Clean Flexibility: Opportunities in Europe

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Contents

I. Summary

II. What is Clean Flexibility?

III. Benefits of Clean Flexibility

IV. The Role of Clean Flexibility in a Reliable Power System

V. Zero-Carbon Power in a Clean Flexibility Future

VI. Country-Specific Clean Flexibility Opportunities Across Europe

VII. Conclusions

Technical Appendix I: Detailed Country Case Studies

Technical Appendix II: Detailed Overview of Clean Flexibility Solutions

Section I: Summary

What is clean flexibility?

Clean flexibility can significantly reduce dependence on gas in the power system, helping deliver electricity that is affordable, reliable, and secure.

In simple terms, "flexibility" is the ability to balance the power system to ensure that the electricity supply is always equal to electricity demand. Flexibility has always been an important part of operating the electricity system, ensuring it is resilient and responsive to changing conditions. Today, flexibility is becoming even more important as Europe realises the benefits of moving from a system based on fossil fuels to one based on low-cost renewable energy.

While power systems have historically relied on gas to provide flexibility, **clean flexibility** is flexibility provided by clean technologies or approaches. These include many mature technologies such as batteries and pumped hydro storage as well as some emerging solutions such as EV smart charging and long-duration energy storage. Additionally, consumers are playing an increasing role and provide value and flexibility through demand-side response. Together, these clean flexibility solutions have the potential to reduce legacy dependence on gas, delivering low-cost, reliable power to customers.

This report presents the opportunity for clean flexibility in Europe. Section II defines clean flexibility solutions in more detail. Section III summarizes the benefits that clean flexibility offers to consumers, households and governments. Section IV provides an overview of the different ways clean flexibility supports the power system. Section V highlights examples of current and future systems that operate without gas. Finally, Section VI identifies specific clean flexibility opportunities for countries across Europe.

WHY CLEAN FLEXIBILITY?

- Lowers energy bills for customers, potentially saving Europeans **€300 billion per year** by 2030
- Reduces reliance on energy imports such as Russian gas, **increasing energy security**
- Supports low-income households by reducing energy bills and providing **resilience to outages** to local communities
- **Keeps the lights on** by filling "gaps" in supply and demand for electricity

Clean flexibility is a multi-billion-euro opportunity

Clean flexibility solutions can make Europe's electricity system cheaper, cleaner, more secure and more efficient. By replacing the role of gas in the power system, clean flexibility provides several benefits to European households, businesses and governments.

Lower Energy Bills

Clean flexibility is already reducing customers' electricity bills today—by **£300 million** in 2024 in Great Britain alone.

By 2030, demand-side flexibility could save Europeans **€300 billion per year.**

Energy Security

Clean flexibility reduces reliance on gas, which was responsible for the **ten-fold increase in electricity prices** during the energy crisis of 2021–2022.

It also insulates Europe from price volatility in the LNG market.

Direct Benefits for Flexible Households

Customers participating in demand-side flexibility could earn up to **€86 million per year** by 2030, or **€600 per household**.

Supporting demand-side flexibility in lower-income households can help improve energy affordability.

Reduced Renewables Curtailment

Clean flexibility avoids the curtailment of low-cost renewable generation.

Without additional clean flexibility, **50–131 TWh** of renewable electricity (equivalent to the annual consumption of Portugal and Sweden), could be curtailed annually by 2030.

Resilient Energy Communities

Clean flexibility has been proven to enable autonomous and energy independent communities to run fully on renewable energy. Households participating in energy community models can **save between 15%–60% on annual energy bills.**

Note: Sources for these estimates are provided throughout the report.

Clean flexibility addresses system needs across multiple timescales

The power system requires different clean flexibility solutions to address use cases on different time horizons—from near-instantaneous balancing, to filling gaps during multi-day periods of low renewable energy generation. This slide summarises these use cases, which are explained in more detail in Section IV.

Operational Time Horizon

milliseconds → *seconds* → *minutes* → *hours* → *days* → *weeks* → *months*

Daily Flexibility

Real-time balancing *(milliseconds to seconds)*
Small, rapid fluctuations in supply and demand require fast-acting resources to help balance.

Daily "ramping" *(seconds to hours)*
"Smoothing" the transition between high renewables in the middle of the day to high electricity consumption in the evenings.

Addressing transmission bottlenecks *(mins to hours)*
Shifting power away from stressed parts of the grid ("congestion").

Peak Flexibility

"Peak" events *(hours)*
Alleviating periods of very high electricity demand that place the grid under stress.

Inter-day Flexibility

Inter-day balancing *(days to weeks)*
Addressing extended periods of low (or high) renewable energy production.

Forecast error *(hours to days)*
Managing deviations between forecasted and actual renewable generation and/or electricity consumption.

Seasonal Flexibility

Seasonal balancing *(months)*
Shifting renewable energy from periods of overabundance of supply relative to demand (spring and autumn) to periods of high demand (winter and summer).

Clean flexibility takes many forms…

Clean flexibility solutions exist across the power system, from technologies that produce electricity to those that store or consume it more intelligently.

In the past, gas generation was one of the primary technologies used to provide flexibility to the power system. Today, technological advancements have allowed for a far greater range of clean solutions to provide flexibility to the system, including:

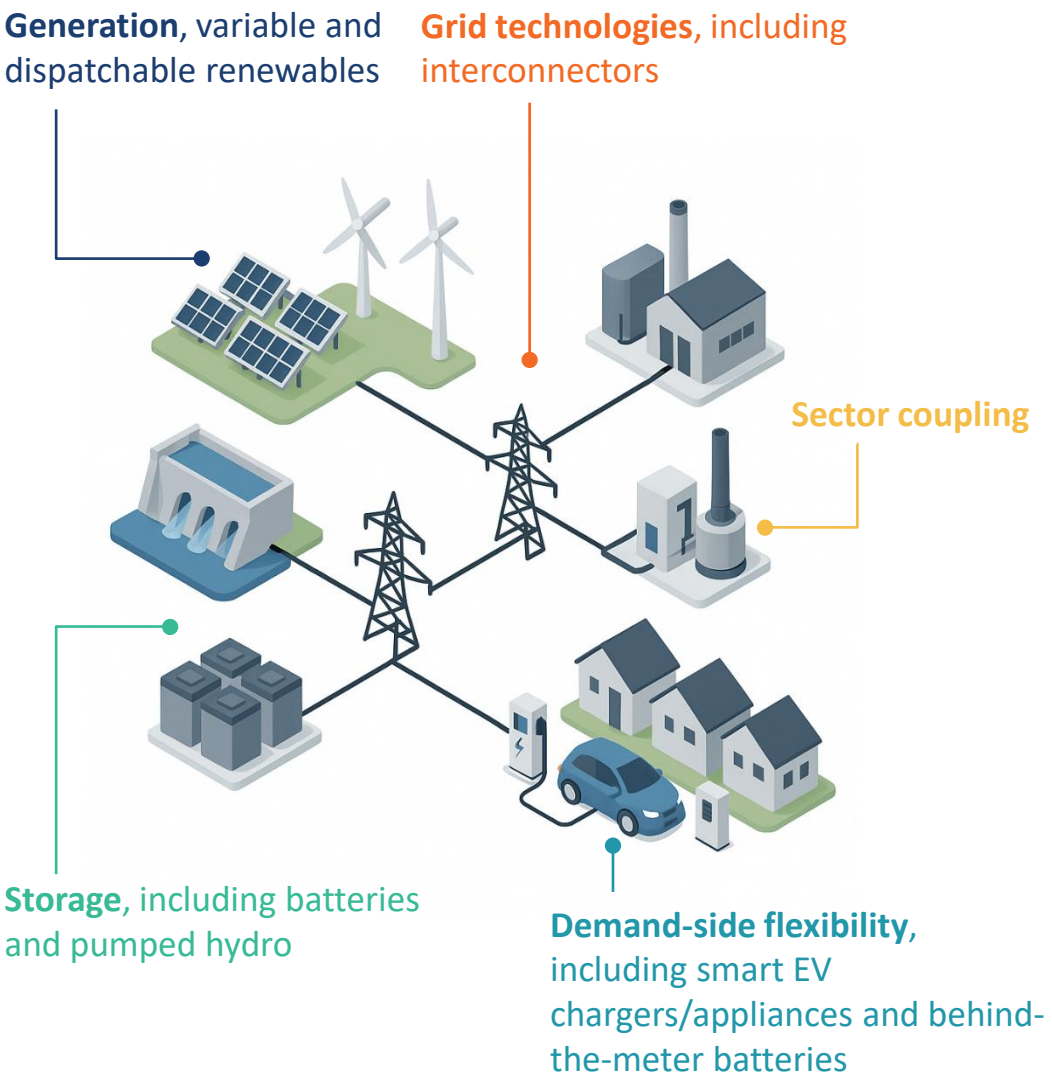
Generation: Large renewable energy power plants that can increase or decrease the amount they generate to provide flexibility;

Demand-side flexibility: Technologies installed by customers that can intelligently change how they consume electricity;

Storage: Large energy storage technologies such as batteries, pumped hydropower, and other forms of long-duration energy storage;

Sector coupling: Converting electricity into other forms of useful energy (e.g., heat or renewable hydrogen); and

Grid technologies: Transmission infrastructure that helps get more capability out of the existing power system.



…and is provided by a portfolio of solutions

Many different types of technologies and solutions provide clean flexibility. A portfolio of many solutions is needed to support a fossil-fuel free power system.

Generation

- Variable Renewables
- Dispatchable Renewables
- Renewable Hydrogen (H_2)

Demand-Side Flexibility

- Behind-the-Meter (BTM) Batteries
- Smart EV Charging
- Heating, ventilation, air conditioning (HVAC)
- Behavioural Demand-side Response
- Large building Demand-side Response

Storage

- Grid Batteries
- Pumped Hydro
- Flywheels & Super-capacitors
- Long-Duration Energy Storage (LDES)

Power-to-X

- Power-to-Heat
- Power-to-Hydrogen (H_2)

Grid Technologies

- Interconnectors
- Grid-Enhancing Technologies (GETs)

Clean flexibility has substantial scale to replace gas

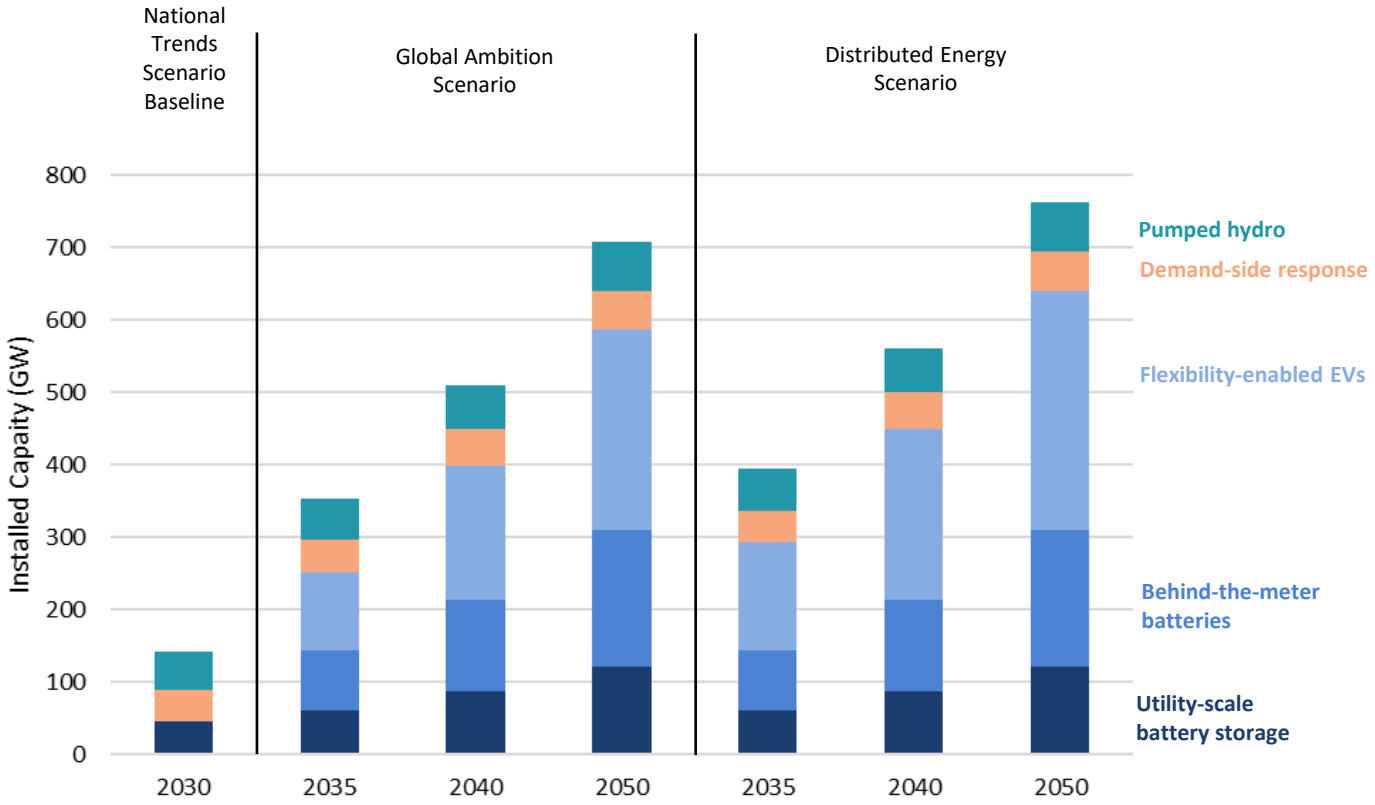
Clean flexibility capacity in Europe is expected to grow from roughly 150 GW in 2030 to over 700 GW by 2050.

700 GW is equivalent to **nearly four times the entire installed capacity of gas plants in Europe today** (186 GW), which highlights the substantial scale at which clean flexibility could replace gas in power systems of the future.

According to the 2024 Ten-Year Network Development Plan (TYNDP) of European countries, key sources of clean flexibility will include pumped hydro, demand-side response, electric vehicles, behind-the-meter battery storage, and utility-scale battery storage.

Additional clean flexibility solutions not modeled in the TYNDP could provide additional flexibility. Those are described in more detail in this report.

OUTLOOK FOR EUROPEAN CLEAN FLEXIBILITY GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Clean flexibility supports a reliable grid without fossil-fuels

Today, clean flexibility already helps power systems operate without gas, performing a range of functions needed to keep the power system running reliably.

The power system needs flexibility across a wide range of timescales, from second-to-second balancing of supply and demand to storing excess solar power during sunny months to use during the winter (see Section IV for more details).

Clean flexibility solutions are able to address all of these needs and already help power systems run without fossil fuel generation for extended periods, as described in the case studies to the right. By using a diverse mix of solutions, countries can unlock clean flexibility across all timescales.

CASE STUDIES: Fossil-fuel free system operation

- Great Britain has been fully powered by clean electricity for a record 87 hours in 2025 as of September.
- Portugal achieved 6 days in a row without fossil fuel generation in 2023, exceeding the previous record of 5 consecutive days in 2019
- The Spanish Canary Island of El Hierro relied only on wind and hydropower generation for 24 days in a row in 2019
- Greece set a record of 5 hours in a row without fossil fuel generation in 2022
- Montenegro generated enough renewable electricity to power the entire country for 9 days in 2019
- South Australia relied on 100% renewable electricity generation for 10 days in a row in 2022, and is aiming for 100% net renewables in 2027
- In California in 2025, the grid has run without fossil fuel generation for an average of 7 hours a day

SUMMARY

Countries are at different points in the transition, but each country has its own clean flexibility opportunities

CASE STUDY HIGHLIGHTS

- Clean flexibility is best understood as a portfolio of solutions that address flexibility needs across time: no single solution does everything, and the benefits to the power system come from deploying the right mix in a timely fashion.
- Opportunities vary from country to country, shaped by each nation's energy mix and interconnections, policy and regulatory environment, and degree of market and technological maturity. Consequently, clean flexibility deployment follows distinct pathways depending on where countries are in their energy transition.

In the UK, the flexibility market continues to grow, with **6.3 GW of clean flexibility contracted in 2024**. Energy flexibility **saved customers £300m in 2024, expected to reach £3 billion before 2030**. New regulations and digital platforms are being deployed to help reach the target of 12 GW of consumer-led flexibility by 2030.

In Italy, full deployment of smart meters enables demand-side flexibility participation at scale. Homeowners with heat pumps can save **€460-1,350 per customer per year** due to flexible pricing. In September 2025 **10 GWh of capacity** was procured in the first ever energy storage procurement mechanism.

In Germany, owners of controllable consumer devices (more than 2 million in 2024) already benefit from **€110–190 per year in savings** for providing consumer flexibility. By 2035, clean flexibility could **avoid 20 TWh of electricity from fossil fuel generation, saving €5.4 billion** in costs. Additionally, clean flexibility can significantly lower grid expansion and operation costs resulting in **€4.8 billion in savings** in 2035 alone.

In Poland, **19 energy community projects** which include energy storage, flexible energy management systems and solutions improving the quality of the grid were approved in 2025. The projects will be supported by the National Recovery Plan (NRP), for a **total value of over €200 million**.

In Greece, new capacity additions are outpacing system readiness: The Greek transmission and distribution system operators are investing **€8 billion** to 2030 in smart grid and demand-side flexibility. New frameworks establish priority grid access for **4.7 GW of battery storage** and allow **more flexibility** from renewable energy plants, while buying time for infrastructure modernization.

In Bulgaria, €2.4 billion in EU funding has been secured to achieve climate targets, including €600 million which led to **10 GWh of battery storage capacity** being contracted in 2025. €1.3 billion is intended to ensure a socially and economically sustainable energy transition and make better use of renewable energy.

In Turkey, in mid-2024 Turkish development banks joined the World Bank in a **$1 billion USD** initiative to modernize electricity grids, expand distributed solar, and pilot battery storage programmes. In **late 2024**, a $1 billion USD complementary programme was agreed to finance transmission and **smart-grid upgrades, decentralized EV charging, distribution-grid digitalization, and 7.5 GW of battery-storage capacity**.

Section II: What is Clean Flexibility?

Introduction

Clean flexibility can fill the legacy role of gas in the power system by helping balance the grid without producing carbon emissions.

“Flexibility” is the ability to operate the power system to ensure that the supply of electricity is always equal to demand. Flexibility has always been a core part of the power system and is increasingly important as Europe realises the benefits of transitioning from a system based on fossil fuels to one based on low-cost renewable energy.

While legacy power systems rely on gas to provide many of their flexibility needs, **clean flexibility** has a key role in modern power systems and is provided by clean technologies or approaches. Clean flexibility solutions exist across all parts of the power system (generation, transmission, and distribution), and can work together to replace the legacy role of gas while delivering low-cost, environmentally friendly, and reliable power to customers.

This section provides an overview of the available clean flexibility solutions, how they work, and compares their cost and technological maturity across each solution.

Generation

Clean generation technologies produce carbon-free electricity and provide flexibility by increasing or decreasing their generation output.

			Cost	Maturity
	Variable Renewables	**"Variable" renewable energy sources are those that generate clean electricity** but depend on the weather and time of day—typically, solar and wind. These technologies cannot increase their power output but can provide some flexibility by turning down their output if there is too much power on the system. In most cases, alternative sources of flexibility are preferable to curtailing cheap renewable generation.	€€	■■■■
	Dispatchable Renewables	In contrast to variable renewables, **dispatchable renewables can control when they generate power**. These technologies include hydropower, geothermal power, and concentrated solar power with thermal storage. Their controllability means they can provide much of the same flexibility as gas plants.	€€€	■■■□
H_2	**Renewable Hydrogen**	**Renewable hydrogen (H_2) is hydrogen produced from water and clean electricity** via electrolysis and can be used as fuel to produce clean electricity. Renewable hydrogen can therefore provide flexibility as dispatchable generation. However, it is unlikely to fully replace gas on a like-for-like basis as there are significant challenges including substantial costs and the need for major infrastructure investment to develop sufficient renewable H_2 supply.	€€€€	■□□□

Click on the name of each clean flexibility solution to see more details in the Appendix.

Demand-side flexibility

Demand-side flexibility refers to flexibility solutions that alter how customers consume electricity.

		Cost	Maturity
BTM Batteries	"Behind-the-meter" (BTM) batteries are **battery storage systems installed on the customer side of the electricity meter** (e.g., at homes, businesses, or industrial sites) where they store on-site generation or grid power for later use. BTM batteries allow customers to shift excess on-site generation (or low-cost electricity) to peak hours in the evening or can export this power to the grid when it's most valuable.	€	■■■□
Smart EV Charging	Electric vehicles (EVs) require significant amounts of power when charging. **Smart EV chargers shift charging patterns away from hours when electricity demand is high** and toward other hours where the power system is under less stress. Additionally, **vehicle-to-grid (V2G) charging enables EVs to serve as energy storage** and export power from their batteries to the grid, providing similar flexibility to a BTM battery.	€	■■□□
HVAC	**Smart heating, ventilation and air conditioning (HVAC) technologies can pause or shift their consumption of electricity** when providing heating or cooling. These interruptions or shifting to HVAC schedules help lower electricity demand when the power system is under strain, but can have annual limits on how often schedules can be altered without negatively impacting the comfort and experience of the customer.	€	■■■■
Behavioural Demand-Side Response	**Behavioural demand-side response refers to incentives to encourage customers to adjust their consumption to support the system**. Customers may be incentivised to shift/lower their consumption in response to electricity rates with high-priced "peak" and low-priced "off-peak" periods (often referred to as time-of-use rates). Other solutions influence customers' behaviour by offering payments or information to reduce consumption in peak hours.	€	■■■■
Commercial & Industrial (C&I) Demand-Side Response	**C&I customers can provide flexibility by reducing their electricity consumption when called upon**. Large industrial facilities can use advanced energy management systems to automate and control their electricity use for process loads such as cooling loads, process heat, and pumping. Similarly, commercial buildings can reduce or shift consumption away from peak hours for electric loads such as refrigeration and HVAC.	€	■■■■

Click on the name of each clean flexibility solution to see more details in the Appendix.

Storage

Storage technologies store electricity from the grid and inject it back when needed. Different technologies are able to store and discharge energy for different amounts of time.

		Cost	Maturity
Flywheels & Super-capacitors	**Grid-scale flywheels are giant spinning discs that store energy as motion** (kinetic energy). **Supercapacitors are electrical devices that store energy in electrical fields**. Both technologies can withdraw and inject power from/to the grid in milliseconds to help with quick flexibility needs, but can only inject for very short durations.	€€€	■■■■
Grid Batteries	**Utility-scale batteries (usually lithium-ion chemistry) store electricity in chemical bonds**. These batteries can typically withdraw or inject power for 2–4 hours at rates of up to 300 MW and can respond within seconds. As a result, they can provide many types of flexibility.	€€	■■■■
Pumped Hydro	**Pumped hydro stores energy using gravity** (potential energy) by using cheap or excess electricity to pump water to an elevated reservoir, then releasing the water through hydroelectric turbines to generate electricity when it is more needed. Typical pumped hydro plants can discharge up to 10 hours, but some can discharge for many days.	€€€	■■■■
Long-Duration Energy Storage (LDES)	**Emerging long-duration energy storage technologies are designed to charge and discharge energy for 10 hours or longer**. Unlike lithium-ion batteries and other forms of short-duration storage, LDES technologies are able to provide longer-term flexibility during periods of low renewable generation.	€€€€	■□□□

Click on the name of each clean flexibility solution to see more details in the Appendix.

Sector coupling

"Sector coupling" means linking electricity to other sectors. In the case of power systems, it refers to using electricity to produce heat or hydrogen, which both can then be used in other sectors such as heavy industry.

			Cost	Maturity
⚡ → ♨	Power-to-Heat	**Thermal batteries use electricity to heat up thermal storage mediums** (such as bricks, sand, or molten salt), the heat can then be used in industrial applications. Power-to-heat processes can act like industrial demand response and reduce electricity consumption, but can also increase consumption to "absorb" excess renewable energy.	€€€	■■□□
⚡ → H_2	Power-to-Hydrogen	**Renewable hydrogen can be produced from renewable power and water via electrolysis**. Like power-to-heat, producing renewable hydrogen can absorb excess renewable energy. This hydrogen can then be used in no-regrets industrial or transportation applications, or it can be stored and used at a later time to produce electricity.	€€€€	■□□□

Click on the name of each clean flexibility solution to see more details in the Appendix.

Grid technologies

Some technologies on the transmission grid can provide flexibility by connecting new parts of the system and modifying how electricity is transferred around it.

			Cost	Maturity
	Interconnectors	**Interconnectors are transmission lines that connect the power systems of different countries**. They provide flexibility by allowing surplus energy in one region to fill energy shortages in other regions. Additionally, high-voltage direct-current (HVDC) interconnectors can directly control how much power flows through them, allowing them to increase or decrease their output in a similar way to generation technologies.	€€€	■■■■
	Grid-Enhancing Technologies (GETs)	**Grid-enhancing technologies is an umbrella term for advanced control and monitoring devices that help operate the grid more flexibly and efficiently**. They include dynamic line ratings, power flow control devices, topology optimisation, advanced grid monitoring, and high-performance conductors.	€	■■■□

Click on the name of each clean flexibility solution to see more details in the Appendix.

Section III: Benefits of Clean Flexibility

Introduction

Clean flexibility solutions make Europe's electricity system cheaper, cleaner, more secure and more efficient.

By reducing or replacing the role of gas in the power system, clean flexibility provides several benefits to European households, businesses and governments.

Using gas to provide flexibility is often more expensive than using flexibility solutions such as battery storage or demand-side response. Because electricity prices have historically followed the cost of gas-fired generation, replacing this generation with clean flexibility solutions could lower everyone's electricity costs. In some instances, clean flexibility can fully replace expensive gas-fired generation and can reduce the need to build transmission and distribution infrastructure. For households and businesses that provide demand-side flexibility, energy cost savings can be even larger than those experienced by other customers.

Furthermore, Europe currently gets the majority of its gas from imports, which can be subject to supply disruptions—as seen in 2022 following Russia's invasion of Ukraine—and price volatility.

This section summarizes the key benefits of clean flexibility and provides findings from recent events and studies.

Clean flexibility lowers electricity bills for all customers

By reducing the need to build and operate more-expensive gas generation, clean flexibility lowers the overall cost of the power system—savings that flow through to household energy bills.

Clean flexibility can also reduce the need for traditional upgrades to transmission and distribution infrastructure, lowering this portion of customers' bills.

At times, the amount of power that needs to flow through transmission lines to meet demand is greater than the capacity of the lines themselves, resulting in expensive remedial efforts known as "re-dispatching". The costs of re-dispatching has been increasing substantially in Europe and could reach as high as €11–26 billion per year for the EU by 2030.[1] These costs are ultimately recovered from customers energy bills. Clean flexibility can alleviate the congestion on transmission lines and thereby reduce re-dispatching costs.

Clean flexibility saved bill payers in Great Britain more than **£300 million** in 2024

An additional **£3 billion in savings** is anticipated between 2025 and 2028.[2]

Expanding clean flexibility capacity could yield cost savings of up to **£16.7 billion per year** by 2050

In Greater London alone, clean flexibility could save bill payers **£480 million per year** by avoiding distribution infrastructure upgrades.[3]

By 2035, demand-side flexibility could reduce energy costs for German bill payers by **10%, or €4.8 billion per year**

Dynamic, efficient utilisation of demand-side flexibility technologies can halve grid expansion costs, saving **€4.7 billion** by 2035, if the government supports the roll-out of smart meters.[4]

By 2030, the contribution of demand-side flexibility to energy bill savings across the EU could be up to **€300 billion per year**, or **€670 per capita**

Including **€71 billion per year** in direct benefits from reduced electricity costs and **€11–29 billion per year** in savings on annual grid infrastructure investment costs.[5]

Sources:
1. European Commission (2024), *Redispatch and Congestion Management: Future-Proofing the European Power Market*
2. UK Energy Networks Association (2025), *GB cements status as world leader in energy flexibility with estimated £300m savings for bill payers*
3. Carbon Trust and Imperial College London (2021), *Flexibility in Great Britain*
4. Agora Energiewende and Forschungsstelle für Energiewirtschaft e. V. (2024), *The benefits of energy flexibility at home*
5. smartEn and DNV (2022), *Demand-side flexibility: quantification of the benefits in the EU*

Clean flexibility strengthens Europe's energy independence and security

By relying on clean flexibility instead of gas, Europe can make its energy system less vulnerable to price shocks from supply disruptions and volatility in global gas prices.

Europe is currently highly reliant on imports of Russian gas, as demonstrated during the energy crisis of 2021 and 2022 when Russia restricted the amount of gas it sent to European countries following its invasion of Ukraine. By replacing gas with clean flexibility, Europe can ensure its energy security and protect itself from future supply disruptions.

During and following the energy crisis, many European countries sought to diversify their gas supply by importing liquefied natural gas (LNG). However, since LNG prices reflect those of the global gas market, they are also susceptible to volatility and geopolitical risk. Clean flexibility allows countries to insulate themselves from these external price shocks.

At the peak of the energy crisis in 2022, electricity was **more than 10 times as expensive** as usual due to Russia's reduced supply of gas	Europe's reliance on Russian gas for electricity generation caused record-high gas prices to flow through to electricity prices.[1,2]
European gas (and therefore electricity) **prices are likely to be highly volatile** if reliant on LNG	EU gas generation declined by 12 TWh and coal by 8 TWh annually in Q3 2024 due to greater volumes of renewables supported by clean flexibility.[2,3]
By 2050, clean flexibility could **avoid over 100 GW of gas-fired power plants** in Great Britain	Clean flexibility replaces the need to use gas to balance the system, reducing reliance on gas imports and insulating Europe from external price shocks.[2,4]
Interconnections provided critical flexibility during the energy crisis, stopping prices from rising even higher	Cross-border exchanges were recognized as playing a crucial role in mitigating local scarcities and ensuring the resilience of the European networks.[5]

Sources:
1. EU Agency for the Cooperation of Energy Regulators (ACER) (2023), *Key developments in European electricity wholesale markets: 2023 Market Monitoring Report*
2. ACER (2023), *European gas market trends and price drivers: 2023 Market Monitoring Report*
3. ACER (2024), *Key developments in European gas wholesale markets: 2024 Market Monitoring Report*
4. Carbon Trust and Imperial College London (2021), *Flexibility in Great Britain*
5. ACER (2023), *Assessment of emergency measures in electricity markets: 2023 Market Monitoring Report*

Households and businesses save on bills by providing demand-side flexibility

Demand-side flexibility not only supports the electricity system, but also offers meaningful energy cost savings to participating customers.

Flexible customer technologies can shift their load to avoid hours where the price of electricity is high. For example, a smart EV charger might charge when electricity prices are low (e.g., late at night), saving the customer money.

Some technologies can earn revenue for reducing their consumption during periods of grid stress. Additionally, if a technology—such as a behind-the-meter battery—exports power back onto the grid, the customer may earn additional revenue.

As such, customers offering demand-side flexibility earn electricity bill savings beyond the savings that all customers receive from a power system with more clean flexibility. Policies that promote demand-side flexibility solutions for low-and-middle income households can help improve affordability for vulnerable groups.

Over **€86 billion per year** in energy bill savings could be realised by EU customers offering demand-side flexibility by 2030	This includes savings to customers with smart EV charging/V2G, flexible electric space heating, BTM battery storage, or industrial demand-side response.[1]
In Germany, households offering demand-side flexibility could **each save €600 per year on average** by 2035	Offering demand-side flexibility can reduce the energy portion of customers' electricity bills by 4.9 c/kWh—nearly 50%.[2]
Homeowners with heat pumps (particularly in Southern Europe) can **save €460- €1,350 per year** through flexible operation	Electrification of heating enables efficiency gains from better technology as well as cost savings by enabling customers to automatically consume electricity when it is cheap.[3]

Sources:
1. smartEn and DNV (2022), *Demand-side flexibility: quantification of the benefits in the EU*
2. Agora Energiewende and Forschungsstelle für Energiewirtschaft e. V. (2024), *The benefits of energy flexibility at home*
3. The European Consumer Organisation (2024), *The Missing Link: Why Dynamic Pricing is Essential in the Switch to Clean Heating*

Clean flexibility reduces renewable generation curtailment

Without adequate clean flexibility, grid operators can be forced to curtail low-cost and clean renewable electricity when output is greater than what the system can accommodate.

During some periods (e.g., days with low electricity demand but high wind speeds), the amount of electricity produced might be more than the system can handle. In these cases, solar and wind farms are often forced to curtail their power to keep the system balanced.

Instead of wasting this excess low-cost renewable generation, clean flexibility solutions can ensure this is better utilized by absorbing it to later discharge back to the grid (e.g. batteries and V2G), adjusting consumption schedules to match renewable output (demand-side response and EV charging) or converting excess renewable electricity to be used for heat or stored for long term flexibility needs (Power-to-X and long-duration energy storage). See Section IV for more examples.

Between **50–121 TWh** of renewable generation in Europe could be curtailed each year by 2030	This can be avoided with additional clean flexibility, which enables greater local consumption or transport via the interconnectors. By 2040, potential curtailment increases to **100–310 TWh per year**.[1]
Demand-side flexibility alone could avoid **15.5 TWh** of renewables curtailment in Europe each year by 2030	Avoiding this curtailment in turn lowers electricity prices for customers.[2]

Sources:
1. European Commission (2024), *Redispatch and Congestion Management: Future-Proofing the European Power Market*
2. smartEn and DNV (2022), *Demand-side flexibility: quantification of the benefits in the EU*

Clean flexibility enables more resilient and secure energy communities

Energy communities enable citizens and local businesses to produce and share clean, affordable energy ensuring equitable access to the benefits of the energy transition

They represent a shift from centralized, utility-driven models toward local ownership and control of energy resources, most often through distributed solar and wind, battery storage, or district heating systems.

These initiatives enhance local resilience by keeping energy generation and profits within the community, creating jobs, improving grid stability, and fostering trust in the clean energy transition. For vulnerable or low-income households, energy communities can directly alleviate energy poverty through shared ownership models, collective self-consumption of low-cost renewable energy, and targeted benefit schemes.

Households participating in these energy community models additionally can save between **15–60% on annual energy bills**, depending on national tariffs and regulatory design.[1]

The town of Osimo, Italy is **combating energy poverty of its 35,000 residents** with renewables and clean flexibility.

Smart controls for explicit demand-side response and behavioural DSR programmes are enabling better sharing of renewable energy among families, **reducing energy poverty and increasing the resilience of their community.**[2]

The Energy Village of Wildpoldsried, Germany is **energy independent, typically generating 7 to 9x more energy than it uses.**

Simultaneously ensuring energy security for the town through storage, demand-side response, and district heating, while creating more than **€7 million per year in added economic value** by selling excess electricity back to the grid.[3]

Tilos Island, Greece integrated clean flexibility into a novel hybrid renewable system serving **all electricity needs largely free from fossil fuel.**

This has ensured energy autonomy and independence for the community of 500 inhabitants while creating more than **€500,000** just in fuel cost savings by replacing expensive diesel.[4]

Sources:
1. European Commission (2024), *Energy Communities Repository*
2. Local RES Renewable Energy Communities, *Osimo Demonstration Project*
3. Acadia Energy Center (2015), *Community EnergyVision*
4. Eunice Projects (2022), *TILOS Island Project: Energy Generation & Autonomy System S4S*

Section IV: The Role of Clean Flexibility in a Reliable Power System

Introduction

A reliable power system needs to be flexible to ensure that electricity generation ("supply") always matches consumption ("demand"). Clean flexibility solutions perform a range of functions to provide this balance while keeping the lights on and the gas off.

Unlike other commodities, electricity cannot be easily stored for long periods and therefore needs to be consumed in the same instant as it is produced. This makes power systems uniquely difficult to manage, and they require flexibility at multiple timescales to constantly balance supply and demand. This balancing is even more important in modern power systems, where power generation from renewables is weather-dependent.

Clean flexibility solutions ensure the grid can adapt to variability, uncertainty, and extreme events—keeping electricity reliable, affordable, and clean across daily, seasonal, and multi-year timescales. This section summarises the use cases of clean flexibility in power systems, and highlights which solutions contribute to each use case.

Daily flexibility: smoothing differences in supply and demand

Throughout the day, flexibility is needed to "smooth out" imbalances in electricity supply and demand that arise due to differences in production and consumption patterns.

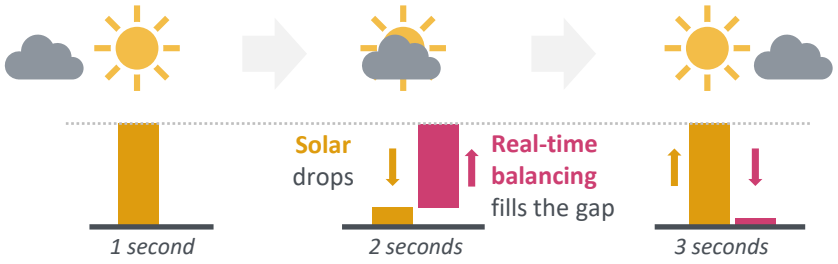
Within a day, there are several types of smoothing that are required.

Real-time balancing: Small fluctuations in electricity generation or consumption can result in temporary mismatches in supply and demand. For example, generation from solar panels might momentarily drop as a cloud passes the sun. In such instances, real-time balancing is needed to make up for this drop. Technologies that provide real-time balancing must respond almost instantaneously, within seconds.

Daily "ramping": With solar generating abundant (and sometimes even excess) power in the middle of the day, flexibility is needed to rapidly increase available power ("ramping up") as the sun goes down and electricity consumption increases in the evening hours. Technologies providing daily ramping must be able to increase and sustain their power output (or in the case of demand-side response, their power reduction) for seconds to hours.

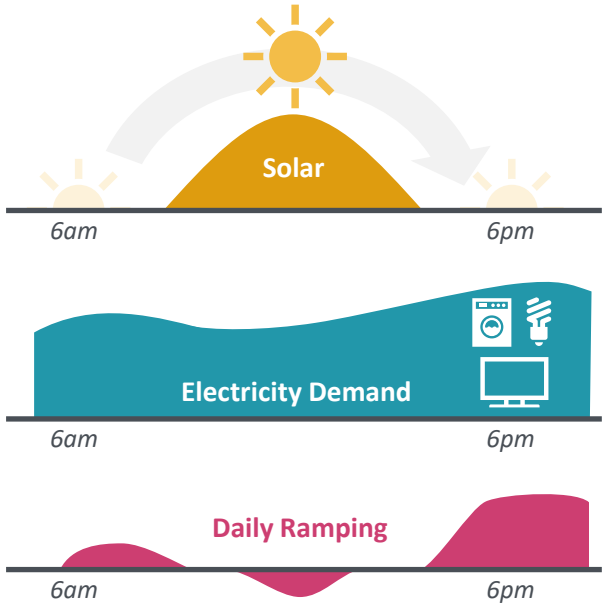
Additionally, some flexibility might be needed to shift power away from parts of the grid that are under stress ("congestion") to ensure it is delivered to customers.

Daily flexibility: real-time balancing



Renewable generation can fluctuate second-to-second. Clean flexibility technologies (such as batteries) are needed to provide **real-time balancing** to manage these fluctuations.

Daily flexibility: daily ramping



Renewable solar energy generation peaks in the middle of the day when sun is at its zenith, providing abundant clean electricity.

By contrast, **electricity demand** typically peaks in the evening after the sun has set and people begin turning on lights, appliances and heating/cooling.

Clean flex solutions that provide **daily ramping flexibility** produce power (or reduce demand) during evening peak hours to fill this gap, and can also absorb excess renewables during the day.

Peak flexibility: supporting the system when demand is exceptionally high

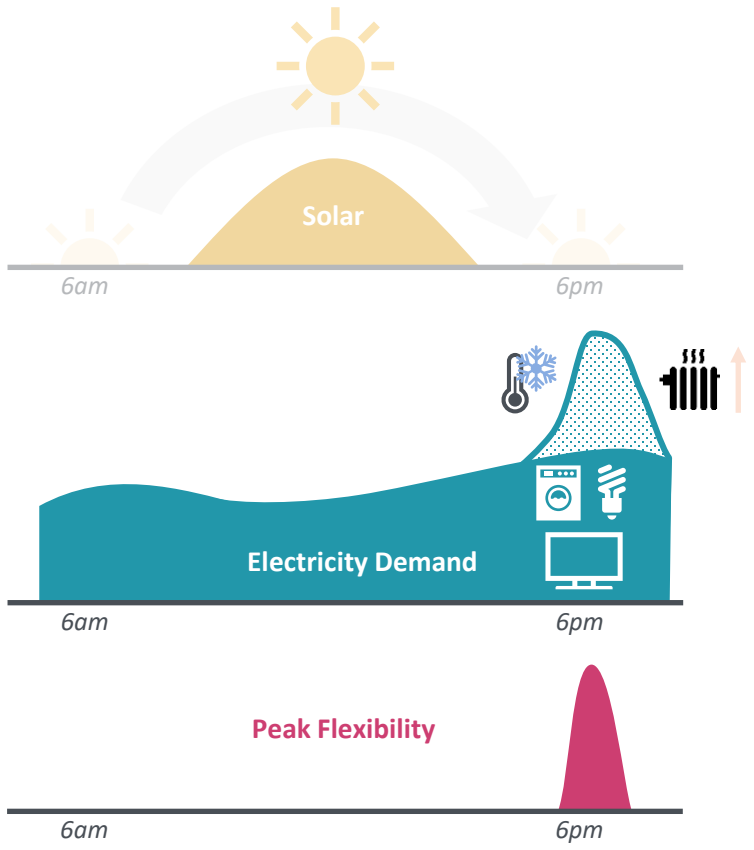
When electricity demand is exceptionally high, it comes close to the total amount of available generation, placing the grid under stress. These "peak" events only occur 10–20 times per year (usually on very cold or very hot days) and typically only last a few hours, but require flexibility to alleviate the stress on the grid.

Peak events are relatively infrequent, but crucial to plan for to maintain system reliability. Without sufficient peak flexibility, the stress on the grid can cause outages.

In Europe, these periods have typically been concentrated in winter months with the exception of a few parts of Southern Europe that use a lot of electricity for cooling in the summer. However, as more households buy electric vehicles and switch from gas heating to electric heating, these events will increasingly be spread across the entire year.

Many types of clean flexibility solutions can provide peak flexibility. Demand-side response is especially well-suited to address peak events and is a cheap source of this kind of flexibility.

Peak Flexibility: high demand on a cold winter day



On very cold winter days, **electricity demand** is higher than usual as more people are using electricity for heating. This creates exceptionally high evening peaks, placing the grid under stress.

To alleviate this stress, **peak flexibility** generates power (or reduces demand) for a short amount of time to offset the increased electricity demand.

Inter-day flexibility: saving power for a rainy day

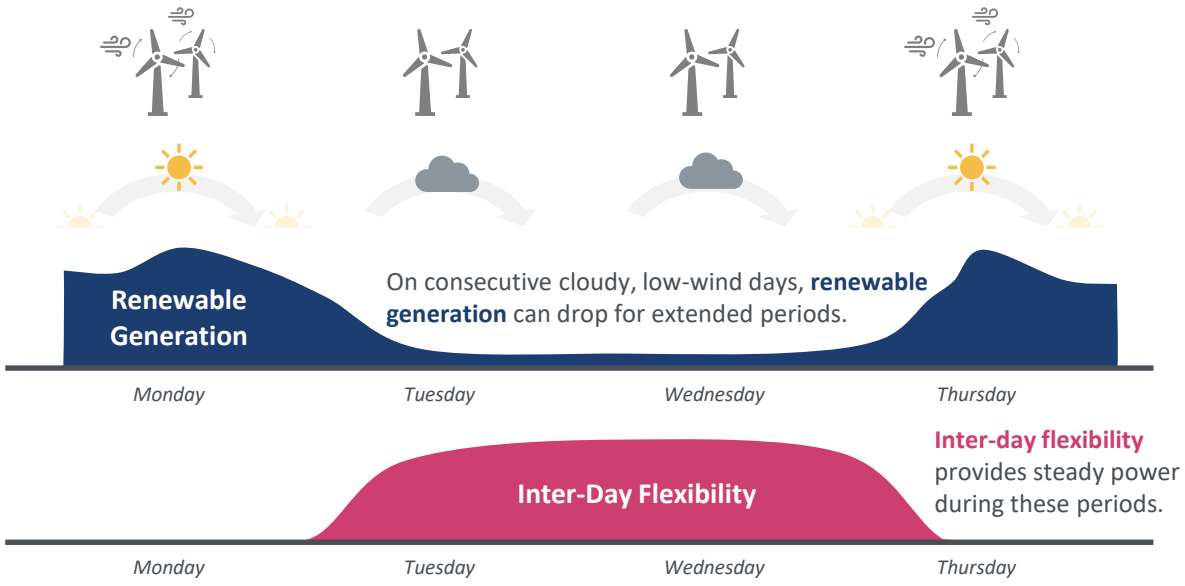
Occasionally, abnormal weather events can result in extended periods of low renewable electricity generation. Inter-day flexibility is needed to step in and replace this missing power, sometimes for several days.

Sometimes referred to by the German term *Dunkelflaute*, low-renewables periods typically have thick cloud cover and little to no wind and might last for several days (or in very rare circumstances, weeks).

These periods of low renewable generation are difficult to deal with, as they require flexibility solutions that can provide electricity to the grid for extended periods without recharging. Clean flexibility solutions that provide daily or peak flexibility (e.g., utility-scale batteries or demand-side response) are typically unable to do this. Instead, clean dispatchable generation (such as hydropower) or long-duration energy storage that can inject electricity for 36 hours or more is needed.

On the flip side, periods of consistently very high renewable generation—for example, a week of very sunny days with very high wind speeds—can present their own challenges to the grid. Under these conditions (sometimes referred to as *Hellbrise*), inter-day flexibility is needed to absorb the excess power over several days.

Inter-day Flexibility: stepping in during *Dunkelflaute*



Separately, sometimes forecasts used to predict renewables generation and demand can deviate from actual conditions—for example, it might be slightly less windy than anticipated. In these cases, inter-day flexibility is needed continuously throughout the day to “top up” electricity production.

Seasonal flexibility: soaking up and supplementing renewables

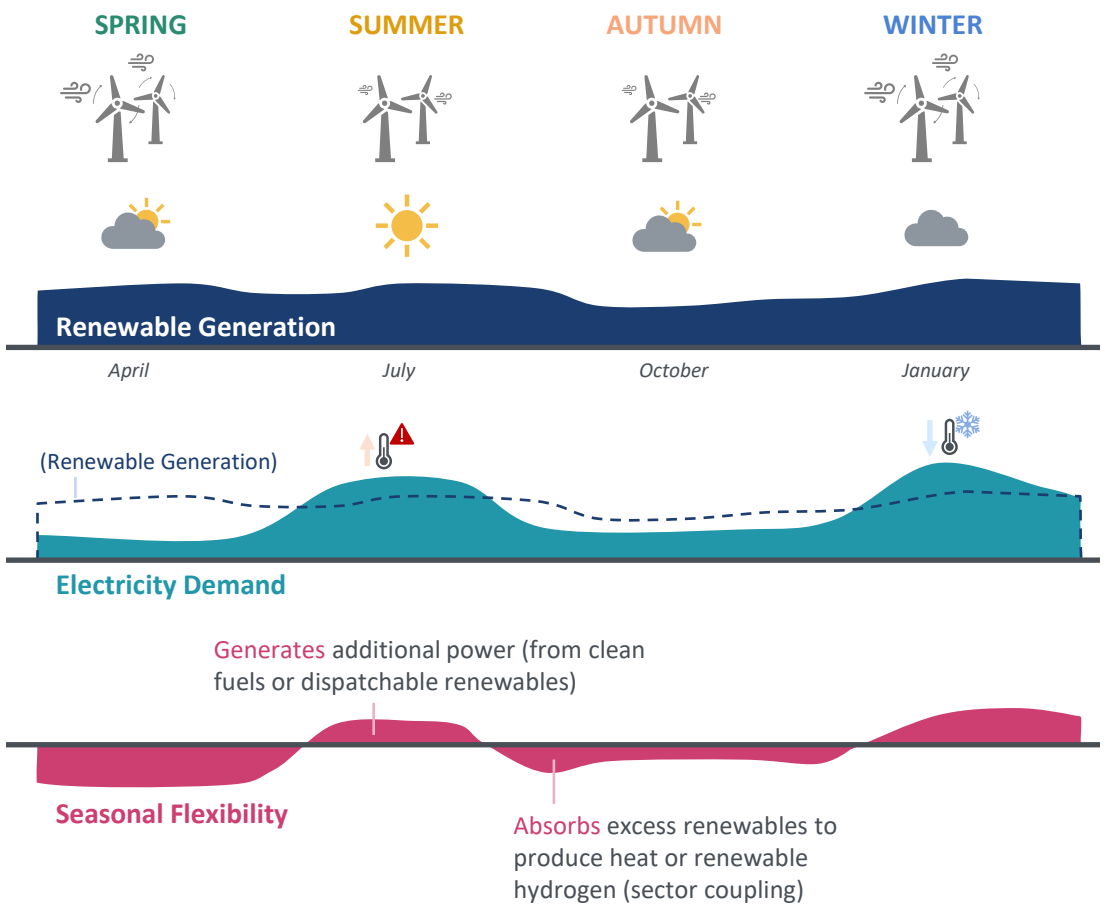
Both renewable generation and electricity demand change with the seasons, with some months seeing net excess generation and some being short on power.

Since winter and summer tend to have the greatest electricity demand due to electricity consumption for heating and cooling respectively, these months can be short on renewable power. By contrast, excess renewable generation is often available in the shoulder seasons (spring and autumn) when mild weather means that electricity demand is not very high.

These timescales make seasonal flexibility one of the most difficult challenges in modern power systems, as they are too long for conventional storage technologies such as batteries and most pumped hydro. Instead, dispatchable renewables and generation from clean fuels like renewable hydrogen are needed to fill in for renewables during high-demand months.

In months where there is excess renewable generation, it can be “soaked up” via sector coupling (such as producing renewable hydrogen via electrolysis) to convert the electricity into useful energy that can be used in other sectors or stored and used to generate electricity later in the year.

Seasonal flexibility: storing excess renewables for summer and winter



Renewable generation varies throughout the year, with high solar output in the summer and increased wind power in the winter.

Electricity demand is highest in summer and winter as people cool and heat their homes. In spring and autumn, there may be more renewable generation than electricity demand on average.

Seasonal flexibility evens out seasonal differences.

N/A	Less Able			More Able
○	◔	◑	◕	●

Different clean flexibility solutions have different use cases

The clean flexibility solutions outlined in Section II are each suitable for different use cases based on their unique characteristics. A portfolio of clean flexibility solutions is needed to ensure all use cases are addressed.

Daily flexibility is best provided by storage and dispatchable generation. Peak flexibility can be provided by many solutions, with demand-side flexibility being a particularly low-cost option.

The need for longer-term, continuous power output makes inter-day and seasonal flexibility more challenging. Long-duration energy storage technologies can provide inter-day flexibility, while dispatchable generation or interconnectors that link different regions are needed for seasonal flexibility.

For more detailed ratings, see Technical Appendix II.

		Daily (milliseconds to hours)	Peak (hours)	Inter-Day (days to weeks)	Seasonal (weeks to months)	Cost	Technological Maturity
Generation	Variable renewables	◔	◔	○	○	€€	■■■■
	Dispatchable renewables	●	◕	●	●	€€€	■■■□
	Renewable H_2	●	●	◕	●	€€€€	■□□□
Demand-side flexibility	BTM batteries	◑	◕	○	○	€	■■■□
	Electric Vehicles	◑	◕	○	○	€	■■□□
	HVAC	○	◕	○	○	€	■■■■
	Behavioural DSR	○	◕	○	○	€	■■■■
	C&I DSR	◔	◕	○	○	€	■■■■
Storage	Supercapacitors & Flywheels	◔	○	○	○	€€€	■■■■
	Grid batteries	●	◕	◔	○	€€	■■■■
	Pumped Hydro	●	●	◕	○	€€€	■■■■
	LDES	◑	●	●	◑	€€€€	■□□□
Coupling	Power-to-X	◑	◕	◔	●	€€€€	■□□□
Grid	Interconnectors	◕	◑	◕	◕	€€€	■■■■
	GETs	◔	◑	○	○	€	■■■□

Section V: Zero-Carbon Power in a Clean Flexibility Future

Introduction

While 100% reliance on clean power is a present-day reality in some countries with abundant hydro, an increasingly diverse mix of clean flexibility options are expected to play a growing role in the evolution of power systems in other countries as well. This section summarizes the status of zero-carbon power system operation today, and the growing role of clean flexibility in the future according to forward-looking modelling.

Today, several European countries run on 100% (or close to) zero-carbon power year-round. While these countries typically rely on abundant hydropower, country-specific modelling in other regions without such resources has demonstrated that transitioning to a zero-carbon system is feasible and that clean flexibility is integral to supporting renewables to operate power systems without fossil fuels.

This section synthesises present-day case studies of zero-carbon power system operation today and highlights forward-looking modelling projections that demonstrate the role of clean flexibility in reaching a zero-carbon grid in the future.

Western Europe

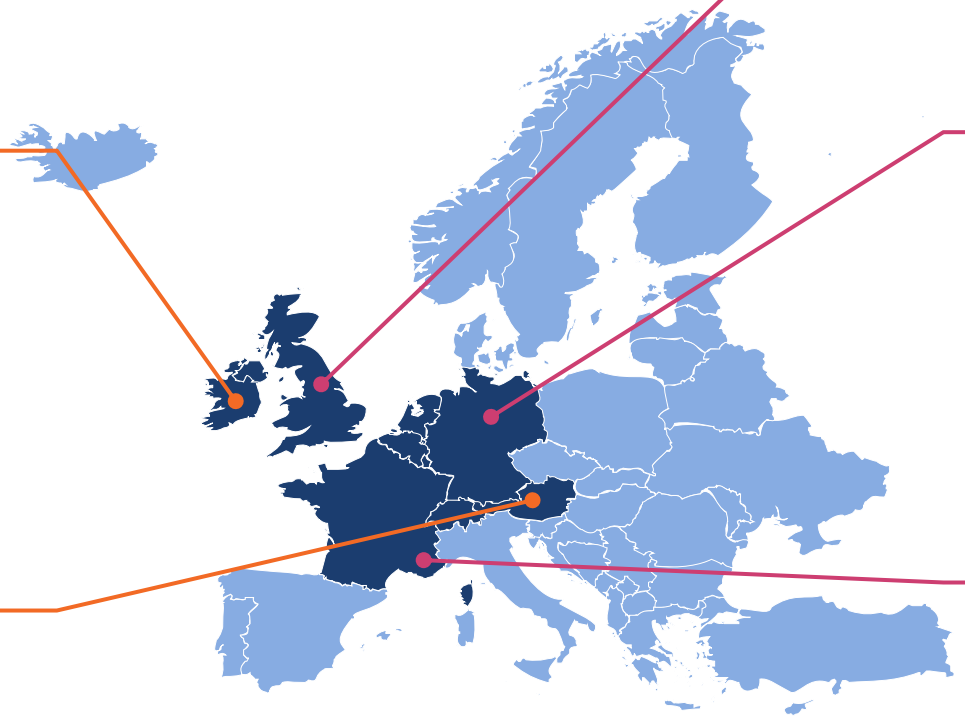
While there are isolated cases of low-carbon power systems in Western Europe today, modelling indicates that ambitious power system decarbonisation targets are achievable with the rapid uptake of clean flexibility solutions.

Zero-Carbon Operation Today

Ireland's power system can run at up to 75% renewables today due to flexible operation of wind farms, demand-side response, interconnectors, and grid-strengthening batteries and flywheels

By 2030, its grid will be powered by 80% renewables and support up to 95% renewables at any given time

Austria produced more renewable electricity (primarily hydropower and wind energy) than it consumed for an entire month in May 2023



The Future with Clean Flexibility

modelling from the **Great Britain's** National Energy System Operator (NESO) highlights the importance of demand-side flexibility in reaching the UK's policy ambitions for a net-zero power system by 2030 and economy by 2050

modelling of the **German** power system found that it could be net zero by 2045, serving more than half of the country's electricity demand with wind and a third with solar if clean flexibility is integrated, provided through rapid growth in power-to-hydrogen, battery storage, electric vehicle charging, and building electrification.

France can decarbonize its power system by 2050 with clean flexibility support from demand-side response, batteries, expanded interconnectors, and hydropower

Northern Europe

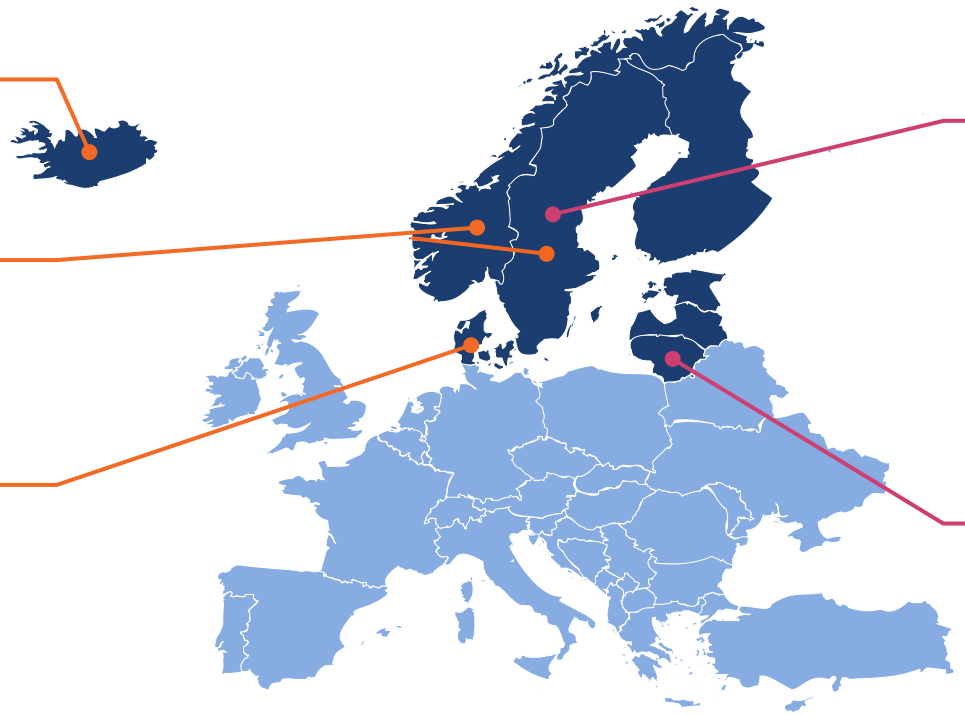
Many northern European countries have goals to completely decarbonize their power systems, with some already running at (or close to) 100% renewable generation (primarily hydro). Modelling shows that additional decarbonization will be supported by flexible clean resources.

Zero-Carbon Operation Today

Iceland produces 100% of its electricity from renewable generation (70% hydropower, 30% geothermal)

Norway and **Sweden** generated 98% and 99%, respectively, of their electricity from low-carbon sources (hydro and nuclear) in 2024

In **Denmark**, the island of Samsø has run a net-zero carbon electricity system since it became energy independent in 2006. The island has plans to be 100% carbon free by 2030 by incorporating battery storage, and electrified transportation and heating



The Future with Clean Flexibility

The **Nordic** power system can reach carbon neutrality by 2050 using primarily hydro and wind power, according to modelling

Clean flexibility will be key in achieving this goal, particularly in the form of hydropower, power-to-X, and EV smart charging

modelling shows **Lithuania** can reach its target of 100% renewable power by relying on batteries, pumped hydro, solar/wind curtailments, and power-to-hydrogen to support significant renewables generation (primarily wind power)

Southern Europe

Exceptional solar and wind resources in southern Europe have already enabled numerous prolonged periods of power system operation without any fossil fuels, and modelling anticipates that the region will continue to lean on clean flexibility solutions for support as more renewables are deployed.

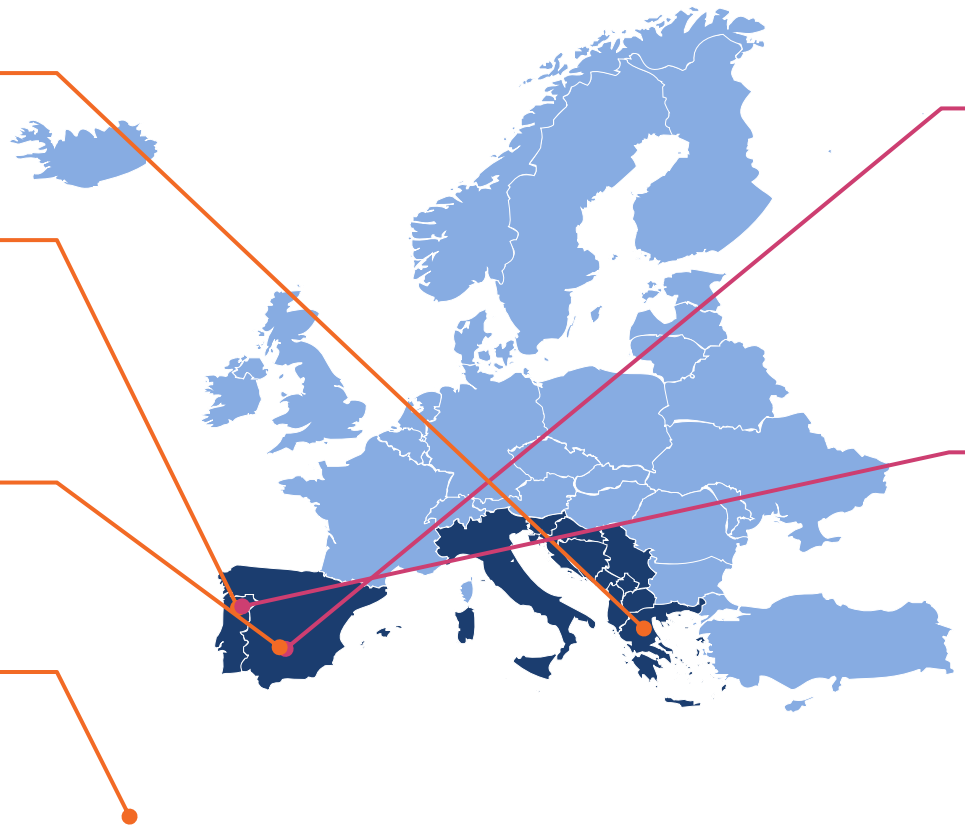
Zero-Carbon Operation Today

Greece ran its power system without fossil fuel generation for a record five hours in October 2022

Portugal achieved 149 hours (6 days) in a row without fossil fuel generation in 2023, exceeding the previous record of 5 consecutive days set in 2019

Spain has reached 77% clean generation today, with commitments to achieving 90% clean (81% renewables) by 2030

The **Spanish** Canary Island of El Hierro relied only on wind and hydropower generation for 24 days in a row in 2019



The Future with Clean Flexibility

Spain is projected to run on 93% zero-carbon electricity by 2050 under current policies, enabled by battery storage, pumped hydro, EV smart charging, and greater interconnector capacity

Portugal models a fossil fuel free power system by 2040 with combination of pumped hydro, battery storage, smart electrification of transport and building space heat, power-to-x for both renewable hydrogen and industrial heat, grid-enhancing technologies, and greater interconnector capacity

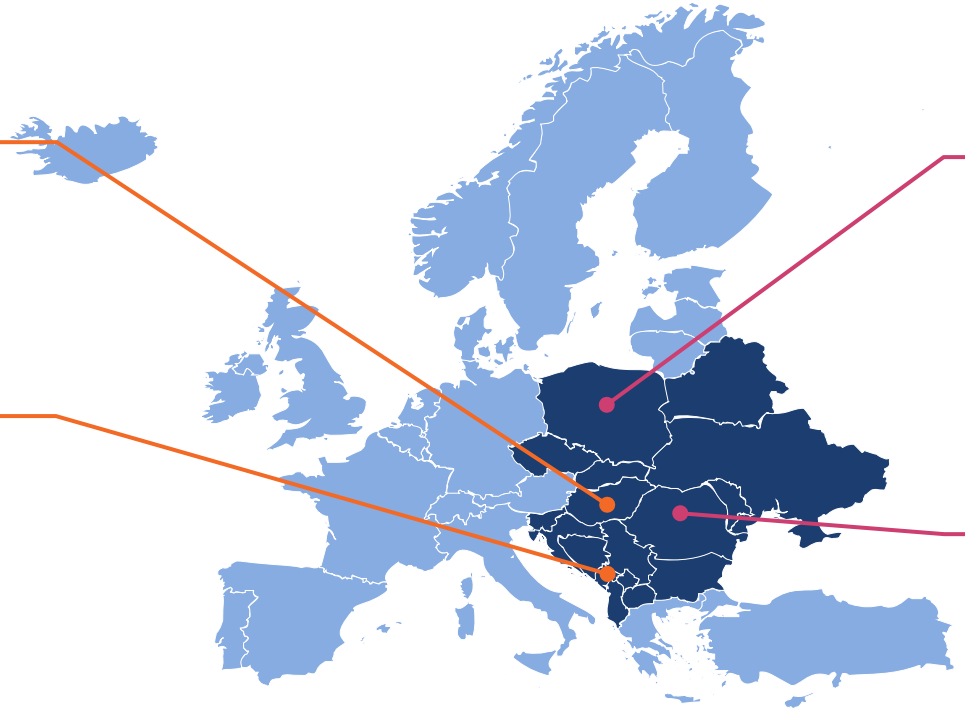
Central and Eastern Europe

While many central and eastern European countries have historically relied heavily on fossil fuels, renewables make up a growing share of many of their energy mixes. Going forward, clean flexibility will be needed to replace gas and firm up renewable generation.

Zero-Carbon Operation Today

Hungary has experienced a boom in solar power deployment, with solar growing from 7% of electricity generation in 2020 to over a third of electricity generation in 2025

Montenegro generated enough renewable electricity to power the whole country for 9 days in 2019, primarily from hydropower



The Future with Clean Flexibility

Poland, despite its reliance on coal today, could fully decarbonize its power system by 2050. modelling indicates that wind power could provide nearly 70% of Poland's energy needs in 2050, with flexibility provided by pumped hydro and growth in battery storage

Romania models an alternative to a gas-centred system via utility scale and BTM batteries, pumped and reservoir hydro, thermal LDES, power-to-hydrogen, EV vehicle-to-grid, and behavioural demand-side response

Section VI: Country-Specific Clean Flexibility Opportunities Across Europe

Introduction

The foundations to deploy clean flexibility in Europe are already established: more clean flexible technologies and solutions are available, public funding is available to support further development, and markets increasingly value flexible resources.

Clean flexibility is best understood as a portfolio of solutions that address flexibility needs across time: no single solution does everything, and the benefits to the power system come from deploying the right mix in a timely fashion.

Opportunities vary from country to country, shaped by each nation's energy mix and interconnections, policy and regulatory environment, and degree of market and technological maturity. As a consequence, clean flexibility deployment follows distinct pathways depending on where countries are in their energy transition.

This section summarises key findings and practical examples drawn from seven countries across western, southern, central and eastern Europe including: the UK, Italy, Germany, Poland, Greece, Bulgaria, and Turkey.

Each country has its own clean flexibility opportunities

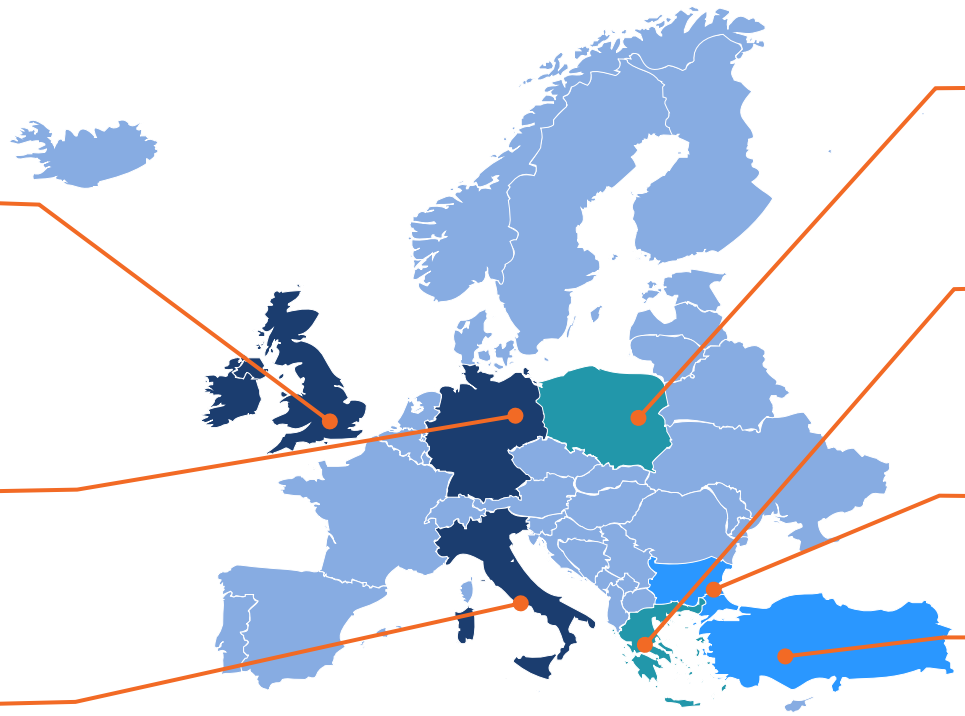
Countries further along the transition (UK, IT, DE), focus on scaling proven clean flexibility solutions and, importantly, refining the policies that support them. Countries with rapidly expanding renewable capacity (PL, GR) share an urgency to deploy clean flexibility to limit curtailments and make better use of existing clean power. Countries at earlier stages (BG, TR) have the opportunity to leapfrog and integrate clean flexibility from the outset to avoid legacy system limits.

Case Studies

UK – Demonstrated multi-dimensional clean flexibility approach, needs to extend benefits nationally. Over 6 GW of operational large battery storage and a further 4 GW in the pipeline.

Germany – Substantial potential demand-side flexibility from rooftop solar and home battery storage, need for more digitalisation to fully unlock

Italy – Large deployments of utility scale storage is paired with substantial demand-side flexibility potential. Policies need rebalancing.



Case Studies

Poland – Curtailment as 'learning', flexibility solutions at hand include: heat electrification + storage co-location, support and integration of 'prosumers'.

Greece – Shows 100% renewable operation is possible for the power system, but needs more clean flexibility to sustain it.

Bulgaria – Rapid renewable growth, but clean flexibility at early stages. Market reforms must continue.

Turkey – Has opportunity to build storage and clean flexibility capabilities in parallel with planned renewable resources, not after.

For the detailed country case studies, see Technical Appendix I.

The examined European markets fall broadly into three groups, based on different clean flexibility emphasis and near-term priorities

Markets with proven flexibility deployments, aiming for scale.

The challenge: refining the policies that support clean flexibility and extending the benefits to all regions and customers.

The UK is one of Europe's most sophisticated flexibility markets, enabling both supply and demand-side flexibility solutions to provide system services and access market revenues for providing flexibility. Opportunity: extension to more geographic locations and better enable equitable access from demand-side resources.

Italy has clean flexibility maturity and digital readiness. Wide-scale deployment of smart meters enables demand-side flexibility participation at scale. Utility-scale storage accelerated decisively in 2024, but capacity markets still award 95% of payments to fossil assets. Policy rebalancing would unlock greater scaling of clean flexibility as well as unlock the demand-side flexibility that digitalisation allow system operators to access.

Germany shows the potential-vs-deployment gap. Extensive deployment of rooftop solar and Europe's largest industrial base offer substantial demand-side flexibility potential, but less than 5% smart meter penetration leaves “behind-the-meter” resources largely inaccessible. Battery storage growth is strong, but its contribution is undersized relative to curtailment and congestion costs (€1.5B in the first half of 2025 alone).

Markets with rapidly expanding renewables outpacing flexibility deployment.

The priority: capitalising on ‘curtailment as learning’ and deploying clean flex solutions to reduce curtailed energy and mitigate congestion.

Poland curtailed 731 GWh in 2024, enough to power three major cities for a year. Utility storage as well as producer-consumer (“prosumer”) programmes are a success to build upon (e.g. 1.5 million ‘prosumers’ as of 2024 with 60% including storage). Residential and industrial heat electrification hold further potential. Smart meter penetration (38%) remains a constraint on benefitting from coordinated demand-side flexibility.

Greece frequently operates at 50%+ renewable generation but curtailed 1 TWh in 2024 due to flexibility gaps. New frameworks establish priority grid access for 4.7 GW of battery storage enable greater control of renewable resources. The 29 non-interconnected island systems are transitioning away from diesel through interconnectors with the mainland and clean flexibility solutions.

Earlier-stage markets.

The opportunity: integrating clean flexibility into planning from the outset, avoiding being locked in into old infrastructure and rules.

Bulgaria secured €600M (EU-RESTORE) for 10 GWh utility storage plus community-scale hybrid projects (e.g., Pernik: 32 MW solar + 61 MWh storage + heat). With solar continuing to grow at pace (+40% in 2024), Bulgaria needs to deploy flexibility in parallel with generation growth to avoid legacy system constraints.

Turkey’s 2035 Renewable Energy Road Map is paired with over $1B USD in World Bank/European Bank for Reconstruction and Development funding. 2024 regulatory reforms enable co-located storage and streamline permitting. Building flexibility into market rules from the start can avoid policy and fossil fuel lock-in, creating a framework to attract investment in modern, flexible systems.

For the detailed country case studies, see Technical Appendix I.

Section VII: Conclusions

Key takeaways

PROVEN PERFORMANCE

Clean flexibility is dependable. Recent experience and analyses have shown how integrating flexibility into modern power systems enables greater utilisation of renewable energy while ensuring security of supply. Clean flexibility solutions exist to address system needs across all timescales and already help enable power systems to run without fossil fuel generation.

VALUE

Clean flexibility is a multi-billion euro opportunity that can lower energy bills, ensure energy security, support low-income households, reduce dependence on gas generation, ensure resilience of local communities, and ensure an equitable access to the benefits of the clean energy transition

SIGNIFICANT SCALE

Already today, large-scale battery storage assets are routinely installed with capacities comparable to those of gas plants. Aggregations of demand-side response are now able to reach scale in the hundreds of megawatts as well to provide valuable flexibility to power system and consumers.

GROWTH POTENTIAL

European sources of clean flexibility are expected to grow to over 700 GW by 2050. Supportive economics and policies are unlocking investment and market access for clean flexibility solutions across nations. Together, these trends position clean flexibility as a cornerstone of Europe's transition to a resilient, affordable, and fully renewable energy system.

LOOKING AHEAD

If efforts to integrate and expand clean flexibility are continued, Europe has substantial opportunities to maximize the value it provides and to enable a cost effective, reliable, and equitable energy transition.

Scaling up clean flexibility – five key areas that underpin success

Advancing clean flexibility is not only about technical innovation or fast deployment. It requires coordinated planning, reliable implementation, functional data reporting, and market and regulatory alignment with a long-term view.

DIGITAL INFRASTRUCTURE FOUNDATION

- Step up smart meter deployment
- Ensure smart meters and networks are interoperable
- Enable real-time data access for aggregators of demand-side flexibility and consumers

MARKET DESIGN & REGULATION

- Refine policies to encourage/incentivize clean flexibility deployment
- Rebalance capacity mechanisms to end fossil asset skew
- Provide regulatory certainty for investors in clean flexibility

COORDINATED GRID PLANNING

- Ensure flexibility-first grid planning and TSO-DSO coordination
- Size and deploy storage and demand response in parallel with renewables
- Target grid bottlenecks strategically

CONSUMER ENGAGEMENT

- Foster dynamic pricing and automation in homes and buildings
- Scale and replicate proven solutions or programmes
- Make participation simple: lower barriers to entry for all consumers

ENABLING POLICIES, SUSTAINED SUPPORT

- Develop support policies based on experience from countries with greater clean flexibility deployment
- Avoid fossil legacy lock-in
- Commit to multi-year funding and policy stability

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Ryan focuses his consulting practice on regulatory, planning, and strategy matters related to emerging energy technologies and policies. His work on the grid edge has been cited in federal and state regulatory decisions, as well as by *Forbes*, *National Geographic*, *The New York Times*, *NPR*, and *The Washington Post*. He has published more than 30 articles on electricity matters, presented at industry events in 11 countries, given lectures on distributed grid economics at Penn, Stanford, and Yale, and served on the advisory boards of a demand flexibility startup and an energy storage trade association. Ryan received his M.S. in Management Science and Engineering from Stanford University, and his B.S. in Applied Science from the University of Pennsylvania.

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Technical Appendix I:
Detailed Country Case Studies

UK's Clean Flexibility Snapshot

The UK is one of Europe's most sophisticated flexibility markets, with success in both supply-side and demand-side flexibility solutions. Clean flexibility is already delivering measurable benefits to bill payers and enabling greater renewable energy integration. The UK must maintain innovation momentum with coordinated policies.

Clean flexibility in the UK aims for scale

Learn

2021-25

Proof of concept: consumer flexibility works. The CrowdFlex project has involved over 60.000 customers in the world's largest consumer flexibility trial. This real-world experience shows that consumers could collectively reduce system peak demand by up to 10% (6.8 GW) in 2030 if expanded to the rest of the UK. 2025 results have shown that automated demand-side response can shift 30% more energy.

Deploy

2026-30

As the UK advances toward its Clean Power 2030 ambitions with substantial investments, there are significant opportunities for clean flexibility solutions to address grid connection backlogs and market reform challenges. New regulations and digital platforms are planned to be deployed to help reach the goal of 51 GW to 66 GW of clean flexibility with 10 to 12 GW of that from consumers by 2030.

Scale

2031-50

The UK Clean Flexibility Roadmap projects an eight-fold increase in flexibility from 2024 to 2050. Batteries, customer-led flexibility, electric vehicle smart charging and vehicle-to-grid could grow clean flexibility from 8.6 GW to potentially 165 GW by 2050. As resources scale up, clean flexibility makes a double contribution: clean flexibility deployed at scale will offer dependable grid services as well as saving costs to consumers. Achieving and maintaining 2050 goals continues to require enabling regulatory and operational policies.

Helping grid congestion

In **Dundee, Scotland** electric vehicles were automatically charged in response to time-varying retail electricity prices, with the aim of shifting demand away from congested times.

This pilot project showed that enabling consumer flexibility at scale can postpone grid infrastructure upgrades, reduce peak loads by more than 25%, save £1 billion in costs, and shift more than 100 GWh of energy each year to non-peak periods.

Making flexibility accessible

A 2025 paper details several examples of how Distribution System Operators can add new programmes centred around flexibility. Recent trials across the UK include home battery and EV charging projects, and alerting customers about cheap or free electricity periods. These efforts focus on using smart pricing, technology, and community involvement to help people use energy at the best times and also support the grid.

Clean Flex Solutions in Residential Communities

In September 2025 a new pilot launched involving approximately 300 residential home batteries across the UK operating as a Virtual Power Plant (VPP). Consumers in this pilot will participate in Wholesale Markets directly as part of the VPP, allowing them to earn revenue for the flexible use of their battery storage, estimated to earn a few hundred pounds per year.

Saving with clean flexibility

A great example of clean flexibility in action comes from Octopus Energy's Saving Sessions, where customers typically saved £320 in 2024 by shifting their energy use to times of low prices when renewable energy is most abundant.

Connecting to Clean Flex Solutions

The UK flexibility market continues to grow, with 6.3 GW of clean flexibility contracted in 2024. Energy flexibility saved customers £300m in 2024, with expectations to reach £3 billion 2025-2028. Elexon is coordinating and developing standardised rules for flexibility markets in the UK, expected in Q4 2025.

Clean Flexibility Opportunities and Challenges in the UK

UK Clean Flexibility Opportunities

- **The National Energy System Operator (NESO) published the first iteration of its energy sector digitalisation plan.** Priorities include accelerating the rollout of digital infrastructure, data access, and AI to support flexible, resilient system operations.
- **The UK has a highly advanced, innovation-driven energy market**: this enables rapid trials for local flexibility, digital platforms, and cross-sector solutions.
- **Digitalisation and deeper integration of data between networks and consumers are key** to harness the value of distributed flexibility and unlock real-time flexibility through smart EV charging, batteries, and time-varying pricing.
- **Scalable access to assets**: as the system evolves, batteries, long-duration energy storage, and demand response become vital to meet network needs quickly and efficiently. Clean flexibility solutions are also fundamental for a cost-effective clean power system. According to NESO (p. 11), " […] a repeat of the gas price spike of 2022 would add around £10 billion to electricity system costs in 2030, but would add only £5 billion in a clean power system".

UK Clean Flexibility Challenges

- **Expanding grid capacity and reducing connection backlogs are essential for scaling up clean flexibility:** as of 2024, over 700 GW of capacity (including 120 GW of battery storage) sat waiting in the connection queue before it can be built. While reformed grid connection processes are underway, more will need to be done.
- **Market reform uncertainty could cause investment pause:** Ofgem will confirm the exact revenue cap and floor levels for the GB long duration energy storage (LDES) regime in Q2 2026 following completion of its cost–benefit analysis. The uncertainty around cap and floor rules for LDES increases risks for investors in these important clean flexibility assets.
- **Administrative, market and regulatory complexity:** Beyond the national pricing model reform, several other key changes to the energy and regulatory design are being considered, which could increase uncertainty and possibly delay investment in new clean flexibility technologies and solutions.

Germany's Clean Flexibility Snapshot

The Bundesnetzagentur, in its 2025 security of supply monitoring report, finds that expanding and integrating clean flexibility is just as crucial as building new renewable or dispatchable generation for Germany's future supply security. Any delay or obstacle in this area poses significant risks to reliability, cost, and climate goals.

Germany's clean flex gap between potential and deployment

Learn

2021-25

Most of recent capacity growth for storage comes from small "behind-the-meter" battery systems (<30kWh). Curtailment and congestion costs totalled €1.5 billion in H1 2025 alone. Additionally, in 2024, solar curtailments totalled 1.4 TWh doubling year-on-year (70%+ of curtailments in Bavaria alone) and wind curtailments amounted to almost 9 TWh. Confirming that current grid flexibility is inadequate to absorb the renewable generation present today.

Deploy

2026-30

Currently there are 720 GW of storage connection requests (2.7x the total installed generation capacity in Germany), but severe grid connection bottlenecks risk preventing these and other clean flexibility projects from being deployed. On the retail side households, commercial users, and small industries, hold substantial untapped demand-side flexibility. Recent studies by the from BMWK (Ministry for Economic Affairs and Climate Action), and the Bundesnetzagentur confirm that these loads could provide significant flexibility if activated at scale.

Scale

2031-50

By 2035, clean flexibility can avoid 20 TWh of electricity from fossil fuel generation saving €5.4 billion in costs. Additionally, clean flexibility can significantly lower grid expansion and operation costs resulting in €4.8 billion in savings in 2035 alone. Distributed, grid-connected flexibility has the potential to reduce total power system costs by billions of euros annually after 2040 if it can be successfully scaled.

Hamm and Neurath Utility-scale Storage

RWE has commissioned one of the largest battery storage systems in Germany, with a total capacity of 220 MW which provides valuable flexibility and frequency regulation.

BürgerEnergie Berlin Community Solar+Storage

Energy community cooperative started in 2012, has solar panels with a peak power output of 36kW for 36 participating units. Customers in the energy community reported 20% lower bills than national rates.

Feldheim village: a self-sufficient town for 15 years

With a population of only 150, it has a 74 MW wind + 2.3 MW solar + 10 MW battery system. Residents pay half of the national electricity rates. Battery storage provides 4-day backup and grid frequency regulation services.

Wildpoldsried "Energy Village" (Bavaria): Combines solar PV, wind and district heating. As of 2023, the town's 'portfolio' spread across 11 wind turbines (17.6 MW), 15 communal solar arrays (0.7 MW), and about 350 private rooftop solar systems (6.2 MW). It produced over nine times the local demand, created €8 million in added economic value for the region and brought in €800,000 to the town budget. Wildpoldsried uses sophisticated smart grid technology (developed through Irene-DE projects) to manage the balance between its renewable generation and local consumption. The village also participated in pilot projects related to peer-to-peer energy trading (Pebbles).

Clean Flexibility Opportunities and Challenges in Germany

Germany Clean Flexibility Opportunities

- **Substantial build-out of residential battery storage:** 13 GW/19 GWh of home battery resources from over 2 million installations already in Q4 2025, co-locating solar PV and batteries is now deemed standard practice even at the residential level.
- **Large-scale battery storage is gaining momentum:** As of October 2025, official data records 2.4 GW (3.2 GWh) of "large-scale" (>1000 kW) battery storage capacity as operational (>900 facilities), and a further 5 GW (10.4 GWh) of capacity in the planning stages with expected commissioning by summer 2027. Estimated potential annual revenues for a 1 MW battery providing reserve services typically range from €60.000 to €100.000 per MW.
- **Expansion of supporting policies:** 2025 "Solar Peak Act" enables home batteries to charge from the grid without losing subsidies, while dedicated support for co-located solar and storage is reinforced by the Renewable Act's (EEG) Innovation Tenders. However, effective coordination, market rules, and full smart meter rollout are still needed to unlock full scale system benefits.
- **Flexibility programmes delivering savings:** Households in Germany can expect annual grid fee savings of €110 to €190 by participating in flexibility programmes.

Germany Clean Flexibility Challenges

- **Incomplete market design:** Financial barriers and rules currently harm fair participation and block market players from reacting to price signals. The 2025 Security of Electricity Supply Report (Bundesnetzagentur) emphasizes these obstacles must be removed as soon as possible to accelerate flexibility deployment and improve system efficiency.
- **Regulatory uncertainty**: Half of respondents in a recent survey of 400 German companies cite regulatory uncertainty as a key barrier to adopting flexibility measures.
- **Digital infrastructure paralysis:** With less than 5% smart meter penetration this is by far the lowest in Western Europe (vs 100% in Spain, Portugal or Italy). Delaying demand flexibility in Germany risks keeping fossil power plants in use longer and in some scenarios may create the need to build new ones to secure the electricity supply.
- **Minimal dynamic pricing adoption**, despite legislative mandate since 2021: less than 5% of households are on time-of-use (ToU) tariffs, and only 52 of over 1,000 suppliers offered real-time tariffs in 2023.

Italy's Clean Flexibility Snapshot

Transmission Operator Terna's 2025 half-year report calls for faster investment across Italy's power system and explicitly notes the need to expand participation of renewable, electric vehicle, and demand response resources in flexibility markets. In September 2025 Terna's first storage auction (MACSE) secured 10 GWh of capacity for 2028 delivery.

Italy needs to harness its demand-side flexibility potential

Learn

2021-25

Flexibility starts being valuable in the home. In Italy, homeowners with heat pumps can save €460-1,350 per customer per year thanks to flexible pricing and operations. Utility-scale storage accelerated decisively in 2024 (10 GWh secured through MASCE), but capacity markets still award 95% of payments to fossil fuel assets: policy rebalancing would unlock further scaling of clean flex.

Deploy

2026-30

Terna's 2025 Development Plan estimates Italy will need much more flexibility by 2030: daily flexibility requirements will rise by 41%, weekly by 32%, and yearly by 28%. Italy has strong potential to use demand side response for daily flexibility, supported by a 100% smart meter penetration. Realizing this potential depends on enabling more granular, real-time pricing and expanding participation in flexibility markets. A new regulatory framework was implemented in 2025 to address current barriers and better integrate demand-side response and other clean flexibility solutions into wholesale markets.

Scale

2031-50

Italy is aiming to scale-up clean flexibility to support a clean power system by 2050. Grid modernisation investments and supportive policy frameworks will be critical to unlocking flexibility deployment at the scale needed beyond 2030. Together with grid modernisation, deploying flexibility at scale, especially batteries and demand-side response, will help manage generation surpluses and reduce grid bottlenecks.

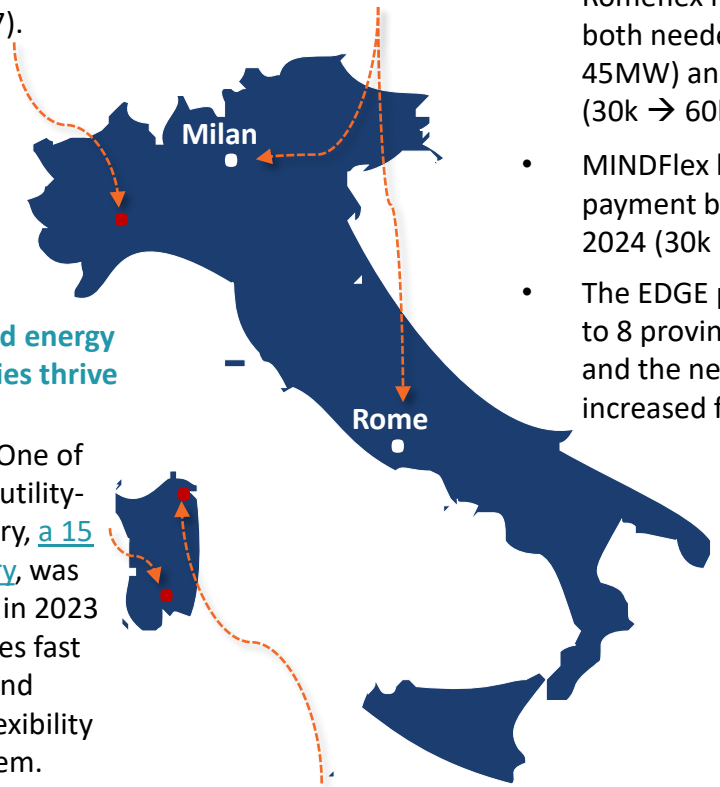
EV charging on a large scale in Turin

The **Mirafiori** EV2G project links hundreds of Fiat 500 electric cars to the system, using the batteries to provide 25 MW of fast frequency regulation services (started 2023, ends 2027).

Localised flexibility: pilot projects show what works, but are still very limited in size

Three pilots of distribution system flexibility Romeflex, MiNDFlex (Milan), and EDGE (8 provinces throughout Italy), have been active since 2024. In these pilots, users accumulate energy in their storage systems to be sold back to the grid and receive payments for participating.

- Romeflex has seen an increase of both needed flexibility (20MW → 45MW) and availability payment (30k → 60k €/MW-year).
- MINDFlex has seen the availability payment base increase strongly vs 2024 (30k → 500k €/MW-year).
- The EDGE pilot has doubled from 4 to 8 provinces (in 7 regions) in 2025 and the needed flexibility has increased from 11MW to 19MW.



Storage and energy communities thrive in Sardinia

Assemini: One of Italy's first utility-scale battery, a 15 MW battery, was connected in 2023 and provides fast response and valuable flexibility to the system.

Berchidda (Limbara energy community): aims to combine solar, batteries, heat pumps, Demand Side Response and e-mobility, into a smart local energy community. Involved in several EU funded projects (LocalRES , Hestia, Masterpiece, Neon).

Clean Flexibility Opportunities and Challenges in Italy

Italy Clean Flexibility Opportunities

- **Installed storage capacity:** Italy has 6.7 GW of installed battery storage as of 2025, 1.6 GW (6 GWh) in utility-scale systems (4-hour duration), and the rest in small integrated systems (2-hour duration). Storage installations have increased by about 10x since 2021 (2021 = 75k; Q1 2025=775k).
- **The first storage auction (MACSE) secured 10 GWh of capacity for 2028 delivery**, with related investments estimated at €1 billion. Going forward, MACSE is envisioned to procure up to 50 GWh of storage to support Italy's flexibility needs.
- **Italy launched its nationwide local flexibility market in June 2025 via Piclo Flex and E-Distribuzione**, within the EDGE pilot programme. The first competitive auctions for supplying local ancillary services have been completed.
- **Italy has 100% smart meter penetration.** This enables coordinated demand response on a large scale. To fully harness this potential, Italy needs dynamic real-time tariffs and digital platforms that reward households and businesses for adjusting their consumption in response to real-time prices.

Italy Clean Flexibility Challenges

- **Storage Auction (MACSE) criticism:** High concentration of winning bids among large players (Enel > 50%) suggest smaller developers face barriers to competing, highlighting possible need for auction design reforms.
- **Capacity Market still favours fossil generation:** the latest three auctions for 2025-27 capacity provision (worth over €5 billion in total) awarded the majority of payments to existing thermal plants (about 40 GW each year).
- **Administrative, technological and regulatory complexity:** inter-institutional coordination and IT readiness are critical risks that delay the deployment of clean flexibility solutions. New solutions such as the TIDE dispatching rules, were designed to enable demand-side flexibility participation. For example, TIDE creates standardized rules that allow smaller resources (home batteries, EVs, and heat pumps) to participate in electricity markets and provide grid services. The rules were piloted in 2017 with planned 2025 implementation. Multiple decision layers and coordination delays between transmission operator Terna and regulator ARERA mean that TIDE's full implementation is only expected after February 2026.

Greece's Clean Flexibility Snapshot

Greece's renewable electricity generation has surged, but curtailments neared 2 TWh in 2025 due to insufficient flexibility:

- **The Main Interconnected System covering mainland Greece experiences congestion that prevents full utilisation of its abundant solar resources**
- **29 non-interconnected island systems run independent diesel-dependent microgrids with voltage and frequency stability challenges as they transition to renewables.**

Clean flexibility is needed to support system stability in Greece

Learn

2021-25

Clean flexible resources, like grid batteries, are beginning to be integrated through subsidy-backed auctions that awarded 900 MW of large scale storage projects (2023-2025). The March 2025 auction alone awarded 189 MW of standalone utility-scale storage with 10-year Contracts-for-Difference (CfDs) for completion by 2026, though administrative delays have created risks for projects. Despite these challenges, immediate opportunities remain as Greece ramps up clean flexibility integration.

Deploy

2026-30

Greece is in the process of transitioning utility-scale energy storage: nearly 5 GW in a new battery storage programme will be operated on a merchant-basis and benefit from grid priority. After 2026, new installations will depend increasingly on revenue generated from grid services, energy price arbitrage, and balancing markets. Clean flexibility becomes more mainstream, but its success must be underpinned by the ability for investors to generate sufficient revenue through markets.

Scale

2031-50

Continued optimisation of the distribution and transmission infrastructure and a push towards digitalisation will allow maintaining system stability via increased amounts of clean flexibility solutions. Greater transmission build-out will facilitate the integration of renewables, reducing reliance on fossil fuels, and digitalisation should unlock demand-side flexibility. Backed by regulatory reforms, clean flexibility resources scale up, leading to sizable value-creating opportunities and a positive system-wide impact.

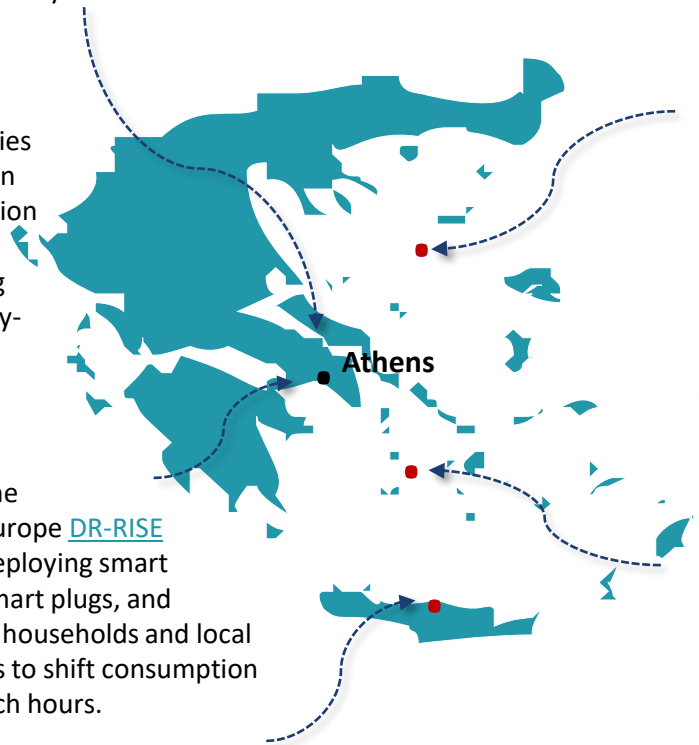
Regulatory Standards for Clean Flex Solutions

As of February 2025, every connected renewable energy plant (above 400 kW) must install remote control hardware and software, giving the transmission system operator (HEDNO) real-time control of >70% of distributed solar installations. This enables renewables to provide more effective, data-driven flexibility.

Clean Flexibility, provided by batteries, renewable energy and smart controls enables small Greek islands to address seasonal demand challenges and greatly reduces fossil fuel dependence

Clean Flex Solutions

Energy communities CommonEn and Hyperion are pioneering community-based demand-response models through the Horizon Europe DR-RISE project, deploying smart meters, smart plugs, and sensors in households and local businesses to shift consumption to solar-rich hours.



Clean Flex Solutions in Crete: In May 2025 the 1 GW Ariadne HVDC link integrated Crete into the mainland grid, This will allow the island to provide and receive energy and grid support from/to the mainland through the transmission system. An example of how transmission enables clean flexibility as well.

In addition, island energy community initiatives raise awareness and acceptance of clean flex solutions:

Agios Efstratios is on track to become one of Greece's first energy-autonomous islands, with the completion of a hybrid renewable system combining 0.9 MW of wind, 0.2 MW of solar PV, and 2.56 MWh of battery storage to cover more than 85% of the island's energy needs through renewable energy and clean flexibility.

One of the early examples comes from **Tilos**, where the hybrid micro-grid includes an 800 kW wind turbine, 160 kW solar array, and 2.8 MWh battery storage with advanced energy management and control systems.

Clean Flexibility Opportunities and Challenges in Greece

Greece Clean Flexibility Opportunities

- **Greece has substantial potential for solar and wind energy:** today Greece demonstrates that power systems can operate at majority-renewable levels when supported by flexibility. In 2023, renewables and hydro covered 51.4% of electricity demand for the first time.
- **Grid-scale batteries and enhanced control and automation initiatives are expanding:** supported by modern policies and new projects. Greek transmission and distribution system operators are investing €8 billion in smart grid and demand-side flexibility.
- **New utility-scale storage regulatory framework**: In March 2025 Greece launched a battery storage programme which establishes priority grid access for 4.7 GW of standalone storage installations.
- **Remote monitoring and control of variable renewables**: Every renewable system above 400 kW must install remote monitoring and control technologies, giving the system operator (HEDNO) real-time curtailment control of over 70% of RES plants connected to the grid. Deploying smart grid automation will allow RES generation to ramp up and ramp down or generate at reduced levels, thereby ending costly “on/off” type decisions which results in curtailment.

Greece Clean Flexibility Challenges

- **Flexibility gaps result in wasted clean energy:** renewable energy curtailments approached 1 TWh in 2024 (vs 0.23 TWh in 2023), equivalent to 3.5% of renewable energy production and almost 2% of total generation. The problem intensified dramatically in 2025, with curtailments reaching nearly 2 TWh, double the 2024 total, and highlighting the urgent need for flexibility solutions.
- **System legacy:** In the interconnected mainland, fossil fuels still supplied about half of electricity production in 2024. Many non-interconnected islands are still very reliant on diesel and oil-fired generation. This fossil fuel presence undermines clean flexibility deployment and scaling up technically, by reducing the urgency for modern balancing solutions, and economically, by dampening price signals and market opportunities for clean flex solutions.
- **Producer-consumer market maturity:** Demand-side response initiatives are encouraged, and aggregators for renewable resource producers are active, but overall is in its early stages, and **retail-level participation is underdeveloped** (smart meters: only 11% as of 2024). Active participation of producers-consumers, based on adaptive behaviour and large, managed flows of data/information is still far from happening at scale.

Poland's Clean Flexibility Snapshot

As Poland gears up for a major leap in clean energy with €1.2 billion in EU-backed funding for at least 5.4 GWh of storage and a refreshed National Energy and Climate Plan (NECP), there are meaningful opportunities for clean flexibility solutions to meet the challenges of a modernizing power system. Poland will benefit from achieving scale in clean flexibility through stable supporting policies.

Clean flexibility will support Poland's energy leap

Learn

2021-25

Integrating clean flexible resources, like grid batteries and demand-side management, is recognised as a necessity. Demand response initiatives like the IZP programme, where large customers are paid to absorb surplus power, enable practical learning. In late 2024 the Moj Prad 6.0 programme allocated over €400M (storage represented nearly 60% of applications). Immediate opportunities are available, but there still are market signal gaps.

Deploy

2026-30

Local flexibility solutions are taking root, increasingly delivering benefits. Poland's energy communities (15 in 2022, 108 as of mid-2025, 300 targeted for 2030) generate and share renewable power at the municipal level, supported by EU funding. Producer-consumer ("prosumer") and community storage programmes have led to over 1.5 million household solar systems installed equivalent to 5% of national production in 2024. EV charging points have doubled since 2023. Clean flexibility becomes more mainstream, supporting local and national resilience.

Scale

2031-50

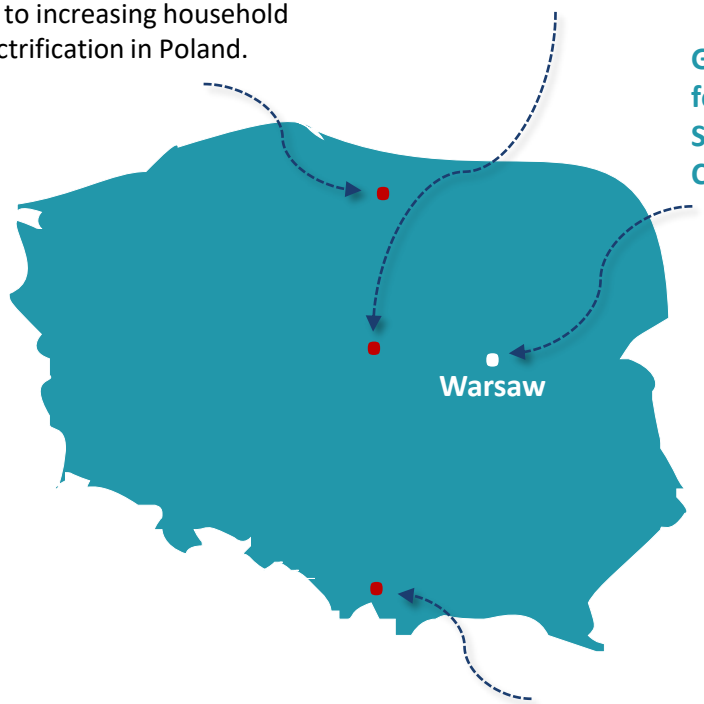
Grid-scale batteries and smart home storage continues to scale up. Poland procured 1.7 GW of storage and demand side-response in the 2023 capacity market auction and 2.6 GW in the 2024 auction (fifteen times more than in 2022). This success has shown that clean flexibility can deliver at scale, however recent rule changes will impact the ability of storage to participate in future auctions. With storage being one of the lowest cost and fastest-to-market sources of new capacity, scaling up clean flexibility will lead to sizable cost savings and system benefits and should continue to be a focus in Poland's transition.

Clean Flexibility in Social Housing

In **Szczytno** and **Ceglowo**, Soviet-era apartment buildings were retrofitted with PV panels on balconies and roofs, together with heat pump systems. Behind-the-meter solar plus heat pumps with thermal mass of buildings provides demand flexibility and fossil fuel independence, in addition to increasing household heat electrification in Poland.

Clean Flex from Cold Storage Facilities

In 2024 a new warehouse extension project was inaugurated in **Kutno**, featuring 2.5 MW of rooftop solar. With 20 smart inverters and automated digital controls, the facility aligns cooling demand with solar generation supporting grid stability, as well as providing energy resilience and grid independence for the company.



Government support for Clean Flex Solutions in Energy Communities

In June 2025 The Ministry of Climate and Environment of Poland selected 19 energy community projects, which will be supported by the National Recovery Plan (NRP), for a total value of over €200 million. Projects include energy storage, energy management systems and solutions improving the quality of grid parameters.

Connecting to Clean Flex Solutions: large storage

The 133 MW / 532 MWh Trzebinia utility-scale storage in **Chrzanów** will be the country's largest battery storage facility when it becomes operational in January 2027.

Clean Flexibility Opportunities and Challenges in Poland

Poland Clean Flexibility Opportunities

- **Renewable curtailment reduction:** Poland saw 731 GWh of renewable energy curtailed in 2024 – enough to power every home in Gdansk, Lublin and Katowice for a year. At the same time nearly 6% of Poland's electricity demand (almost 10 TWh) in 2024 required operator intervention to keep the grid balanced due to too much power trying to move through congested power lines, the highest share in the EU. Clean flexibility solutions are increasingly critical for helping the system and capturing the value that is lost through curtailment of renewable sources.
- **Utility-scale storage:** The December 2024 capacity auctions (2029 delivery) attracted 2.5 GW of battery storage (vs 1.7 GW in 2023 and 0.16 GW in 2022), at prices lower than gas plants.
- **Rooftop solar paired with storage**: The Moj Prad programme is a national initiative backed by €430 million in EU funds, now in its 6th year. It subsidizes solar and energy storage for individual, collective and virtual prosumers (producer-consumers) up to 20 kW. Over 1.5 million prosumers (almost entirely rooftop solar) fed 8.8 TWh of energy into the grid in 2024 (+27% vs 2023), over 4 times as much energy provided to Poland by cross border inflows. In 2024, 60% of Moj Prad applications included storage, up from just 11% the year before.

Poland Clean Flexibility Challenges

- **System legacy:** The fossil fuel phase-out is proceeding slowly, which hinders the scaling up of clean flexibility. The energy mix is still fossil-fuel heavy which produced over 65% of total electricity in 2024.
- **Regulatory uncertainty:** recent rule changes have impacted clean flexibility solutions directly (by derating the amount of remuneration allowed for battery storage systems relative to gas) and indirectly by increasing support for fossil fuel (the Polish government has introduced supplementary capacity auctions for 2025-2028 explicitly allowing high-emitting fossil fuel generation to compete for capacity contracts, subject to EC derogation).
- **Market maturity:** Poland's market design and regulations are still catching up with digital innovation. For example, modern smart metering policies are crucial for enabling clean flexibility. As of end 2024 only about 38% of Polish electricity consumers had a smart meter (vs a European average of about 60%, with leading countries like Italy or Spain at 100% penetration), indicating potential for quick wins in this area.

Bulgaria's Clean Flexibility Snapshot

Rapid renewable growth has increased flexibility needs, but clean flexibility is at early stages. While still at early stages, Bulgaria already demonstrates that implementation of renewable energy paired with clean flexibility has the potential to replace centralised, fossil-based energy systems, and offers lower-cost, lower-risk pathways than either coal or gas.

It is early days for clean flexibility in Bulgaria

Learn

2021-25

In 2023, Bulgaria passed laws that make electricity storage a separate, license-free activity with clear grid access, simplifying development for standalone and co-located projects. The pathway is complicated by heavy reliance on fossil-fired generation, legacy policies, and the need for grid modernization. Immediate opportunities are available, but clean flexibility solutions are at early stages.

Deploy

2026-30

Modernization is underway, with flexibility recognized as critical for both stability and efficient renewable integration. €1.5 billion of investments in renewable energy sources, electricity storage, and interconnection capacities are planned as part of Bulgaria's €6.2 billion recovery and resilience plan. Additionally, €860 million is allocated to reconstruct and strengthen the grid through the system operator's Greenabler project by 2030. Early pilots and regulatory adjustments can help the system adapt, but large-scale deployment of clean flexibility requires enabling policies.

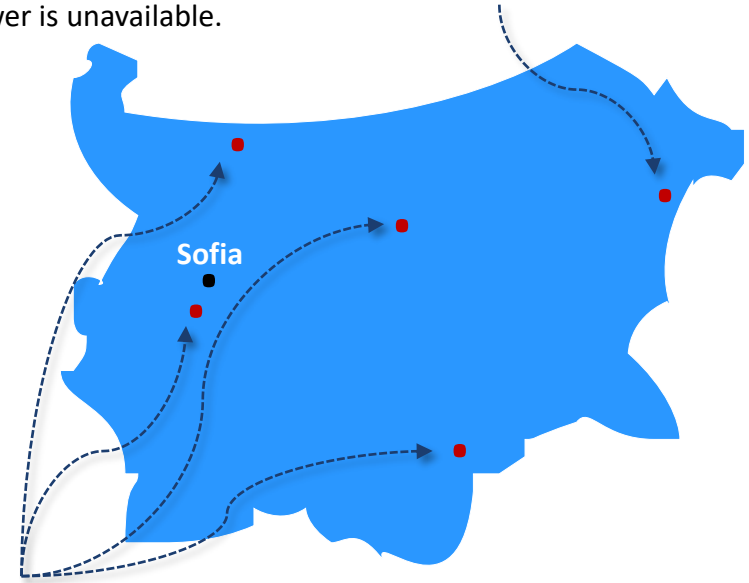
Scale

2031-50

The rise of new technologies and smart grids will provide a more dynamic and proactive approach to grid flexibility. Bulgaria will need a drastic increase in smart meter penetration and digital automation to benefit from this. Post 2030 active demand management and clean flexibility will become core elements of power systems, with local flexibility markets offering an alternative to more grid investment. Digitalization is needed to support clean flexibility scale-up and to deliver significant benefits across the power system.

Clean Flex Solutions in the Danube Region

The ESINERGY pilot project (2024) provided energy storage and management systems for a social enterprise producing glass in **Beloslav**. The pilot combines a solar PV system of 54.6 kW, as well as battery storage of 10 kWh paired with smart controls to enable flexible operations. The system can store enough electricity for several hours of backup or provide a stable supply for critical loads when grid power is unavailable.



Clean Flex Solutions for repurposed industrial sites

The Solaris Parks near **Pernik** (a hybrid solar-plus-storage energy project built on a reclaimed industrial site, with 32 MW of photovoltaic capacity + a 61 MWh battery storage system, is able to supply approximately 10,200 households with clean electricity. In **Selanovtsi** (60 MW solar + 107 MWh battery) hybrid system stabilizes output and enables green power delivery at fixed prices, proving that clean flexibility works within local distribution grids. The 2026 **Knizhovnik** project will combine 122 MW of solar and up to 200 MWh of battery storage. One of Europe's largest battery storage systems, the 124 MW/496 MWh battery system in **Lovech** is helping Bulgaria stabilize its power grid and advance the shift to renewables.

Clean Flexibility Opportunities and Challenges in Bulgaria

Bulgaria Clean Flexibility Opportunities

- **Deploying clean flexibility in tandem with renewable build-out:** Clean flexibility is a viable pathway to enable Bulgaria's energy transition. Bulgaria has an opportunity to deploy clean flexibility in parallel with renewable generation growth to avoid inheriting legacy issues, but market reforms must continue to realise this potential.
- **In 2025 large-scale storage initiatives have received enormous interest**: Nearly €600 million in EU-RESTORE funding has been secured and in April 2025 nearly 10 GWh of standalone large-scale battery storage was approved, comprising 82 projects (with 30 further projects in reserve).
- **A second RESTORE tender launched in September 2025**: funded under Bulgaria's National Recovery and Resilience Plan (NRRP) with plans to deploy at least 1.9 GWh of utility scale storage systems by 31 July 2026 to boost grid resilience.

Bulgaria Clean Flexibility Challenges

- **Generation expansion outpacing flexibility infrastructure**: Bulgaria's solar capacity doubled in 2023, adding over 2 GW to reach 3.9 GW total, but critical infrastructure such as energy storage, transmission capacity for exports, and system balancing capabilities, has not kept pace. One incident in 2023 with a surplus of 1,176 MW caused grid balancing issues across the entire continental EU synchronous zone, forcing costly redispatches in Germany, Austria, and Italy.
- **System legacy:** Bulgaria's power system was designed for large, dispatchable fossil plants, rather than distributed, variable renewables. Ongoing grid investments and integration with European platforms are gradually improving flexibility from a low base. However, fully unlocking clean flexibility will require a fundamental shift in system design from fossil-based dispatch to renewables-driven operations where storage, interconnectors, and demand response serve as the main balancing tools.

Turkey's Clean Flexibility Snapshot

Turkey's solar capacity reached 19.8 GW by the end of 2024, with small self-consumption installations making up 90% of new capacity. Grid flexibility in Turkey continues to constitute a critical structural challenge, with congestion and curtailment risks rising as intermittent generation sources increase.

Turkey can leapfrog legacy fossil power for clean flexibility

Learn

2021-25

Turkey's power system offers some immediate opportunities for clean flexibility, such as demand response and initial battery deployments, but market rules, grid codes, and incentives are still evolving. Turkey's new aggregator license allows companies to manage energy from smaller producers, consumers, and storage facilities into one portfolio, facilitating greater participation of clean flexibility solutions.

Deploy

2026-30

Turkey's clean flexibility market is poised for rapid growth, estimated at $1.7 billion USD (2024-2029). The Turkish government has ambitious smart meter rollout plans from 2026 and if deployment of demand-side response including space heating/cooling and smart EV charging is supported, this could reduce system peak demands in summer and winter by up to 10 GW by 2030. Building flexibility into development plans and market rules from the start avoids policy and legacy systems lock-in, creating an attractive environment to enable a modern and flexible power system.

Scale

2031-50

Turkey's goal of sustainably meeting rising energy demand and achieving its net-zero target by 2053 will require clean flexibility. Recent analyses estimate that total battery storage capacity of 7.2 GW/28.8 GWh could be reached by 2035. Green hydrogen electrolyzers are expected to play significant role in enhancing grid flexibility as well, projected to reach 5 GW by 2035. Scaling clean flexibility across multiple sectors will be crucial to support Turkey's clean energy transition.

Funding is available to develop Clean Flex Solutions in Turkey

Turkey's clean-flexibility strategy centers on large-scale storage, demand-side response, and smart-grid digitalisation. In mid-2024, Turkish development banks joined the World Bank in a $1 billion USD initiative to modernize electricity grids, expand distributed solar, and pilot battery storage programmes. In late 2024, a $1 billion USD complementary programme – backed by the Climate Investment Funds, European Bank for Reconstruction and Development, and World Bank – agreed to finance transmission and smart-grid upgrades, decentralized EV charging, distribution-grid digitalization, and 7.5 GW of national battery-storage capacity.

Antalya Metropolitan Municipality is operating a solar energy in Döşemealtı–Dağbeli with a 4.86 MW municipal power plant that supplies around 74% of the electricity needs of 51 agricultural irrigation cooperatives, helping reduce farmers' input costs. In Korkuteli–Bozova, four Antalya Water and Wastewater Administration owned solar power plants generate electricity that is offset through the distribution company to cover drinking water, wastewater services, and administrative building energy demand. The municipality has also installed rooftop solar and storage systems on its Service Building and Antalya Transportation Inc., with 330 kW of solar generation and 400 kW of energy storage capacity, becoming Türkiye's first municipality to both produce and store its own electricity while integrating clean flexibility into public infrastructure.

Integrated Storage Plants

Gaziantep Metropolitan Municipality is establishing a 58 MW solar power plant with integrated storage capacity, positioning itself as a pioneer in addressing energy storage challenges for municipal renewable energy projects in Turkey.

Eskişehir will soon have a 141 MW wind + 141 MWh battery storage with many other hybrid projects planned in other provinces.

Clean Flexibility Opportunities and Challenges in Turkey

Turkey Clean Flexibility Opportunities

- **Turkey's 2035 Renewable Energy Road Map presents an ambitious yet achievable plan:** With clean flex solutions Turkey can move from a centralized import and fossil-fuel dependent system to a self-balancing, renewable-driven national grid over the next decade. To achieve this will require a technological and a regulatory leap.
- **The need for storage has become a policy priority:** New regulatory frameworks encourage co-location of renewables and storage, accelerating storage deployment using complementary legislative and permitting reforms. The National Energy Plan targets 2.1 GW of installed battery storage by 2030 and 7.5 GW by 2035.
- **New rules to better enable co-located storage with renewables:** The Energy Market Regulatory Authority (EMRA) and the Ministry of Energy have drafted new rules to enable co-located battery storage facilities alongside renewable generation. Additionally, in late 2024 renewable energy auction regulations were amended to simplify and reduce permitting timelines from four years to under two years.
- **Opportunities exist with heating and cooling:** Heat electrification via heat pumps and district thermal storage has vast potential to cut natural gas reliance while providing multi-hour flexibility. Cooling demand is rapidly rising in Turkey, and because its peaks align with solar generation, it enables smart systems with storage to provide flexibility by shifting demand.

Turkey Clean Flexibility Challenges

- **Grid congestion and regional imbalances:** to harness the full potential of Turkey's rapidly expanding renewable energy capacity, investments in grid enhancement, digitalisation, and flexibility options are all essential. With around 34 GW of battery storage in the pipeline and additional pumped hydro projects under consideration, Turkey is well-positioned to strengthen system resilience and address regional imbalances.
- **Regulatory gaps:** electricity market rules and incentives for demand response, storage, and digital flexibility are still being developed. By delaying closure of fossil fuel assets, legacy capacity mechanisms act indirectly as barriers to more widespread adoption of clean flexibility solutions.
- **Bureaucratic burden:** notwithstanding the recent developments, permitting and timelines are slow and complex bureaucratic processes and regulatory requirements are a challenge for project deployment and grid improvement.
- **Consumer and aggregator engagement:** without widespread smart meter access and open market participation for aggregators, small consumers or distributed energy resources are locked out of participating in electricity markets, hampering uptake of clean flexibility in these sectors.

Technical Appendix II:
Detailed Overview of Clean Flexibility Solutions

Introduction

In this Appendix, we provide additional details on each of the clean flexibility solutions described in this report.

First, we provide detailed ratings of each solution's suitability for the flexibility use cases described in Section IV.

We then provide a more detailed description of each solution, including its flexibility use cases and its expected deployment out to 2050.

Deployment outlooks are based (where possible) on the *2024 Ten-Year Network Development Plan* (TYNDP) from the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Network of Transmission System Operators for Gas (ENTSOG). The TYNDP includes a *Baseline Scenario*,* which is a 2030 snapshot of the aggregated system plans of European countries.

Looking forward, the TYNDP's *Global Ambition Scenario* envisions a future built on large, centralised projects and cross-border energy trade. By contrast, the *Distributed Energy Scenario* highlights a more local, community-driven approach powered by households, small renewables, and flexible demand. Both scenarios provide forecasts for 2035, 2040 and 2050.

*Note that the *Baseline Scenario* is referred to as the "National Trends Scenario Baseline" in the body of the TYNDP report.

N/A	Less Able			More Able
○	◔	◑	◕	●

Detailed Use-Case Suitability of Clean Flexibility Solutions

		Daily			Peak Events	Inter-day		Seasonal	Cost	Technological Maturity
		Real-time Balancing (milliseconds to seconds)	Daily Ramping (seconds to hours)	Congestion Mgmt. (mins to hours)	Capacity Events (hours)	Forecast Error (hours to days)	Inter-day balancing (days to weeks)	Seasonal energy balancing (weeks to months)		
Generation	Variable RES	◔	◔	◔	◔	○	○	○	€€	■■■■
	Dispatchable RES	◕	●	●	◕	◕	●	●	€€€	■■■□
	Renewable H_2	◕	●	●	●	◑	●	●	€€€€	■□□□
Demand-side flexibility	BTM batteries	◕	◕	○	◕	○	○	○	€	■■■□
	Electric Vehicles	◕	◕	○	◕	○	○	○	€	■■□□
	HVAC	○	○	○	◕	○	○	○	€	■■■■
	Behavioural DSR	○	○	○	◕	○	○	○	€	■■■■
	C&I DSR	◑	◔	◔	◕	○	○	○	€	■■■■
Storage	Supercapacitors & Flywheels	●	○	○	○	○	○	○	€€€	■■■■
	Grid batteries	●	●	●	◕	◕	○	○	€€	■■■■
	Pumped Hydro	◕	◕	●	●	●	◔	○	€€€	■■■■
	LDES	○	◑	◕	●	●	◕	◑	€€€€	■□□□
Coupling	Power-to-X	○	◑	◕	◕	◔	◔	●	€€€€	■□□□
Grid	Interconnectors	◑	◕	●	◑	●	◑	◕	€€€	■■■■
	GETs	○	○	◕	◑	○	○	○	€	■■■□

Generation

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◔	◔	○	○	€€	■■■■

Variable Renewables

Variable renewable energy sources generate clean electricity vital for the energy transition and can provide limited flexibility.

Overview

Variable renewables, such as solar and onshore/offshore wind, are the backbone of Europe's clean power transition, delivering abundant, low-cost electricity but with output that depends on weather and time of day.

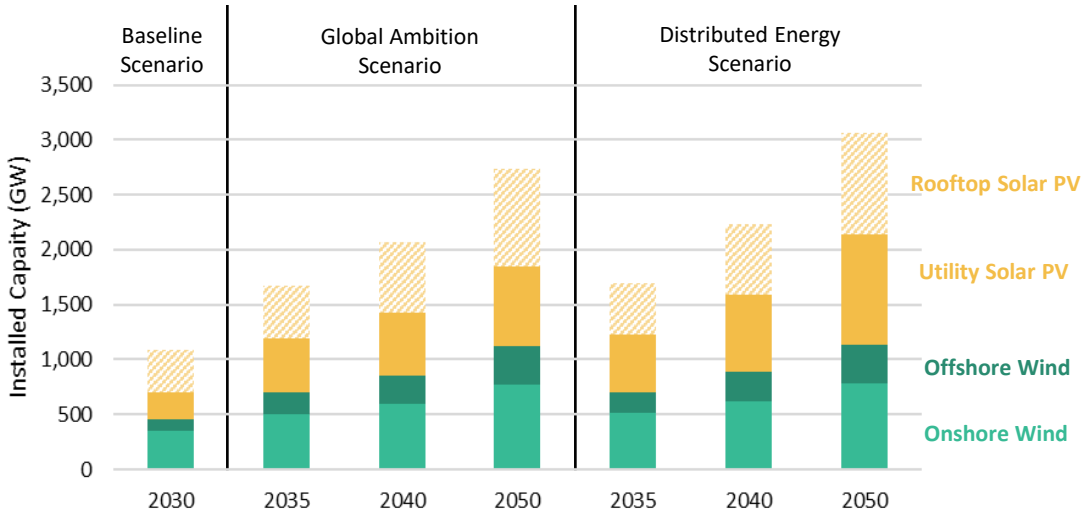
Flexibility Use Cases

Variable renewables can provide flexibility by curtailing production or smoothing weather-induced fluctuations by actively controlling their output. Additionally, aggregations of solar or wind farms provide ancillary services by controlling active power or injecting/absorbing reactive power to balance the grid in real-time, allowing them to offer many of the same ramping, reserves, inertia, and voltage support services as thermal gas plants.

Deployment Outlook

By 2050, variable renewables are expected to provide the bulk of generation in Europe under all scenarios, led by wind (onshore and offshore) and solar. Projections from ENTSO-E (shown below) anticipate over 1,000 GW of variable renewables deployment by 2030 with the need to grow to over 2,500 GW in 2050 to meet EU climate goals. Key enablers are improved energy densities from technology improvement and continued cost declines driven by economies of scale.

OUTLOOK FOR VARIABLE RENEWABLES GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG. Assumed 40% share of utility solar PV in 2030 based on SolarPower Europe. Note that rooftop solar PV is typically unable to provide curtailment flexibility for the bulk power system.

Generation

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
●	◕	●	●	€€€	■■■□

Dispatchable Renewables

Dispatchable renewable energy sources are highly effective in providing clean flexibility services to the grid.

Overview

Dispatchable renewable energy sources such as hydropower, geothermal, and concentrated solar power with storage provide controllable, on-demand generation that ensures reliability and balances variable renewables.

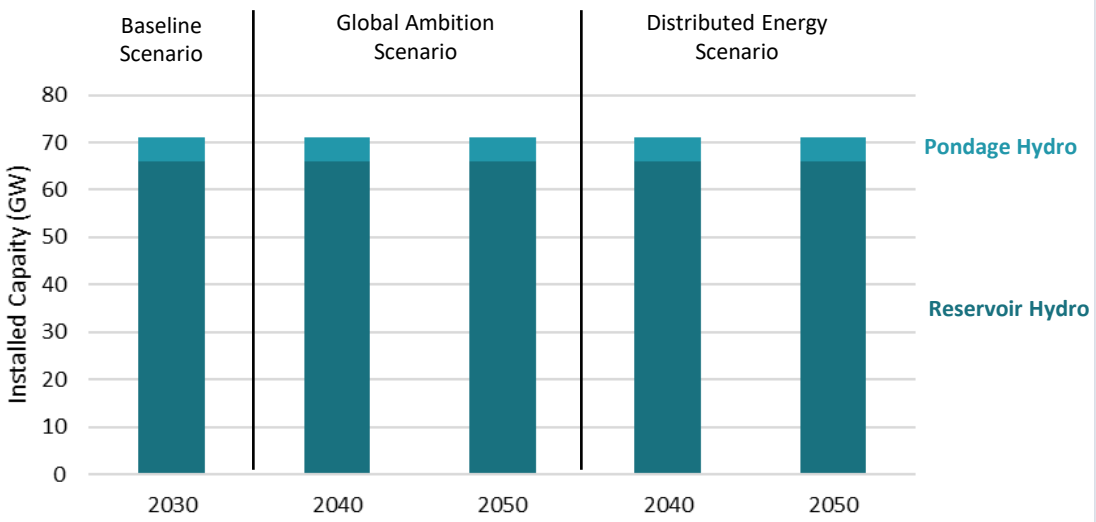
Flexibility Use Cases

Dispatchable renewables have very similar capabilities as gas plants without the associated carbon emissions. They provide firm, low-carbon capacity that can be called upon when variable renewables output is low. Hydropower reservoirs can ramp quickly, offering balancing services and support like frequency and voltage regulation. Geothermal and CSP with thermal storage add predictable, controllable output. Their ability to provide on-demand, carbon-free energy reduces reliance on gas peakers and ensures system stability during stress events.

Deployment Outlook

While deployment of dispatchable renewables capacity is expected to be much smaller than variable renewables, dispatchable renewables will continue to be required for flexibility and reliability. An important source of dispatchable renewables is hydropower (non-pumped). ENTSO-E predicts hydro capacity to remain stable to 2050. Key enablers include upgrades of existing infrastructure to install more efficient turbines, funding and risk-sharing for capital-intense upgrades, and more streamlined permitting practices.

OUTLOOK FOR DISPATCHABLE RES GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Generation

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
●	●	◕	●	€€€€	■□□□

Renewable Hydrogen

Renewable hydrogen storage paired with turbines that run on renewable hydrogen could be important in a zero-carbon future to address seasonal energy needs and absorb excess renewables.

Overview

Renewable hydrogen can be burnt to produce electricity and water vapor, and could play an important role in utilising excess renewables that would otherwise be curtailed. Over time, these clean fuels could be used to generate electricity and ensure supply during periods of low variable renewables generation.

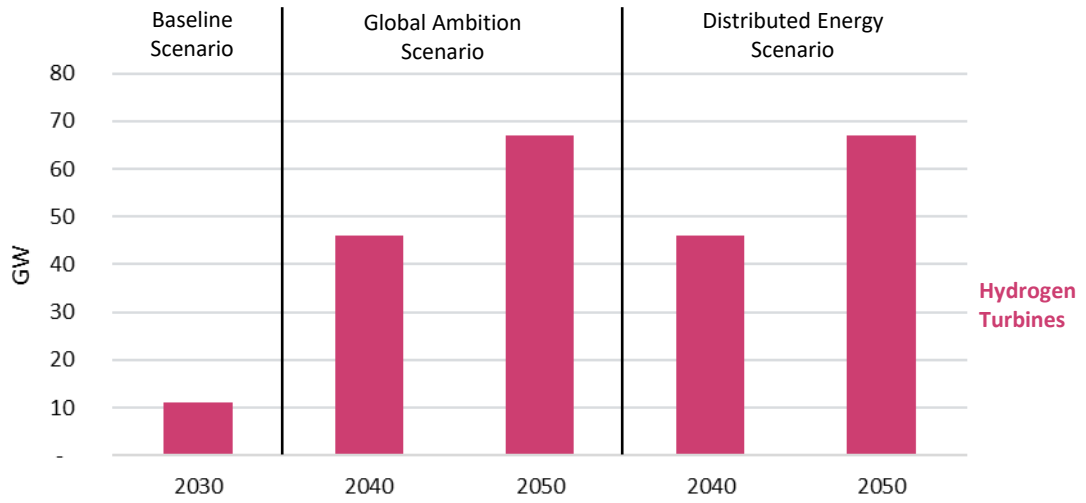
Flexibility Use Cases

Given the substantial costs and infrastructure upgrades necessary, it is unlikely that renewable hydrogen would replace gas on a like-for-like basis. Instead renewable hydrogen is needed primarily to address seasonal flexibility needs (but can help with other shorter-term needs though as an expensive alternative). To achieve seasonal balancing, excess electricity from variable renewables can be used to produce hydrogen via electrolysis, which can be stored in bulk over long periods of time. Later, these clean fuels can be used to generate electricity and ensure supply during periods of low variable renewables generation.

Deployment Outlook

Hydrogen electrolysis is still technologically immature, but significant growth in capacity is expected between 2030 and 2050. Much of this projected growth arises from the replacement of gas generation capacity with combined cycle turbines running on renewable hydrogen. However, the immaturity and high cost of this technology may see actual deployment lag these projections if alternate capacity solutions are favoured. Key enablers include improved electrolyser technology and supply chain buildout to achieve technological/market maturity, and clear regulatory and safety frameworks.

OUTLOOK FOR RENEWABLE HYDROGEN GENERATION CAPACITY



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Demand-side Flexibility

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◑	◕	○	○	€	■■■□

Behind-the-Meter (BTM) Batteries

BTM batteries allow customers to store self-generated or low-cost electricity, reducing energy bills and providing valuable flexibility to the grid through demand shifting and peak-load reduction.

Overview

BTM batteries are storage systems on the customer side of the electricity meter (e.g., at homes, businesses, or industrial sites) where they store on-site generation or grid power for later use.

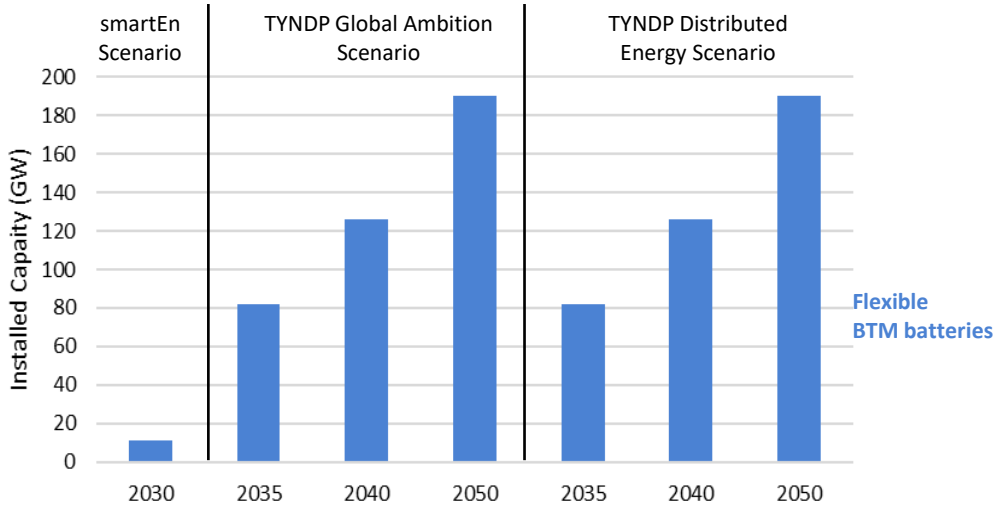
Flexibility Use Cases

BTM batteries allow customers to shift excess on-site generation (or low-cost grid power) to peak hours in the evening or export this power to the grid when it's most valuable. This lowers customers' bills while reducing stress on the grid. They can also provide system-wide demand-side flexibility by dispatching during peak-price hours. Their low storage durations (typically 2–3 hours) limit their applicability to meet longer-duration flexibility needs.

Deployment Outlook

BTM batteries are expected to grow substantially in Europe. The TYNDP did not model BTM batteries in its Baseline Scenario, but smartEn anticipates roughly 10 GW of flexibility potential by 2030. By 2050, ENTSO-E expects almost 200 GW of BTM battery capacity to be required, exceeding the total installed capacity of natural gas generation today. Key enablers are the uptake of battery-electric vehicles and related expansion of battery production, and support schemes or market designs that enable provision of wholesale services.

OUTLOOK FOR BTM BATTERY FLEXIBILITY GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG and 2022 smartEN 2030 Demand-Side flexibility report.

Demand-side Flexibility

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◑	◕	○	○	€	■■□□

Electric Vehicles (EVs)

Electric vehicles not only reduce transport emissions but can also provide valuable flexibility to power systems through smart charging and vehicle-to-grid (V2G) or building (V2B) services.

Overview

EVs eliminate tailpipe emissions by using electric motors powered by onboard batteries that are charged from the grid or on-site generation. Smart EV chargers can be controlled to modulate their charging in response to system conditions, while V2G technology enables EVs to inject stored electricity back onto the grid.

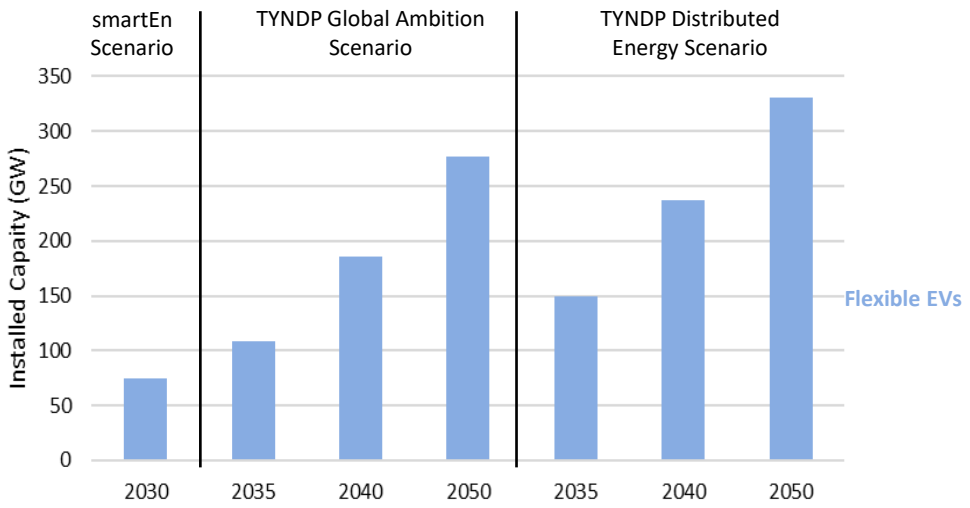
Flexibility Use Cases

Smart chargers provide similar daily load shifting functionality as BTM batteries. With bi-directional V2G technology, EVs can act as distributed storage assets, charging during times of high renewable generation and discharging power back to the grid during peak demand or emergency events.

Deployment Outlook

The economics of EVs relative to internal combustion engine vehicles continues to improve, and there is both increasing national policy support for EVs and an EU requirement for all new cars from 2035 onwards to be electric. The TYNDP did not model EVs in its Baseline Scenario, but smartEn projects 75 GW of flexible capacity to be provide by EVs by 2030. Key enablers are expanded battery production, increased deployment of charging infrastructure, and technology/software development for smart charging and bi-directional charge control.

OUTLOOK FOR EV FLEXIBILITY GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG and 2022 smartEN 2030 Demand-Side Flexibility report.

Demand-side Flexibility

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
○	◕	○	○	€	■■■■

Heating, Ventilation & Air Conditioning (HVAC)

Heating, Ventilation & Air Conditioning (HVAC) technologies can pause/shift duty loads to provide flexibility. This potential will increase with heating and cooling electrification.

Overview

HVAC technologies (including heat pumps, electric resistance heating, and AC units) comprise a significant share of customer electricity demand and can provide flexibility by altering their heating and cooling schedules.

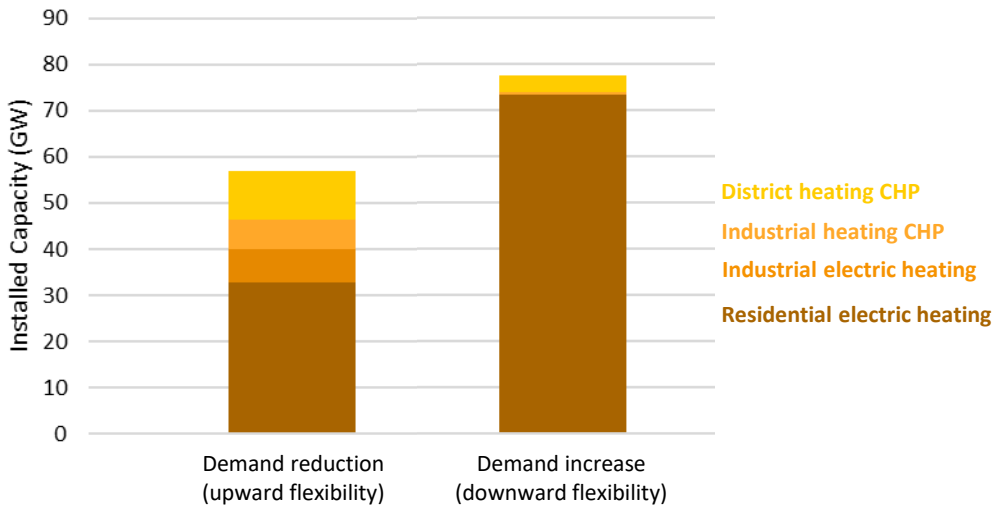
Flexibility Use Cases

Smart thermostats and switch-based controls can be used to shift heating/cooling loads outside of peak hours. Aggregated across multiple customers, HVAC loads can reduce peak demand during capacity events. These responses are both duration-limited (i.e., unsuitable for long-term flex needs) and event-limited (since customers prefer minimal interruptions).

Deployment Outlook

The shift from gas to electric heating systems represents a significant expansion in HVAC flexibility potential, with 50–63% of residential heating expected to be from fully electric heat pumps by 2050. European AC adoption is expected to roughly double between 2025 and 2050. Key enablers are greater technology development (especially for efficiencies in cold-weather), more smart controls and automation, and support schemes that shorten pay-back periods to enable replacement of gas-based heating with electric heating (e.g. heat pumps).

PROJECTED HVAC DSR CAPACITY IN 2030



Notes: Based on Brattle analysis of 2022 smartEn 2030 Demand-Side Flexibility report.

Demand-side Flexibility

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
○	◕	○	○	€	■■■■

Behavioural Demand-Side Response

Behavioural demand-side response provides incentives for customers to reduce their electricity consumption during peak events.

Overview

Behavioural demand-side response refers to incentives to encourage customers to adjust their consumption to support the system. Customers may be incentivised to shift/lower their consumption in response to electricity rates with high-priced "peak" and low-priced "off-peak" periods (often referred to as time-of-use rates). Other solutions influence customers' behaviour by offering payments or information to reduce consumption in peak hours.

Flexibility Use Cases

Given uncertainty in customer behaviour and ability to respond to incentives, behavioural demand-side response is best suited for limited peak flexibility use cases where short-duration, infrequent reductions in load are needed to keep the system in balance.

Deployment Outlook

One form of behavioural demand-side response, time-of-use rates, is seeing increased (although heterogenous) uptake across Europe. Key enablers are continued roll-outs of digital smart meters, better design of tariff incentive structures, and education/sharing of successful programmes.

In 2023, **27% of European households were on dynamic electricity contracts**[1]

In Italy, **20 million households** are on dynamic rates,[2] while in Spain **10 million households**[3] (40%) are on dynamic hourly pricing rates

1. ACER (2024), Active consumer participation is key to driving the energy transition – how can it happen?
2. Benini et al. (2015), Italy – Impact of the enforcement of a time-of-use tariff to residential customers in Italy
3. Uxo, Chapter 7 – National responses to the energy price hike: the case of Spain

Demand-side Flexibility

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◔	◕	○	○	€	■■■■

Commercial & Industrial Demand Response

Commercial & industrial (C&I) customers are large-scale electricity consumers that can reduce their load to provide flexibility.

Overview

Industrial facilities with advanced energy management systems can automate and control their electricity use for process loads such as cooling loads, process heat, and pumping. Similarly, commercial buildings can reduce electricity loads such as refrigeration at retail businesses.*

*Note that many commercial facilities also provide flexibility through HVAC control, which is captured on an earlier page.

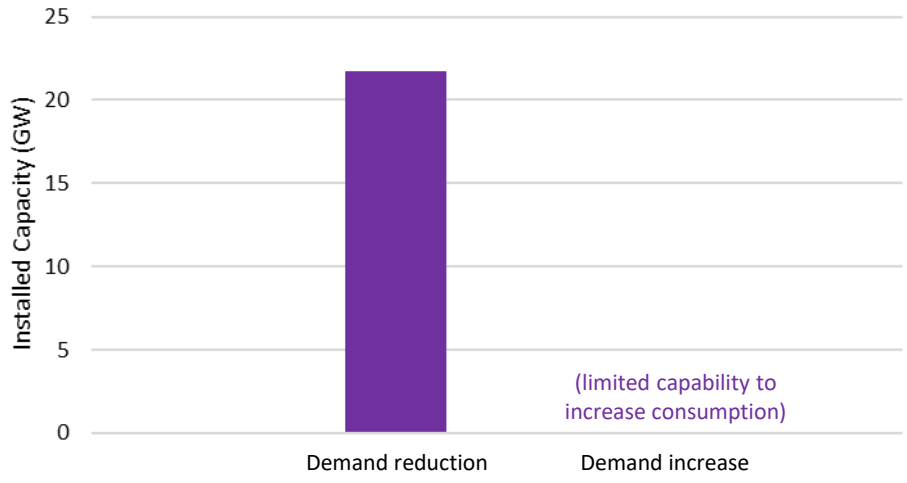
Flexibility Use Cases

C&I demand response has demonstrated its ability to provide capacity reductions during peak events in Europe, the UK, Australia and the US. Given the high opportunity cost of disrupting C&I operations, demand response is only suitable for intraday, short-duration flexibility needs.

Deployment Outlook

Growth in C&I demand response is largely dependent on the development of appropriate price signals and market participation pathways. By 2030, it is expected that over 20 GW of C&I load will be available to provide flexibility. Key enablers include greater uptake of smart controls and automation, more retail tariffs that incent demand-side flexibility, and greater coordination in operations between TSOs and DSOs.

PROJECTED C&I DEMAND RESPONSE CAPACITY IN 2030



Notes: Based on Brattle analysis of 2022 smartEn 2030 Demand-Side Flexibility report.

Storage

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◔	○	○	○	€€€	■■■■

Flywheels and Supercapacitors

Supercapacitors and flywheels are extremely fast-responding sources of clean flexibility.

Overview

Supercapacitors are devices that store energy in an electric field, which enable them to discharge extremely quickly, unlike batteries that store energy chemically. Flywheels are mechanical spinning masses that store rotational kinetic energy. Both technology types can inject and absorb power in milliseconds.

Flexibility Use Cases

Supercapacitors and flywheels have extremely fast charge and discharge capability but have a very short durations. These technologies are useful to provide short-duration needs like frequency regulation, stability, and inertia.

Deployment Outlook

Deployment of supercapacitors and flywheels in Europe has been relatively modest and mostly contained to pilot projects in England, Scotland, Wales, Ireland, and Germany. However, there are expectations that deployments will grow as system operators gain more experience with the technologies. Key enablers include increased renewable generation and inverter-based resource penetration, expanded manufacturing capabilities, and greater deployment/industry experience of low-intertia grid operations in power systems.

Supercapacitors

Skeleton Technologies (a leading European supercapacitor manufacturer) is investing more than $223 million in Europe's largest supercapacitor factory, near Leipzig in Germany. The new plant is due to enter operation in 2025 with an initial capacity of 2.4 gigawatts per year with the potential to expand to 6.6 GW per year.

Flywheels

Great Britain's National Energy System Operator (NESO) has lead European deployment of flywheels with at least five projects online as of 2022 and plans for additional expansions to provide net zero solutions to grid stability issues.

Storage

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
●	◕	◔	○	€€	■■■■

Grid batteries

Utility-scale battery storage technologies are highly flexible and dispatchable assets that can meet most short-duration needs.

Overview

Utility-scale batteries (typically Li-ion, but also sodium-ion, Li-sulphur, solid-state batteries, and other chemistries) store electricity from the grid to be dispatched when it is more valuable. Typical storage durations for utility-scale batteries range from 2–4 hours with current power ratings of up to 300 MW.

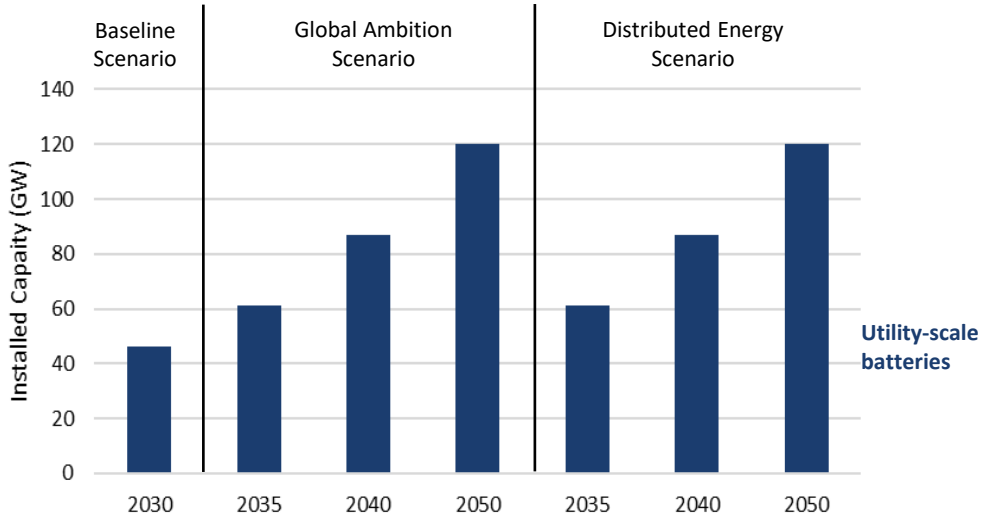
Flexibility Use Cases

Batteries can meet supply/demand imbalances on varying time scales. Their ability to respond within seconds makes them highly effective in providing frequency and voltage control services. They are also useful for daily balancing by shifting solar and wind output to peak demand periods.

Deployment Outlook

Utility-scale batteries are expected to be the main driver of battery energy storage systems (BESS) growth in Europe in the coming years. SolarPower Europe (2025) estimates that battery installation volumes will be more than five times greater in 2029 compared to 2024. By 2050 the TYNDP estimates BESS storage will need to reach 120 GW to meet climate goals. Key enablers include better inverter technology (e.g. grid-forming inverters) to enable more system support services, expansion of battery production, and wholesale market designs that allow for revenue stacking.

OUTLOOK FOR EUROPEAN BATTERY GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Storage

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
●	●	◕	○	€€€€	■

Pumped Hydro

Pumped hydro can store large amounts of energy, making it an attractive technology for providing clean flexibility where grid batteries are unable to during inter-day needs and longer duration daily needs.

Overview

Pumped hydro storage stores electricity by pumping water into a reservoir and releasing it at a later time through hydropower turbines to generate electricity. Pumped hydro can typically store 6–12 hours worth of power.

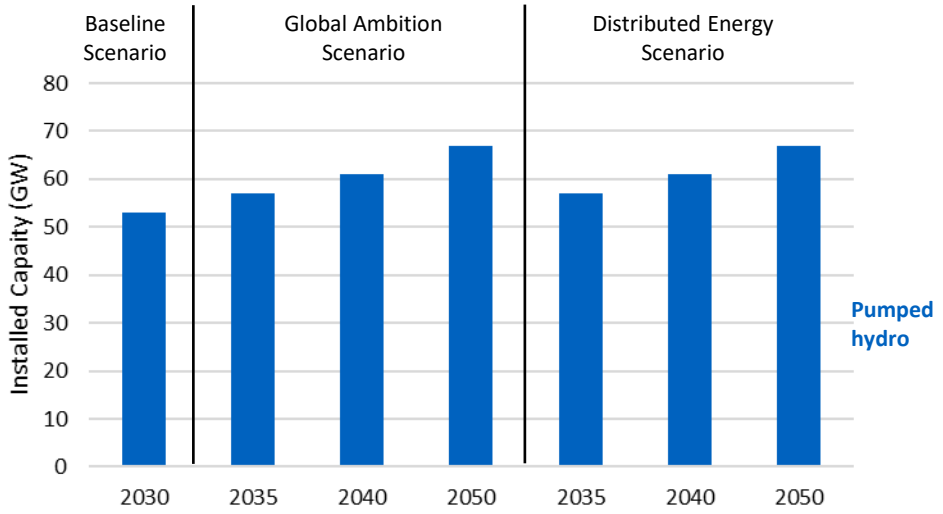
Flexibility Use Cases

Pumped hydro can typically generate electricity at its maximum power output for 6–12 hours, making it suitable to address daily and peak flexibility needs as well as some shorter-duration inter-day needs. Pumped hydro does not have the storage duration necessary to provide seasonal flexibility.

Deployment Outlook

Pumped hydro is an important form of LDES in Europe, with the largest installation being the Cortes – La Muela complex in Spain (1,293 MW pumping capacity). ENTSO-E forecasts steady growth in pumped hydro to be necessary over the 2030 to 2050 horizon. Key enablers will be adding pumped storage capability to existing reservoirs, availability of funding and risk-sharing for capital-intense upgrades, and more streamlined permitting practices.

OUTLOOK FOR PUMPED HYDRO GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Storage

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◐	●	●	◐	€€€€	■□□□

Long Duration Energy Storage (LDES)

LDES can charge/discharge electricity for many hours and even days to provide critical system flexibility and ensure reliability during prolonged renewable excesses/shortfalls.

Overview

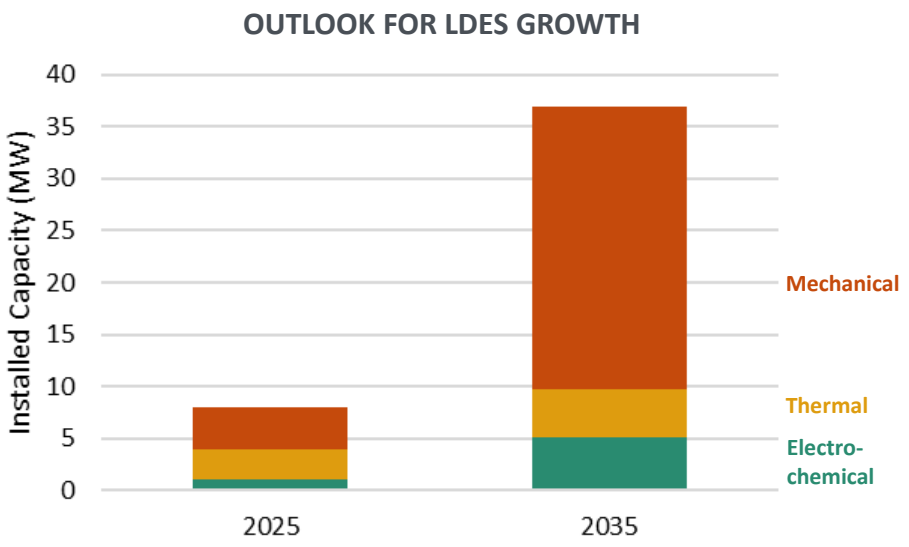
LDES technologies include electrochemical battery technologies, compressed and liquid air energy storage (CAES/LAES), novel mechanical storage, thermal storage, and others. Each of these technologies can deliver bulk energy shifting, energy adequacy, and grid resilience beyond the capabilities of short-duration batteries.

Flexibility Use Cases

LDES is well placed to support flexibility needs arising from day-ahead forecast error and inter-day, longer-duration needs. Intraday LDES (less than 36 hours duration) can provide greater availability during peak events while Inter-day LDES (36 hours +) can help to ensure reliable supply during extended periods of low renewables generation.

Deployment Outlook

LDES deployment is limited today but is anticipated to increase significantly over the next decade. Part of this increased deployment will depend on technological innovations that enable LDES solutions to be delivered at lower cost. Key enablers will be funding and risk-sharing for capital-intense and early-stage novel technology, ramping up manufacturing capabilities, and technological progress regarding round-trip charge/discharge efficiency, energy density, and lower costs.



Notes: Based on Brattle analysis of 2024 Annual Report from LDES Council (2035 projection builds on 2025 data using global growth trends).

Sector coupling

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◐	◕	◔	●	€€€€	■□□□

Power-to-H_2 and Power-to-Heat

"Power-to-X" processes store electricity in alternate energy carriers. Using electricity to produce hydrogen or heat provides grid flexibility by absorbing excess electricity.

Overview

Electrolysis can be used to produce green hydrogen from electricity and water, while thermal batteries use electricity to generate heat that is stored in a thermal storage medium—this heat can be stored for 1–2 days before being used for industrial applications and can help decouple heat demand from electricity demand.

Flexibility Use Cases

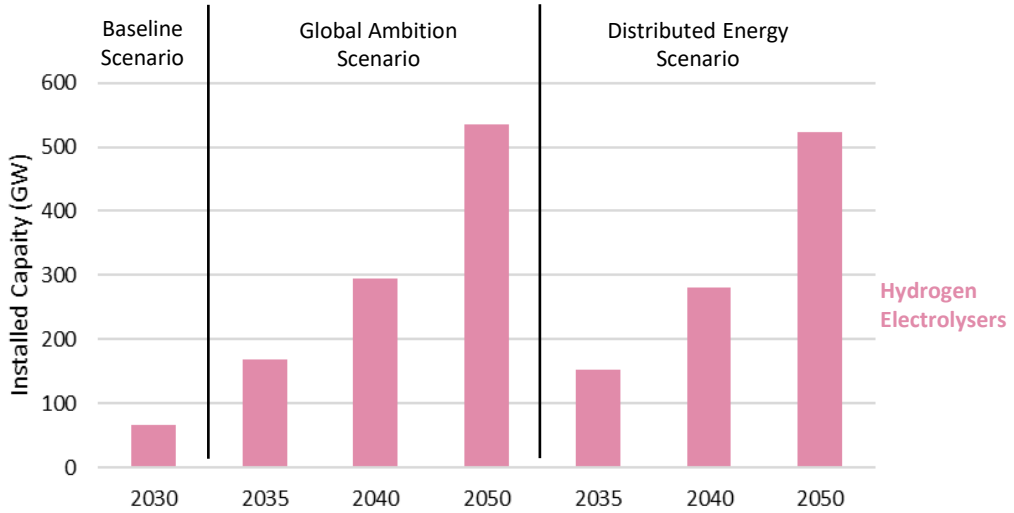
Both these "power-to-X" technologies can be flexible in a similar manner as industrial demand response by reducing electricity consumption during periods of system stress. However, their primary role is to increase demand to absorb excess renewable electricity production. Additionally, if hydrogen or stored thermal energy is used at a later time to produce electricity, this coupling can address inter-day or seasonal energy balancing needs.*

*Note that the ratings for applicability to different flexibility needs reflect the fact that not all electricity stored as hydrogen or thermal energy will be used to produce electricity at a later time.

Deployment Outlook

The IEA expects that by 2030, 32% of global hydrogen electrolyser capacity will be located in Europe. The REPowerEU plan requires 80 to 100 GW of electrolyser capacity by 2030. Currently, ENTSO-E forecast suggests that Europe is not on track to meet this target, with significant growth required for electrolyser capacity between now and 2050 to meet climate goals. Key enablers include improved technology and realisation of economies of scale through deployments, development of H_2-compatible technologies and retrofits to stimulate demand, greater sector coupling between electric, heat, and gas networks.

OUTLOOK FOR HYDROGEN ELECTROLYSER CAPACITY GROWTH



Notes: Based on Brattle analysis of 2024 TYNDP from ENTSO-E and ENTSOG.

Grid

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◕	◑	◕	◕	€€€	■■■■

Interconnectors

Interconnectors enable more flexibility by balancing diverse weather and demand patterns across regions and due to enhanced controllability from High-Voltage Direct Current (HVDC) lines.

Overview

Interconnectors, the transmission lines connecting Member States, are a key enabler of flexibility and are among the fastest, proven ways to add clean flexibility at scale.

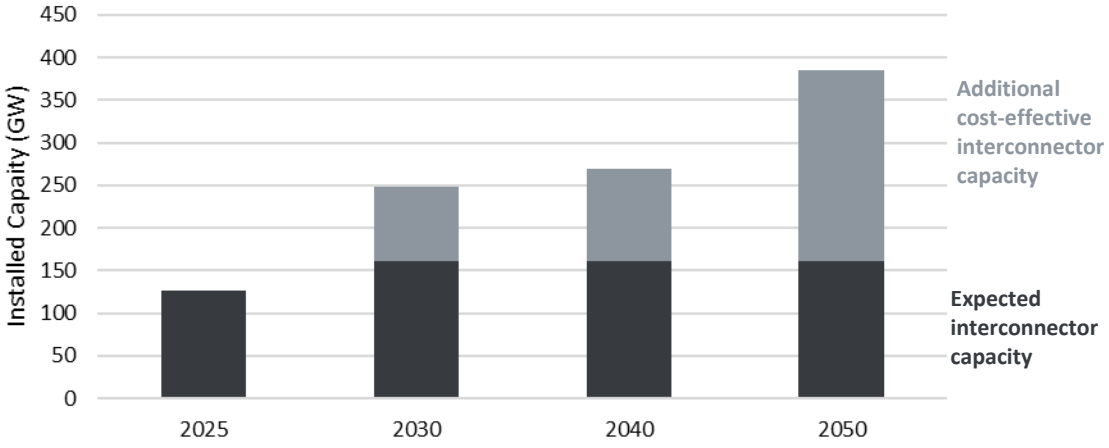
Flexibility Use Cases

Interconnectors let surplus energy flow where it is most needed, smoothing out weather intermittency, reducing renewable curtailment, and enabling less reliance on fossil backup generation. HVDC lines enable greater controllability to provide ramping and frequency support. Additionally, HVDC interconnectors can provide grid services including synthetic inertia and black-start capability to recover the power system in the case of an outage.

Deployment Outlook

The EU is aiming for each Member State to have an interconnection capacity equal to at least 15% of their installed generation capacity by 2030 and further plans for expansion of the interconnectors out to 2050. Key enablers include ensuring ability of interconnectors to participate in wholesale markets, greater market coupling and harmonised trading rules, streamlined permitting, and more regional coordination and planning for cross-border transmission expansion.

OUTLOOK FOR EUROPEAN CROSS-BORDER TRANSMISSION CAPACITY



Notes: Based on Brattle analysis of 2024 TYNDP Infrastructure Gaps Report from ENTSO-E and ENTSOG.

Grid

Daily	Peak Events	Inter-Day	Seasonal	Cost	Maturity
◔	◑	○	○	€	■■■□

Grid Enhancing Technologies (GETs)

GETs enable electric utilities to maximise the value and extract more capacity & flexibility out of the existing transmission grid without building new lines.

Overview

GETs include Dynamic Line Ratings (DLR), Power Flow Control Devices, Topology Optimisation, Advanced Grid Monitoring, and High-Performance Conductors (HPC). They use advanced control and monitoring devices to operate the grid more efficiently.

Flexibility Use Cases

GETs enable greater visibility and use of real-time operational and weather data to monitor and adjust transmission line ratings to system conditions, instead of relying on static ratings. Together, the hardware and software of GETs can increase capacity on the grid, reduce network congestion bottlenecks, improve reliability during peak demand or outages, and make it easier to integrate more flexible generation and load.

Deployment Outlook

While the benefits of GETs are very location and application-specific, experience shows that these technologies often can be deployed in less than a year and reliably and cost-effectively enhance existing grid capacity by 10% to 40%. GETs are increasingly being deployed as priority technologies in transmission planning processes due to their low cost and deployment timelines, as illustrated below. Key enablers include regulatory approvals to allow GETs to be treated as standard grid investments, improved incentive structures for TSOs and DSOs to use non-wire alternatives, and integration of GETs into market and operational planning tools.

OUTLOOK FOR GRID ENHANCING TECHNOLOGIES DEPLOYMENT

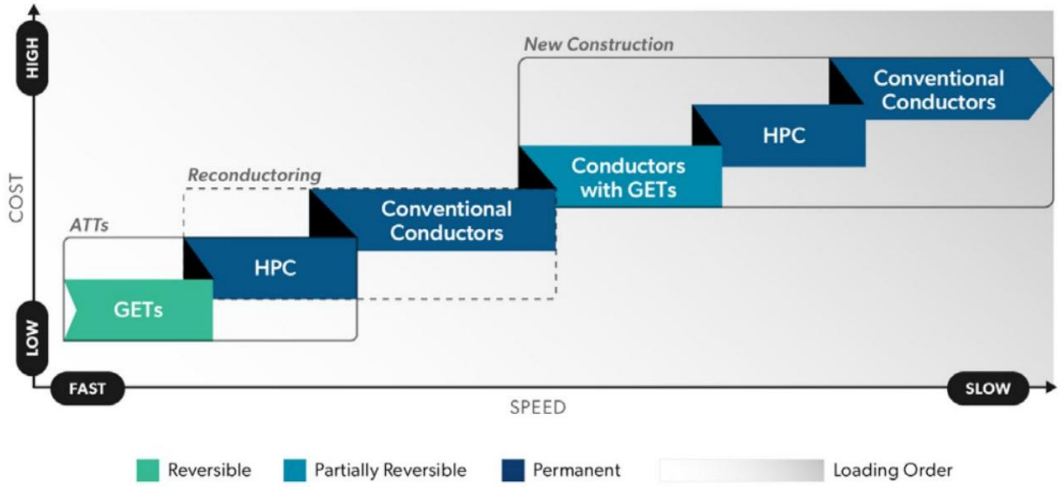


Image source: Tsuchida et al., Incorporating GETs and HPCs into Transmission Planning Under FERC Order 1920, April 2025.

Clarity in the face of complexity

Brattle