Clean flexibility is the brain managing the clean power system

There are nine clean flexibility tools that can be combined into a portfolio to fully harness renewable energy and ensure our electricity is clean every hour, not just the sunny and windy hours.

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About

This report explains the concept of clean flexibility and its role in a clean electrified energy future. It outlines the nine tools that enable clean flexibility to optimise the use of renewable electricity and ensure grid stability, detailing how they work, their strengths and limitations.

Executive Summary

Clean flexibility is the brain of the clean power system

Clean flexibility uses a variety of tools to fully harness renewable energy and ensure grid stability as we transition to a clean, electrified energy future.

Renewables are the heart of a clean power system, but clean flexibility is the brain that keeps it running smoothly, constantly balancing supply and demand in real time to maintain grid stability. It makes the most of renewable electricity by **storing** some of that renewable electricity for later use, **shifting** non-critical demand to periods of abundant supply and **sharing** it across an expanded grid where it's needed more. At the same time, clean flex optimises **supply** from fully flexible generation assets that can easily turn off when there's excess solar and wind.

These tasks—shift, store, share and supply—are managed through a portfolio of clean flexibility tools. As the share of wind and solar grows, the clean flex brain starts building its portfolio starting from the most basic and easy to use tools, gradually adding more complex tools that allow it to handle increasing levels of wind and solar.

Each step builds on the previous one and strengthens the portfolio, but the optimal mix will vary depending on the specific power system. Some systems may achieve a clean power supply by relying mostly on the earlier, cheaper steps, while others may need the more advanced but also more costly tools to reach their goals.

As fossil fuels are phased out, the old way of supplementing gaps in renewable electricity supply by turning on and off coal and gas power plants is coming to an end. The transition to a clean, electrified energy future is entering a critical phase of rapid acceleration and we need clean flexibility to make our electricity clean every hour, not just the sunny and windy hours.

01 Store

There are four key clean flexibility tools that enable electricity to be stored across minutes, hours and days to save excess renewable power for times of higher demand. Pumped hydro storage and enhanced hydropower store energy using water. Batteries store electricity chemically. Long-duration energy storage comprises several types of innovative technologies. Green hydrogen can store electricity over weeks and months, but high energy losses and high capex costs make the economics challenging.

02 Shift

Two clean flexibility tools help consumers shift demand to times of abundant renewable supply and lower energy bills: "peak shaving," with one-time payments for reducing consumption during critical periods, and "smart electrification," which adjusts EVs and heat pumps to use energy during windy and sunny hours.

03 Share

Grids and interconnectors are an essential clean flexibility tool that enable places with excess renewable supply to share it.

04 Supply

There are two clean flexibility tools that ensure all generation assets are as flexible as possible so that supply can be optimised in the most cost-efficient way for the grid. The first step is improving the ability of fossil plants, even with CCS, to switch off when not needed. The second is to make wind and solar smarter and easier to optimise to grid needs.

Clean flexibility is how we ensure our electricity is clean every hour, not just the sunny and windy hours. Beyond storage and grids, there is a whole portfolio of tools. Most of these clean flexibility tools are already being deployed across the world and bringing considerable benefits such as lower electricity bills for consumers.

Kostantsa Rangelova
Global Electricity Analyst, Ember

Store

Storing renewable electricity for later use

Electricity can be stored across minutes, hours and days to save excess renewable power for times of higher demand.

Four clean flexibility tools enable storing renewable electricity for later use. Pumped hydro storage and enhanced hydropower are essential first steps in building a clean flexibility portfolio, where geographic conditions allow for their development. In a second step, batteries are also an essential tool for any clean power system, with especially strong complementarity with solar. For power systems that want to achieve very high wind and solar shares, long duration energy storage is a key third step, especially if they do not have much pumped hydro potential. Finally, some power systems may need to also develop green hydrogen in a fourth step, if long duration energy storage proves to be insufficient.

Step 1: Pumped hydro storage and enhanced hydropower

Pumped hydro storage uses electricity to pump water to an elevated reservoir when electricity is abundant and cheap, and releases it back down through turbines to produce electricity like a traditional hydropower plant when demand is high. Pumped hydro storage and traditional hydropower plants are already widely deployed across the world and can provide clean flexibility. Existing ones often need upgrading and optimising to improve their responsiveness through digital controls and automation. Existing hydro power plants could be retrofitted to boost their storage capacity, for example through more efficient equipment and heightening of existing dams. Retrofits are expected to account for almost half of all hydropower capacity added over 2020-2030 globally.

Strengths

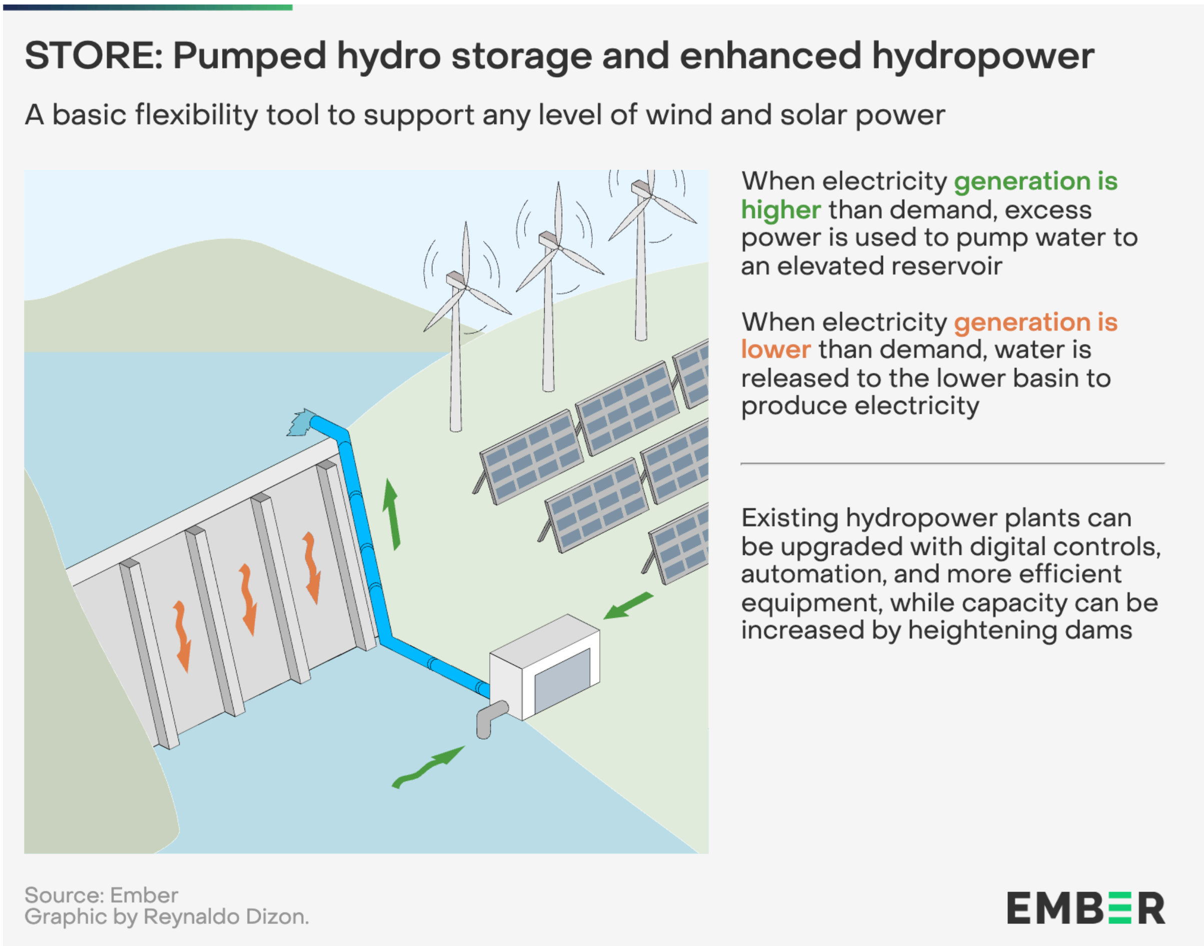
- A well-established technology
- Low operating costs
- Long lifespan
- Enhancements to existing infrastructure can be a low-cost solution with limited environmental impact
- Can store energy for long periods, including across entire seasons
- High complementarity between solar and hydro, as droughts often coincide with sunnier weather

Limitations

- New infrastructure needs significant upfront investment and long construction periods
- Depends on favourable geographical conditions
- There is limited untapped potential globally; much of the remaining potential exists in Asia, sub-Saharan Africa and Latin America
- Environmental and social concerns, including inundation of land, barriers to fish migration, potential resettlement of local communities and water competition with other sectors
- Climate change risks (e.g. droughts)

It is already happening

This year, China completed the commissioning of the world's largest pumped storage station, at 3.6 GW. The earlier stages of its development enabled venues for the Beijing Winter Olympics to achieve 100% green electricity supply. Now at its full capacity, it is expected to save 480,000 tons of standard coal and reduce carbon dioxide emissions by 1.2 million tons each year.



Step 2: Batteries

Batteries can store excess renewable energy – during periods of abundance and low demand – as chemical potential energy and release it when supply is scarce. Lithium-based batteries dominate the market, but many other types of battery are in development.

Strengths

- Fast response time and versatility, making them ideal for a high number of applications – from stabilising the grid within milliseconds to providing daily flexibility
- A game changer for solar, allowing solar-generated electricity to be used whenever it

is needed most, either during the day or even through the night

- The cost of lithium batteries has plummeted as they've become easier to produce
- Rapid innovation means new battery technologies like LFP (eliminating the need for nickel and cobalt) and sodium-ion (eliminating the need for lithium) are quickly entering the market, bringing massive improvements to costs and performance
- Modular technology that can be deployed anywhere in the world; at grid-scale (up to several GW), as well as at smaller scale (a few kW) in a residential or commercial building to enhance consumption of energy produced on site

Limitations

- Current market-ready battery technologies become uneconomical for storing large amounts of energy because more battery cells are required to do so
- Battery manufacturing uses critical minerals like lithium, cobalt and nickel. Supply chain disruptions and geopolitical challenges are being mitigated faster than initially expected by increased recycling, expanded mining and refining in diverse regions, and the rapid shift towards new battery technologies like LFP that use considerably less critical minerals.

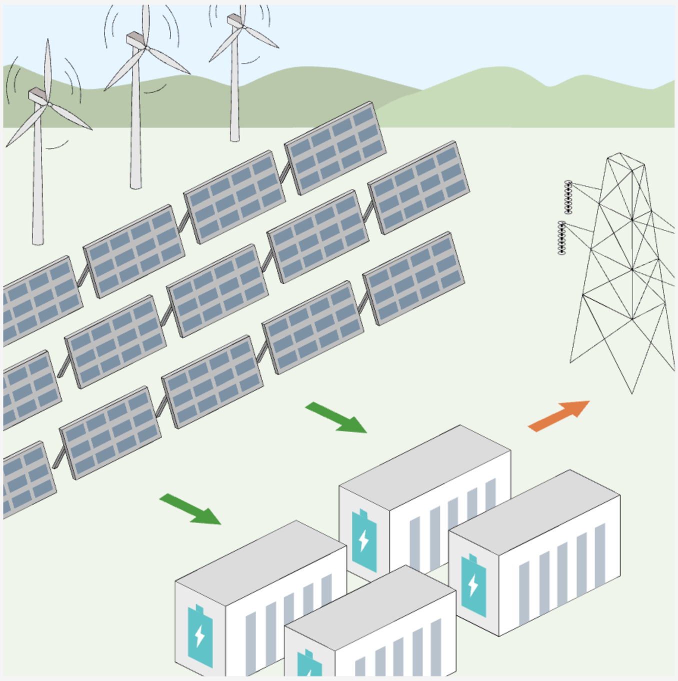
It is already happening

In California, battery capacity was expanded thirteen-fold in five years, reaching 10 GW in April 2024, and batteries are already moving solar power from daytime to evening, making gas power plants redundant. During one evening in 2024, batteries were the single biggest source of electricity flowing into the California grid. The role of gas in the evening peak in April 2024 has been roughly halved compared to April 2021, and more batteries are continually being deployed.

As of October 2024, a total of 16 GWh of grid-scale battery storage has been tendered in India, while 211 MWh is already operational. The cost of battery storage has fallen significantly, from $450/kWh (Rs 75 million/MW for 2-hour storage) in 2021 to around $200/kWh (Rs 32 million/MW for 2-hour storage in 2024). Ember analysis found that a15% annual decline in the BESS costs would avoid new coal capacity additions after 2030.

STORE: Batteries

A basic flexibility tool to support any level of wind and solar power



When electricity generation is higher than demand, excess power is stored.

When electricity generation is lower than demand, the deficit in power can be filled by releasing the stored energy.

In California, battery capacity was expanded thirteen-fold in five years, reaching 10 GW in April 2024 and batteries are already moving solar power from daytime to evening, reducing reliance on gas power plants.

Source: Ember
Graphic by Reynaldo Dizon.

Step 3: Long duration energy storage

New LDES technologies are capable of storing and discharging electricity for days and even up to several weeks. This includes newer battery technologies such as flow batteries and metal-anode batteries, but also concepts such as thermal storage, gravity-based storage and compressed air storage.

Strengths

- Able to address the infrequent but critical times when wind and solar output is very low for extended periods (known as "dunkelflaute"), making them essential for power systems dominated by wind and solar
- Modular technologies that can be scaled up faster and are not as limited by

geographical conditions as pumped hydro

Limitations

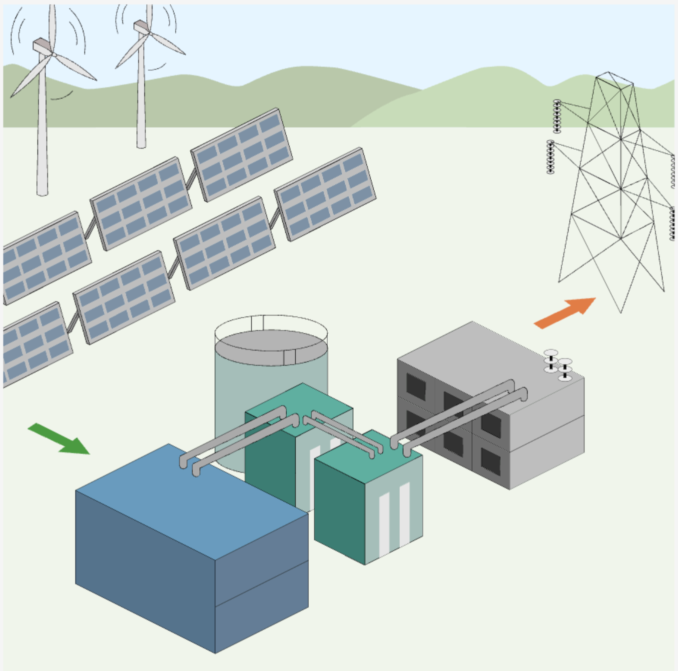
- Still in the early stages of research and demonstration, and may not start scaling up quickly or cheaply without initial government support.

It is already happening

In China, a compressed air storage project was brought online in April 2024, with a capacity of 300 MW / 1500 MWh. The facility ensures power supplies for between 200,000 and 300,000 local homes during peak consumption periods. By replacing coal power use during these peak hours, it is projected to save about 189,000 tons of standard coal and reduce carbon dioxide emissions by approximately 490,000 tons per year.

STORE: Long duration energy storage*

A long duration energy storage technology to support a high level of wind and solar power



When electricity generation is higher than demand, excess power is used to compress air which is stored underground in caverns or tanks.

When electricity generation is lower than demand, air is released and expanded which drives turbines and generates electricity.

In China, a compressed air storage project was brought online in April 2024, with capacity of 300 MW/ 1500 MWh. The facility ensures power supplies for between 200,000 and 300,000 local homes during peak consumption periods.

Source: Ember
*Illustration uses compressed air storage as an example of long duration energy storage but there are many other concepts being developed such as thermal storage and gravity-based storage.
Graphic by Reynaldo Dizon.

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Step 4: Green hydrogen

Green hydrogen is hydrogen gas produced from water through electrolysis using renewable electricity. It can then be burned as a fuel for power generation, sometimes after further conversion into ammonia. However, more than two thirds of the initial electricity supply is lost in conversions, making hydrogen a viable storage solution only when there is no cheaper option.

The biggest flexibility use for green hydrogen may not be in storing renewable electricity for later use in the power sector, but rather in absorbing excess electricity supply from wind and solar in times of structural oversupply such as peak solar hours. Low-utilisation electrolysers are well placed to take cheap excess renewable electricity to convert into green hydrogen for other non-power purposes such as steelmaking and ammonia production.

Strengths

- Allows excess renewable energy to be stored over long periods and used when needed
- Able to address the infrequent but critical times when wind and solar output is very low for extended periods (known as "dunkelflaute"), though it will be in competition with long duration energy storage

Limitations

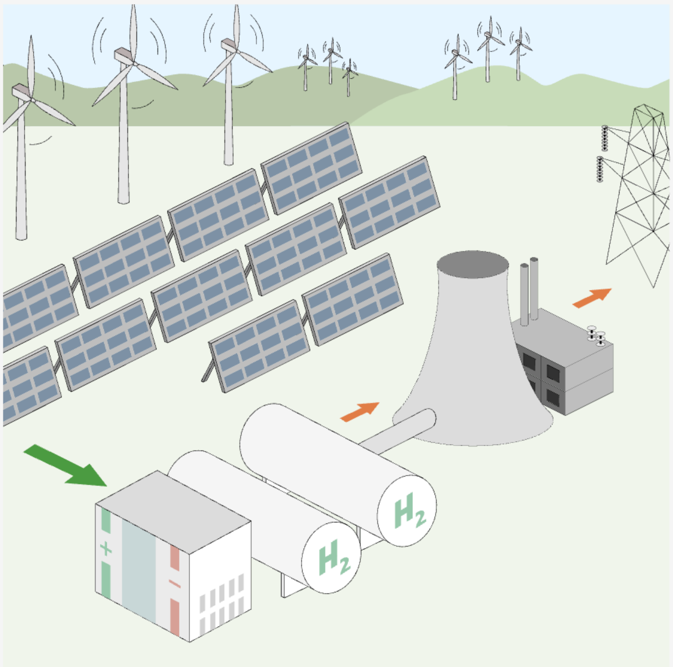
- Energy losses during electrolysis and the burning of hydrogen for power generation mean that only around two thirds of the initial electricity is lost in conversions, making hydrogen extremely inefficient as electricity storage.
- Water competition with other sectors
- Hydrogen is more challenging to transport and store than traditional fuels, requiring significant investment
- There are some concerns regarding hydrogen leakage, especially in transport and storage due to safety and climate issues. The global warming potential of hydrogen leakage could be equivalent to about 100 million tonnes of CO2 per year by 2050.
- Green hydrogen costs aren't dropping as quickly as expected, leading to low demand. Electrolysers remain too expensive to operate profitably during only peak solar and wind hours.

It is already happening

In 2023, around $2.9 billion USD were invested in electrolyser projects under construction — five times the amount invested in 2022. Despite this significant increase, large-scale deployment is still not taking place.

STORE: Green hydrogen for electricity storage

An inefficient flexibility tool to support a high level of wind and solar power



An **abundance of renewable electricity** can be used to separate hydrogen from water through electrolysis; resulting green hydrogen can be stored.

When electricity generation is **lower than demand**, the green hydrogen can be burned to generate electricity.

Note: when making hydrogen, more than two thirds of the initial electricity supply is lost in conversions, making it a viable "storage" solution only when there is no cheaper option.

Source: Ember
Graphic by Reynaldo Dizon.

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Shift

Shifting demand to periods of abundant supply

It's beneficial for grid stability to enable consumers to take advantage of windy and sunny hours with the cheapest electricity, helping them to reduce their bills.

Demand-side flexibility – which is the ability of consumers to adapt their demand according to external signals, such as periods of low power prices – is an essential part of clean flexibility. There are two clean flexibility tools for shifting non-critical demand to windy and sunny hours. The first and easiest to implement step, 'peak shaving', is with one-off payments for individual actions at critical times. The second step is smart electrification: systematically adapting demand patterns by ensuring key technologies like EVs and heat pumps optimise their consumption patterns to windy and sunny hours on a daily basis.

Step 1: Peak shaving

Alerts are sent to consumers to offer payments to alter their consumption – either to reduce their use if electricity is in short supply, or to increase their use if renewable electricity is so bountiful it risks being wasted.

Strengths

- Works well with existing infrastructure and can be implemented across a wide range of consumers, and can be implemented with a month's notice
- Reduces electricity price shocks (spikes and negative price crashes)
- Gives the grid extra security at times of extreme stress in a way that is cheaper and cleaner than back-up generators
- Brings financial benefits for consumers, for those willing to participate

Limitations

- Effectiveness and scale are limited by how many users participate and their willingness to reduce demand and at what price

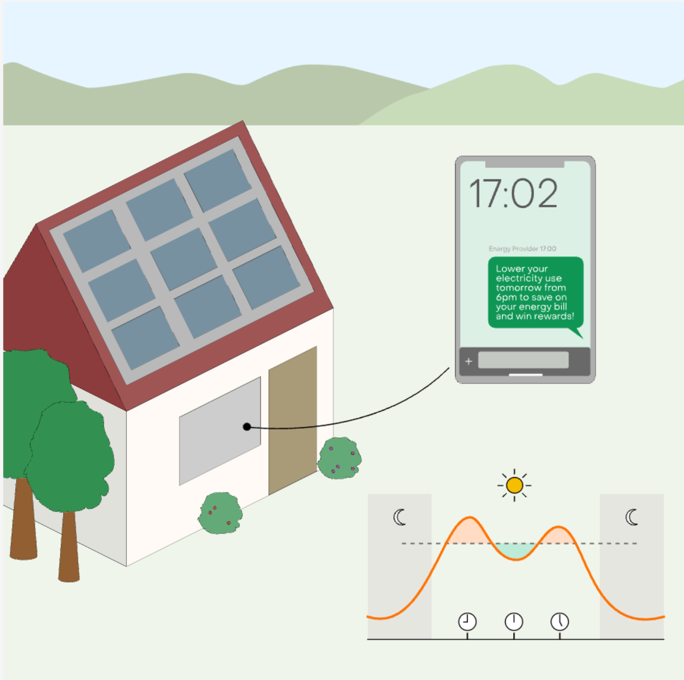
It is already happening

In India, consumers can sign up for text alerts to reduce demand during system stress, earning rewards for participation and helping to reduce the need for spare coal power plants.

In Australia, the use of peak shaving during a demand peak in May 2022 reduced demand by 40 MW from several large consumers – a minor fraction of total peak load of several thousand MW. While some gas and diesel generators were still used, even this small-scale demand response helped avoid additional reliance on generators that would have charged $10,000–$15,000 per MWh, helping to reduce the peak wholesale price by $1,270 per MWh or about a tenth.

SHIFT: Peak demand shaving

A basic flexibility tool to support any level of wind and solar power



When electricity generation is expected to be lower than a predicted spike in demand, consumers are offered incentives to reduce consumption.

When electricity generation is higher than demand, consumers are encouraged to use more electricity to prevent excess energy from being wasted.

In India, consumers can sign up for text alerts to reduce demand during system stress, earning rewards for participation and helping to reduce the need for spare coal power plants.

Source: Ember
Graphic by Reynaldo Dizon.

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Step 2: Smart electrification

Electricity demand is rising, and much of this rise comes from new electric vehicles, heat pumps and air conditioners. There is an opportunity to ensure that these technologies are built in a way that effortlessly shifts demand patterns to better match windy and sunny hours, supporting consumers to access the cheapest electricity.

Simple time-of-use tariffs mean consumers get cheaper electricity to, for example, charge an electric car during the middle of the day when there is solar electricity, or to set a heat pump outside of expensive peak demand hours.

More advanced dynamic tariffs can unlock more flexibility. Digital technologies allow the demand from thousands of EVs, heat pumps and other technologies to be aggregated and managed simultaneously in a virtual power plant. Additionally, vehicle-to-grid technology can even enable EVs to feed electricity back into the grid.

Smart grids are a key enabler of smart electrification. Building smart grids requires the roll-out of smart metres, sensors, automated controls and world-class modelling to handle data to ensure real-time two-way communication between producers and consumers of electricity.

Strengths

- Reduces electricity prices for the consumer
- Is a low cost solution that leverages an already growing sector
- Can provide flexibility across the day
- Automation allows for quick response times, making this a much more agile and sophisticated measure than peak shaving

Limitations

- Depends on supplier initiative to offer dynamic tariffs and on consumer involvement and education
- Requires smart grid infrastructure, both hardware (e.g. smart metres, smart chargers) and administrative (e.g. time-of-use tariffs, data sharing protocols)
- Concerns regarding personal data protection and cybersecurity

It is already happening

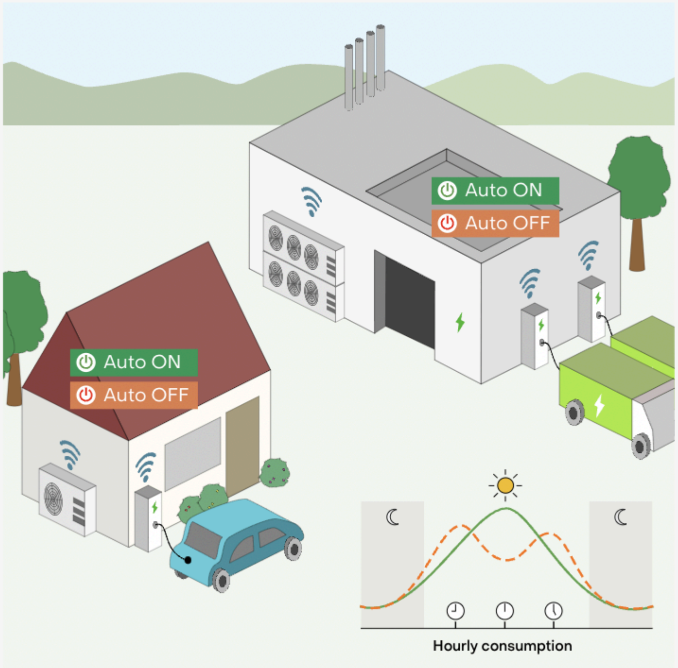
In Norway, consumers can earn €70–100 per year by simply enabling smart charging of their EV, on top of any potential cost savings from dynamic tariffs.

In the UK, switching to a tariff specifically designed for heat pump owners reduces customers' electricity expenditure by 18% of annual energy costs (£318 per year) on average.

Since June 2023, India has implemented special tariffs that offer 10-20% cheaper electricity to commercial and industrial consumers during solar hours, covering the eight sunniest hours of the day, while electricity is made more expensive during peak demand hours.

SHIFT: Smart electrification

An advanced flexibility tool to support a high level of wind and solar power



Technologies respond to dynamic pricing:

- Electric vehicles and heat pumps used when electricity supplies are abundant
- Smart metres and sensors automate technologies to turn down during expensive peak demand hours

In Norway, consumers can earn €70–100 per year by simply enabling smart charging of their electric vehicles, on top of any potential cost savings from avoiding higher electricity prices.

Source: Ember
Graphic by Reynaldo Dizon.

Share

Sharing excess renewable electricity through grids and interconnectors

At any one point in time as weather conditions vary, there will be places of excess renewable electricity, and places with less electricity supply. Grids and interconnectors bring the excess supply to places with less electricity.

Enhancing existing grid infrastructure and building new lines is critical to ensure that cheap renewable electricity is delivered to the place where it is needed most at any given time.

Grids and interconnectors

Grids are networks of power lines that carry electricity from where it is produced to where it is needed. Interconnectors are cross-border power lines linking national power grids.

Together they allow two types of sharing. Structural sharing enables places with high wind or solar potential to fully develop it and share it with places that need cheap electricity. The second type of sharing is temporal, which helps exploit variations in weather conditions and electricity demand across different provinces of a larger country and across neighbouring countries. Interconnectors also allow several countries to jointly develop large scale regional renewable projects, e.g. offshore wind. Longer distance cables may also have a role: north-south cables in Europe can help share wind (more in the north) with solar (more in the south), and east-west cables can help share solar as the sun moves around the Earth.

Strengths

- Reduce price volatility and lower generation costs through optimised, more efficient price signals
- Makes the most of currently available renewable electricity at any moment
- Allow more renewable generation capacity to be built and reach consumers
- Interconnectors diversify the generation base available to a country and optimise the use of generation assets across connected countries
- Relatively small investments in grid-enhancing technologies can deliver similar benefits to building new lines and at a significantly lower cost

Limitations

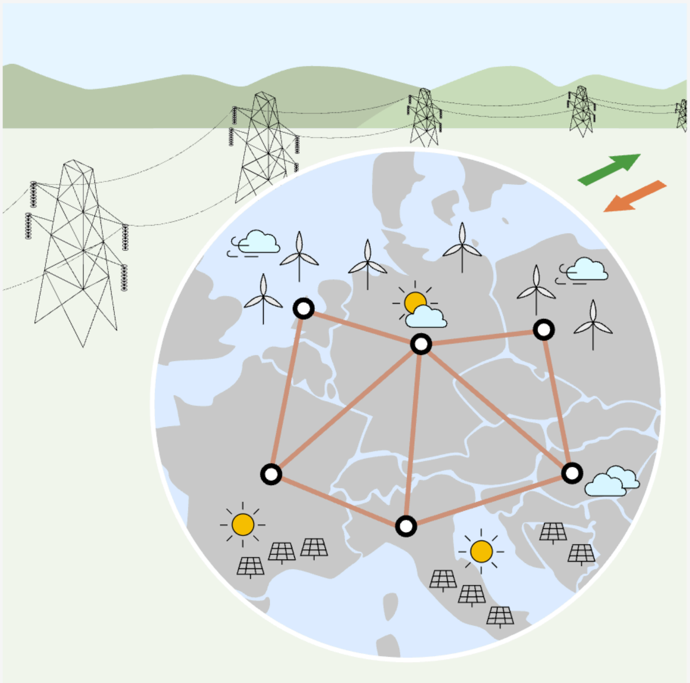
- New power lines, especially interconnectors, need significant upfront investment and a long construction period
- Interconnectors require synchronisation of market rules and a high degree of political trust

It is already happening

The European electricity system is the world's largest interconnected grid, linking 39 national electricity systems. In 2021 alone, cross-border trade delivered €34 billion of benefits from lower price volatility than with isolated national markets. At the EU level, interconnectors could cover 15% of the daily and 33% of the monthly flexibility needs by 2030.

SHARE: Wider grid networks and interconnectors

Essential flexibility tools to balance variable wind and solar power across a wider geographic area



Grids and interconnectors carry electricity from areas with excess renewable energy to regions with higher demand.

When weather patterns turn, supplies may be lower than demand, relying on inflows of electricity from other countries or elsewhere in the grid.

The European electricity system is the world's largest interconnected grid, linking 39 national electricity systems. In 2021 alone, cross-border trade delivered €34 billion of benefits from lower price volatility than with isolated national markets.

Source: Ember
Graphic by Reynaldo Dizon.

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Optimising supply from fully flexible generation assets

As the share of wind and solar in electricity supply grows, all sources need to be able to switch off to make room for the cheapest electricity while keeping the grid stable.

As the share of wind and solar in the electricity system grows, a first crucial step to maximise the available renewable electricity and keep costs low is to ensure fossil plants can turn down and operate only when really needed, even if they have CCS. As wind and solar supply becomes more abundant, electricity systems with high or very high share of wind and solar may face structural periods of oversupply when there is no additional economically competitive use for that excess supply. In this case, the ability of wind and solar to switch off temporarily to stabilise the grid becomes cost-effective.

Step 1: Improve downward fossil flexibility

With wind and solar growing fast, fossil plants will need to operate more flexibly – turning on and off more quickly, and operating less and less each year. This is done by technical improvements, like increasing ramping rates and lowering minimum stable load, and by removing contractual obligations on how much power they produce, like power purchase agreements or take-or-pay clauses in fuel contracts that require the fossil plant to pay for fuel even if they don't take delivery. In the longer term, if some fossil or biomass power plants with CCS are maintained in the system to play a minimal role as a strategic reserve for moments of extreme adverse conditions, they also need to be built to be as flexible as possible, providing electricity only when all other cheaper and cleaner flexibility tools have been exhausted.

Strengths

- The ability for fossil plants to quickly turn on and off is, at least in the short term, essential for ensuring solar and wind achieve their two main aims of creating cheaper electricity and reducing emissions

Limitations

- Removing contractual obligations can be challenging from a legal perspective
- CCS technology has existed for decades with little progress in costs and deployment
- It is a transitional solution that will increasingly have to compete with cheaper batteries and long duration energy storage technologies
- CCS technology does not capture all carbon dioxide emissions, while carbon dioxide leakage and long-term storage are key concerns, together with upstream methane emissions from gas extraction
- Risks continuing reliance on fossil fuels – for many countries, imported – or on biomass with all its social, ecological and energy security downsides

It is already happening

India is implementing new operational practices and technical improvements, lowering the minimum load at which its thermal power plants can operate safely from 70% to 55% of their capacity, saving an estimated $311 million annually in system costs. A roadmap for a 40% load target has been published by the Central Electricity Authority.

Step 2: Smarter wind and solar

The huge potential for cheap renewable electricity requires us to shift from a mindset of limited fuel to abundant supply. In systems with low or medium share of wind and solar, wasting renewable electricity in curtailment is a sign of a lack of flexibility. However, in systems with very high shares of wind and solar, depending on the local context, some curtailment may be cost effective when other flexibility resources like storage and demand shifting have already been employed.

Because wind and solar are so cheap, it makes sense to overbuild, knowing that there will be some periods when the system produces more electricity than can be used or stored, resulting in some limited waste or curtailment. It can be more cost effective than building additional, more expensive flexibility tools aiming for near zero curtailment. This means ensuring wind and solar can be turned off smartly, for short periods — from milliseconds up to a few hours on rare occasions – when supply exceeds demand. Wind and solar can also be built smarter. For example, building east-west facing solar panels may generate less power per panel but will produce more electricity in the morning and evening, and better match demand patterns.

Strengths

- A small amount of easy and cheap curtailment helps enable a high share of wind and solar on the grid
- Reduces price volatility, especially negative prices

Limitations

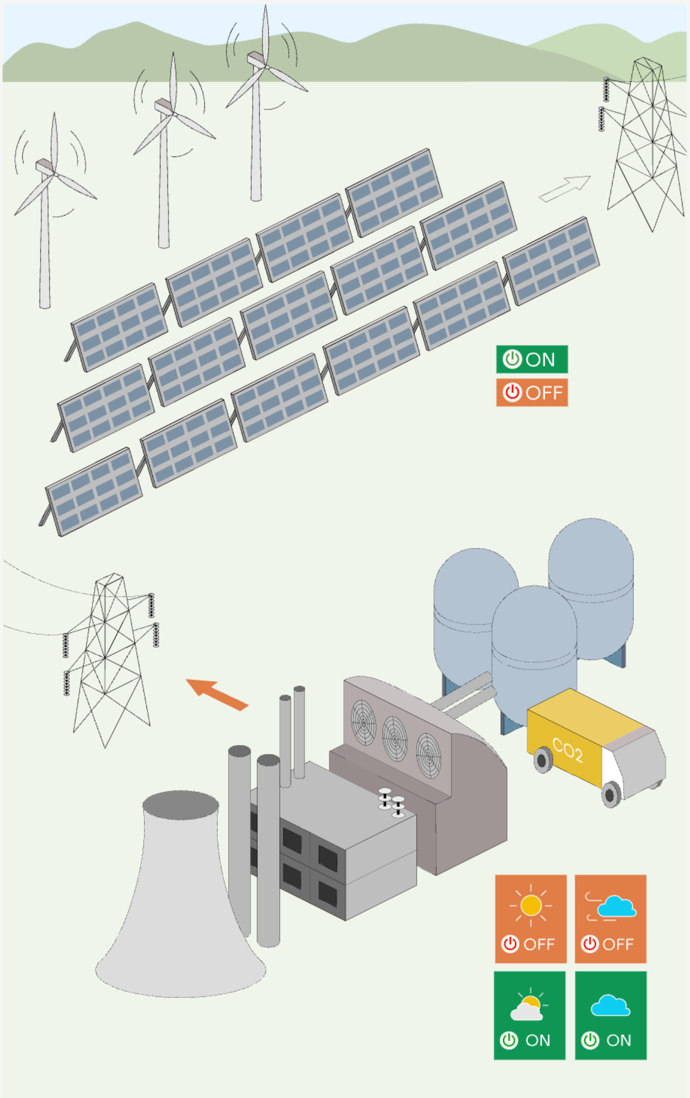
- Requires renewable projects to have modern control systems with automated controls and advanced communication systems
- Requires an adequate remuneration system that is not energy-only to compensate renewable projects for grid services

It is already happening

In California, a 300 MW solar plant with no storage has been able to provide essential grid services with greater precision than a gas power plant. By running the solar plant at a slightly lower level, it can quickly ramp up to meet short periods of higher demand instead of a gas plant. The solar power plant was curtailed by 30 MW from its available peak capacity to have manoeuvrability to increase its output in response to a frequency decline and stabilise the grid, showing it can perform this better than a gas power plant. It demonstrated that some curtailment can be beneficial to the system and even lead to less reliance on fossil fuels.

SUPPLY: Optimising supply from fully flexible generation assets

Last-resort flexibility tools to support a high level of wind and solar power



- When electricity **supplies are much higher than demand**, wind and solar power outputs can temporarily and quickly be turned down, or off.
- Technical improvements can be made to fossil plants, enabling them to turn off and on more easily and cheaply if cleaner flexibility tools have been exhausted.

Wind and solar can also be built smarter. For example, building east-west facing solar panels may generate less power per panel but will produce more electricity in the morning and evening, and better match demand patterns.

Source: Ember
Graphic by Reynaldo Dizon.

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Conclusion

Clean flexibility is an urgent policy priority

Key clean flexibility tools have been included in the COP29 agenda but more action is needed on the whole portfolio of nine tools

At this year's COP29, the Azerbaijani delegation is proposing three key measures on clean flexibility – a global storage target, a grid expansion target, and action on green hydrogen.

These three measures aim to significantly enhance the flexibility of the global power system. However, they only partially address the whole portfolio of nine clean flexibility tools, completely leaving out tools related to shifting demand and to making supply more flexible, while focusing strongly on hydrogen, which can play a much more niche role.

Clean flexibility is a much broader concept, and achieving the tripling of global renewable capacity requires a full portfolio of solutions, beyond storage, grids and hydrogen, to truly unlock the potential of renewable energy.

The task for COP29 is not just to achieve consensus on the storage and grid goals, but to initiate a wider urgency for governments to focus on clean flexibility.

By creating a platform for clean flexibility, COP29 can create the right enabling environment for tripling global renewable capacity, ensuring a sustainable and prosperous future for all.

Supporting Materials

Acknowledgements

Contributors

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Cover photo

Lincoln Fowler / Alamy Stock Photo