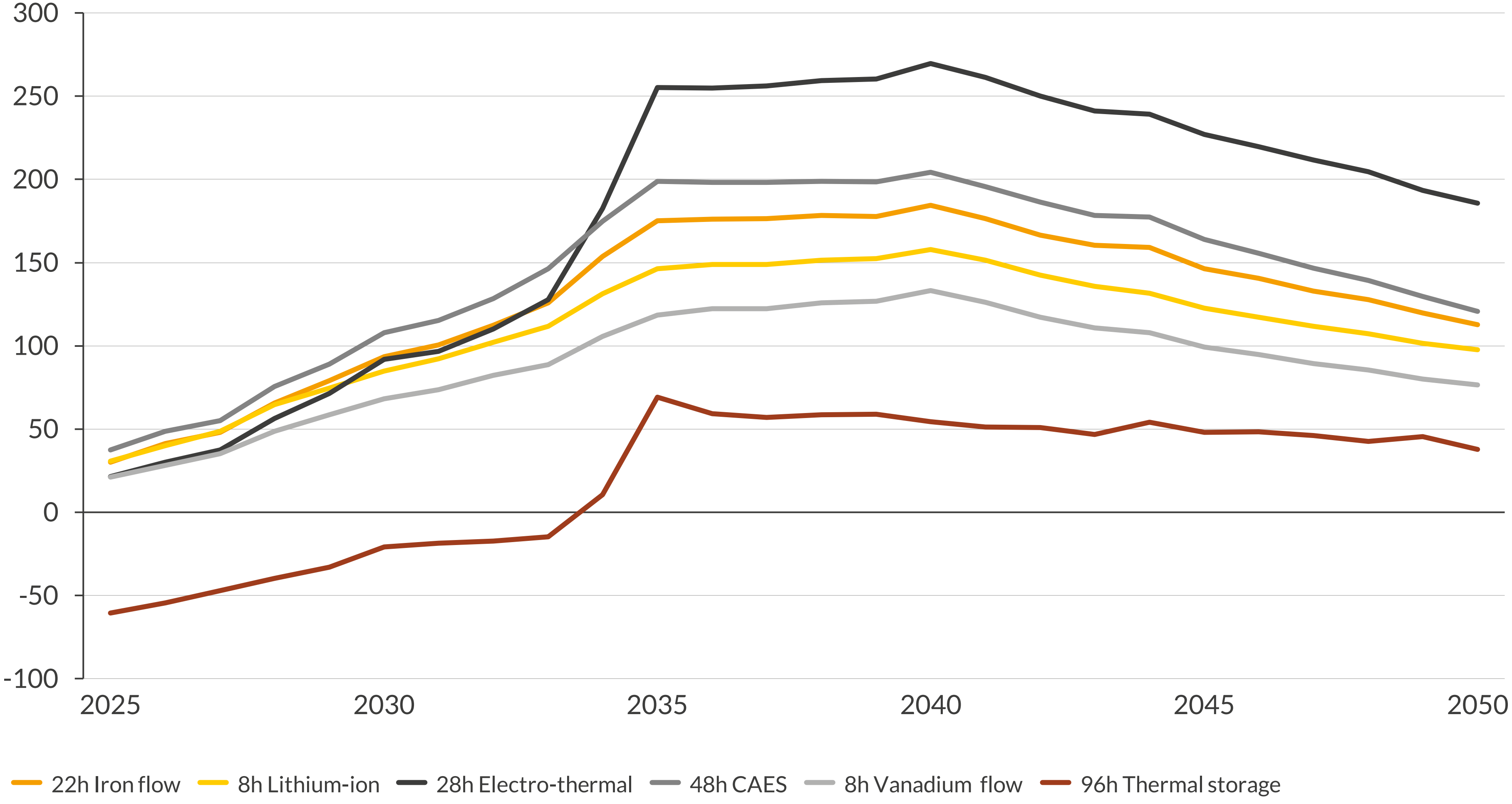
22h Iron flow · 8h Lithium-ion · 28h Electro-thermal · 48h CAES · 8h Vanadium flow · 96h Thermal storage

Source: Aurora Energy Research

Additional revenues from the heat market top up net margins after fixed costs for the electro-thermal storage technology

Wholesale margins of selected LDES technologies after fixed OPEX

EUR/kW of capacity installed (real 2021)



- Because fixed operations costs are negligeable compared to gross margins for all LDES technologies, the difference compared to gross margins shown on the previous slide is marginal
- The margins of the heat dispatching technologies (Electro-thermal and thermal storage) show a significant increase between 2032 and 2035
- This is due to the phase out of natural gas and the phase in of hydrogen for heat generation in gas boilers which drives up the peak price for heat captured by storage assets

Source: Aurora Energy Research

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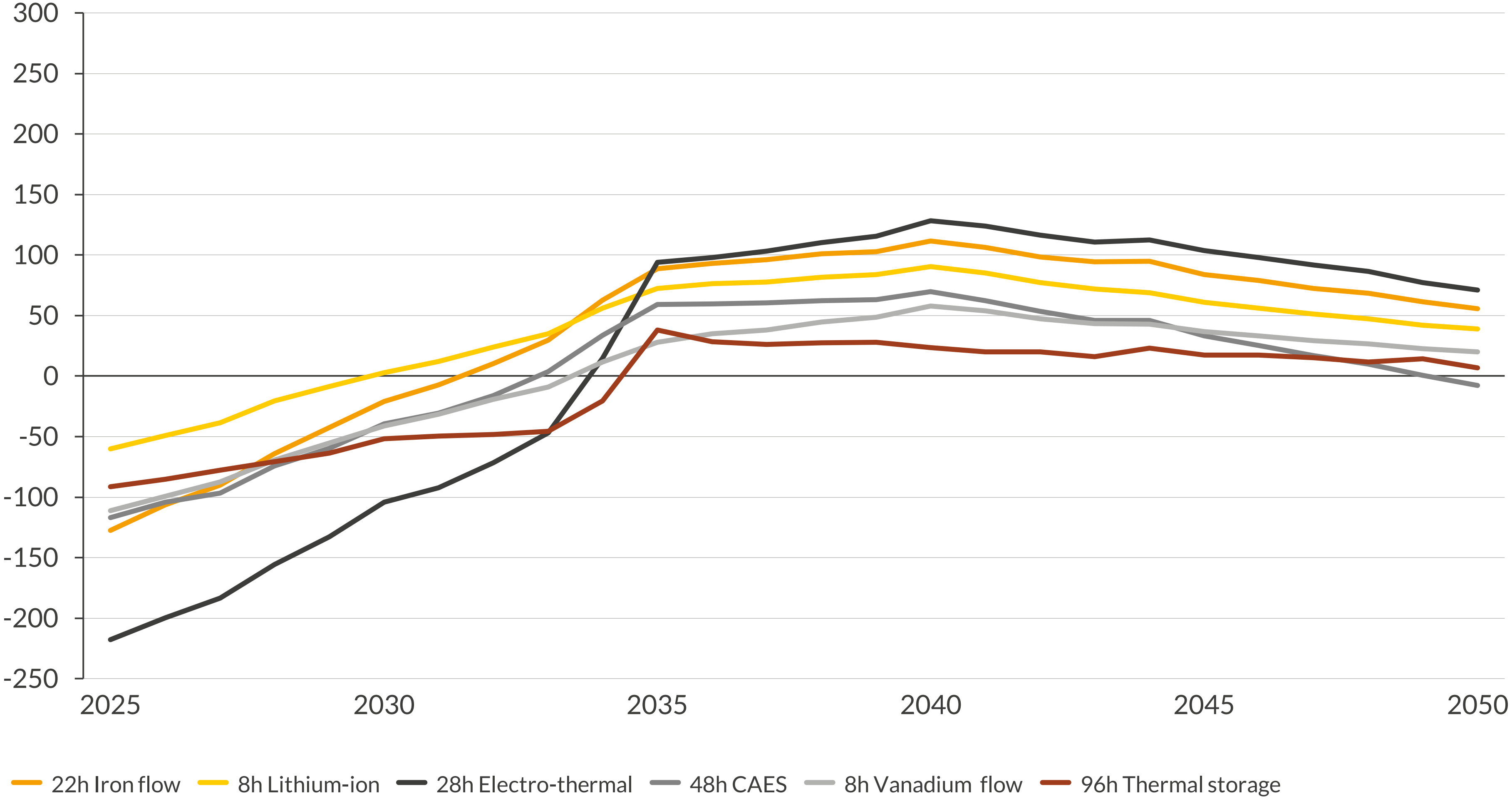
Assuming optimal market conditions, LDES technologies break even between 2030 and 2035 after deducting CAPEX annuity

Wholesale margins of selected LDES technologies after fixed OPEX and CAPEX annuity[1]

EUR/kW of capacity installed (real 2021)



1) An interest rate of 4% is assumed for CAPEX annuity, reflecting optimal market conditions

Source: Aurora Energy Research

- Between 2025 and 2030, wholesale revenues are not sufficient to cover CAPEX annuity and fixed costs for any of the LDES technologies considered
- After turning positive, the highest net margins can be generated around 2040
- Lithium ion batteries and iron flow batteries are the first to achieve positive net margins in 2030 and 2032, respectively
- After 2035, net margins of the electro-thermal technology are the highest, but the delta to other technologies is smaller in comparison with the sole consideration of gross margins and fixed costs due to its high CAPEX intensity

The profitability of investments in LDES are expected to improve significantly until 2035 and reach the investible range of 9-13%

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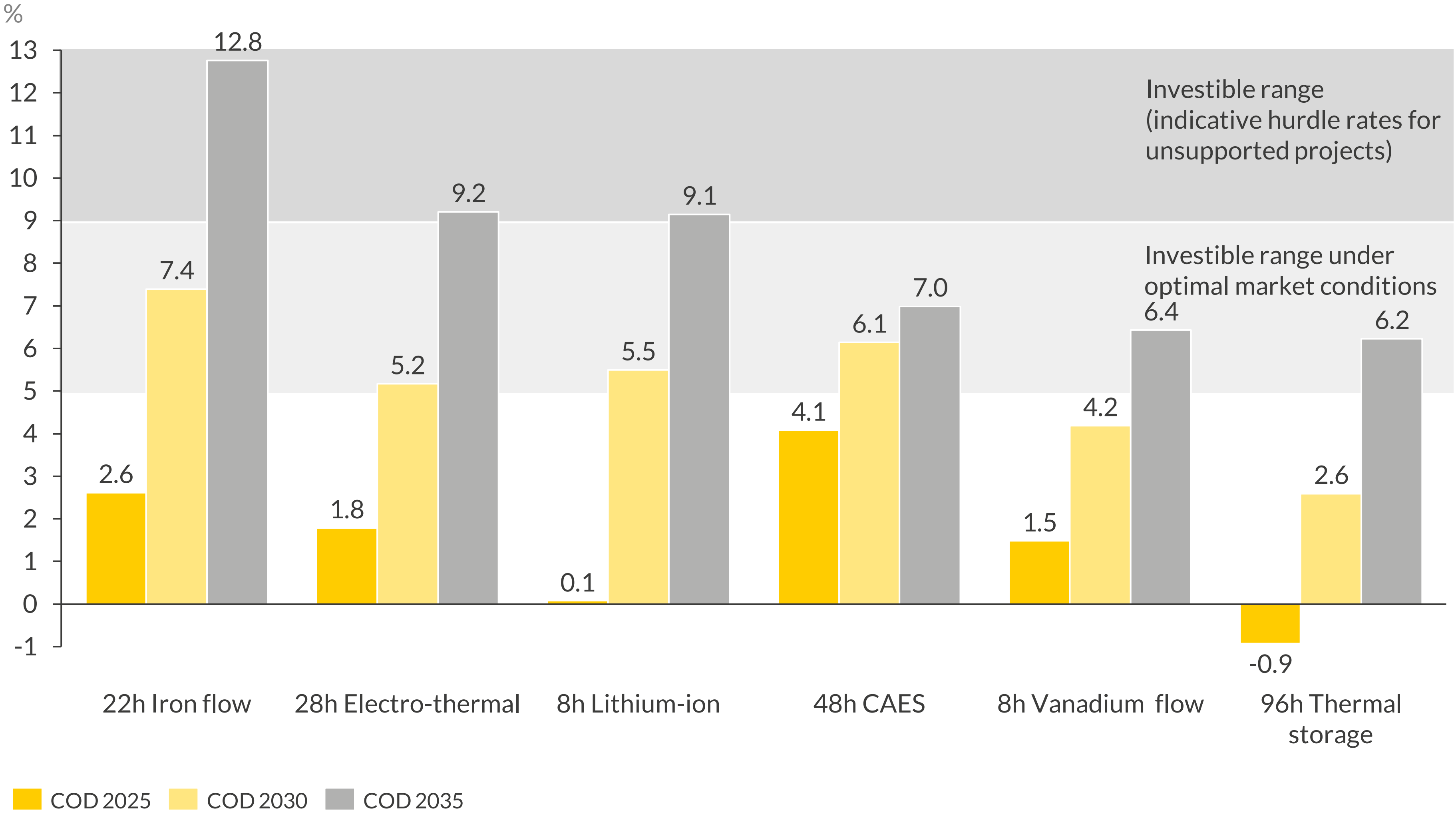
IRR forecast for three commercial operation dates (COD)



Assumptions

- IRR behaviour varies between technologies and is heavily dependent on the assumed date of roll-out
- Improved IRRs for emerging technologies such as iron flow and electro-thermal in 2035 are driven by CAPEX cost declines
- Expectations for CAPEX reductions of compressed-air energy storage (CAES) are modest, so the IRR increases by only a small fraction between CODs 2030 and 2035 compared to other technologies

Source: Aurora Energy Research

Agenda

Despite the benefits LDES could provide to the system, there are a number of challenges to its deployment that need to be addressed

Benefits

LDES has the capability to help keep lights on in a Net Zero scenario, while lowering energy bills and reducing import dependence.

1. **Increases renewables utilization** by reducing the need for curtailment due to network constraints by up to 30% in 2040
2. **Lowers consumer bills** by reducing wholesale power prices as well as the need for additional network & capacity
3. **Reduces the need for hydrogen in the power sector**, thereby limiting Germany's future dependence on H_2 imports
4. **Serves as an effective cushion against upwards price risks on the H_2 market**

Challenges

Despite the evident benefits LDES is able to provide, investments in projects in next ten years could be challenged by 3 primary factors:

1. **Lack of incentives for efficient grid connection use** by co-locating renewables with LDES because the grid connection for renewables projects is indirectly subsidised
2. **Uncertainty about the future market landscape;** future market reforms could impact LDES revenue streams
3. **High capital costs for certain technologies,** many LDES investments only become profitable in 10 to 15 years, but capacity needs to be built up before

These combined factors make it difficult to gain the confidence necessary to raise and allocate large capital sums

Policy response

Due to high upfront capital investment requirements and long development timescales, LDES cannot rely on near-term price signals for investment.

The primary issues that investors will want to be addressed by policy makers are:

1. **Policy confidence;** policy support for LDES which recognises the value and long-term need for this resource to facilitate investments in the short- and medium term
2. **Address missing markets and market access;** LDES is able to provide beneficial grid services that are not currently procured individually; grid connection timelines need to be shortened

Source: Aurora Energy Research

Details and disclaimer

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Prepared by
Benedikt Ziegert
Daniel Böhmer

Approved by
Dr. Casimir Lorenz

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ENERGY RESEARCH