EMBER

Publication date
22 June 2022

# New Generation

## Building a clean European electricity system by 2035

Ember modelling of power system pathways reveals that a clean power system by 2035 should be at the core of energy planning for a net-zero continent by mid-century.

COAL TO CLEAN ENERGY POLICY

### About

This study explores the least-cost pathways to a clean power system in Europe, compatible with the Paris Agreement climate goals (1.5C).

Detailed, country-by-country, hour-by-hour power system modelling confirms the feasibility of almost completely decarbonising Europe's power sector by 2035, while expanding the electricity supply. Key metrics are quantified in order to benchmark progress, while accounting for a range of uncertainties. Crucially, the costs of competing routes are assessed, including the costs of developing the power system according to current plans.

This report summarises the results of three modelled pathways for the European[1] power sector. The **Stated Policy** pathway is aligned with stated national policies[2] until 2035. The other two pathways – **Technology Driven** and **System Change** – are computed to minimise cost while remaining within a carbon budget compatible with the Paris Agreement climate goals. The latter two pathways expand clean electrification, but differ in their assumptions about available technologies and the levels of energy savings resulting from societal change.

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With thanks to expert peer reviewers: Léa Hayez and Andrzej Ceglarz (Renewables Grid Initiative), Jörg Mühlenhoff (CAN Europe), Claire Maraval (ReClaim Finance), Artur Patuleia and Pieter de Pous (E3G), Prof Tom Brown (Technische Universität Berlin), Christian Redl and Alexander Dusolt (Agora Energiewende), Keith Allott and Molly Walsh (European Climate Foundation), Bram Claeys (Regulatory Assistance Project).

[1] The term Europe is used in this study to refer to the collection of countries included in the power system modelling: EU27 + UK + Norway + Switzerland + the Western Balkan six (AL, BA, KX, ME, MK, RS). Turkey and Ukraine are not included.

[2] As at end October 2021

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**Acknowledgements**

Document design and layout by Diva Creative.

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Foreword

# A new vision for Europe's electricity generation

There have never been more reasons to end the fossil age in Europe. Continued reliance on fossil fuels endangers the climate, damages public health, and undermines the sovereignty and affordability of Europe's energy. Transformation of the power sector will be central to building a new energy system that addresses these challenges. Wind and solar provide the key tools to decarbonise power production, and are abundant and cheap. Moreover, electrification can unlock fossil fuel reductions across the economy, meaning an expanded clean power system should be considered the crucial enabler of wider decarbonisation. In this context, this study explores the least-cost pathways to clean power in Europe compatible with the Paris Agreement climate goals (1.5C).

Evidence is growing that power systems in advanced economies can and should be decarbonised in the 2030s. The IEA's 1.5C-compatible global energy scenario strongly recommends that advanced economies achieve this milestone by 2035. Accordingly, the G7 have committed to a goal of achieving 'predominantly decarbonised' electricity sectors by 2035.

The modelled clean power pathways present an optimistic vision for the future power system that will require coordinated action by governments, manufacturers, system operators, and consumers to realise.

The results reveal that taking early action could unlock billions in cost savings over the coming decades, in addition to the climate and health benefits of phasing out fossil energy. Achieving a clean power system by 2035 should be at the core of credible plans for a net-zero continent by mid-century. Making this vision a reality will require substantially higher investment in wind and solar power and key flexibility technologies this decade, above and beyond existing plans. Such a mobilistion would cement the EU's position as a climate leader and boost the European economy. As such, the up-front investments required to build a cleaner and bigger power system could be viewed as a down-payment on the quality of life and prosperity of future Europeans.

Now is the moment for Europe to grab the opportunity for cleaner, cheaper energy.

**Dr Chris Rosslowe**
Senior Energy & Climate Data Analyst

# Clean power 2035

**95%** clean power, **70–80%** wind and solar

### Cleaning the power supply for Net Zero

Carbon intensity 90% lower than 2020

Less than 5% unabated gas generation remains

### Electrifying Europe

Power supply increases by more than 50%

Europe's green hydrogen demand met

### Building security and resilience

More flexible power system provides secure supply

Wind and solar boost domestic energy

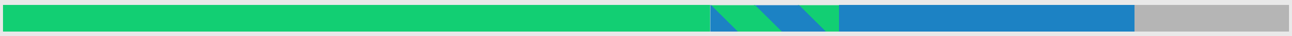
### Boosting the green economy

€530–1010bn saved in avoided fossil fuel costs

€300–750bn additional investment in the economy

## 2030 – Highlights

>**85%** clean power, **55–65%** wind and solar



Projects in place to double interconnection by 2035

Coal phase-out (<1% in power generation)

Europe's total fossil fuel consumption halved

## 2025 – Highlights

**66%** clean power, **29%** wind and solar

150 GW new wind and solar every year after 2025

No new baseload gas after 2025

## From today

Place a clean power system by 2035 at the centre of plans to transition Europe to a net-zero economy

= Wind and solar = Other clean = Fossil

Executive summary

# A clean European electricity system by 2035

A clean power system in Europe can be achieved by 2035; at no extra cost above stated plans and without compromising security of supply. In least-cost pathways, wind and solar scale rapidly this decade to provide the backbone of an expanded power system. This enables higher electrification that could halve Europe's fossil fuel consumption by 2030. Upgrading the system and quadrupling growth in wind and solar capacity requires an additional upfront investment of €300–750bn. The avoided fossil fuel consumption would save Europe an estimated €1 trillion by 2035, with multiple benefits to climate, health, and energy security.

**This analysis reveals that an expanded and (~95%) clean power system in Europe can be achieved by 2035 at no extra cost above stated plans**. Larger upfront capital costs for wind and solar in the power system are offset by avoided carbon costs and avoided costs associated with new nuclear and fossil capacities. There is no cost penalty for choosing the clean power path, even when the electricity supply is simultaneously expanded to enable further electrification. **If the full potential of electrification and energy savings can be realised, Europe's consumption of fossil fuels could fall by 50% by 2030**.

At the EU level, this represents a greater reduction than the REPowerEU plan, albeit not as targeted at reductions in fossil gas. Nonetheless, it would deliver major improvements in Europe's energy sovereignty at a time when reducing fossil fuel dependence is an urgent priority for climate, the economy, and security.

The resulting fossil fuel savings – mostly delivered by electrification – could save **Europe at least €530–1010bn in total by 2035**. This amount is likely an underestimate given high fossil fuel prices are likely to persist. A clean and expanded power system is the critical enabler of this wider energy sector decarbonisation and the huge potential cost savings that follow.

## Building a bigger, cleaner, cheaper power system

**In the least-cost pathways, wind and solar provide the backbone of an expanded electricity supply by 2035.** These technologies expand to provide between 70–80% of electricity generation by 2035. To achieve this, **annual growth in wind and solar capacity must quadruple by 2025 compared to the last decade; this is the central challenge to deliver a clean power sector by 2035.** Over the period 2025–2035 the combined deployment rate should reach 100–165 GW per year, compared to an annual growth of 24 GW per year between 2010–2020. There are signs of acceleration, with additions hitting a record 36 GW in 2021, but a big deployment challenge lies ahead. Meeting the challenge requires permitting times to be slashed, and supply chains and manufacturing capacity to be secured. In least-cost pathways Europe's wind fleet quadruples to 800 GW by 2035, and solar expands 5–9 fold reaching 800–1400 GW.

Stated policies would deliver just 45–65% of the wind and solar capacity required by 2035. Ambitions for 2030 set out previously by the European Commission as part of the Fit-for-55 package also fall short. However, recently enhanced proposals in the REpowerEU plan go a long way to closing the gap between stated ambition and the pathways to 2035 clean power presented here. While this is encouraging, major challenges remain in translating this higher ambition into European and national policy, and deploying the infrastructure on the ground.

Despite leading to lower overall energy system costs, **building a clean, wind and solar dominated power system by 2035 will require an additional upfront investment of between €300–750bn above existing plans.** While larger upfront investment is needed, cost savings are rapidly realised (as stated above). Extra investment needs are dominated by wind and solar, which require €460–720bn above existing plans by 2035. These additional capital requirements are partially offset by avoided investments in new nuclear capacities (€170bn by 2035) and unabated coal and gas (€100bn by 2035). Further investment is also required in infrastructure to increase system flexibility, such as doubling interconnection by 2035, adding clean dispatchable power sources, and deploying an electrolyser fleet to supply green hydrogen. Cost savings are quickly delivered, providing strong justification for these additional upfront investments.

**Coal must be phased out by 2030 and unabated gas reduced to <5% of generation by 2035 to make Europe's power system fit for the Paris Agreement.** Planned investments in unabated fossil capacities – particularly baseload gas power stations – are currently higher than what is needed for clean power by 2035. While the conventional gas fleet maintains a role in balancing until 2035, current energy plans deliver an estimated 60 GW of excess baseload gas assets. Instead, modelling reveals that **no new baseload (unabated) gas plants need to be commissioned beyond those expected by 2025.**

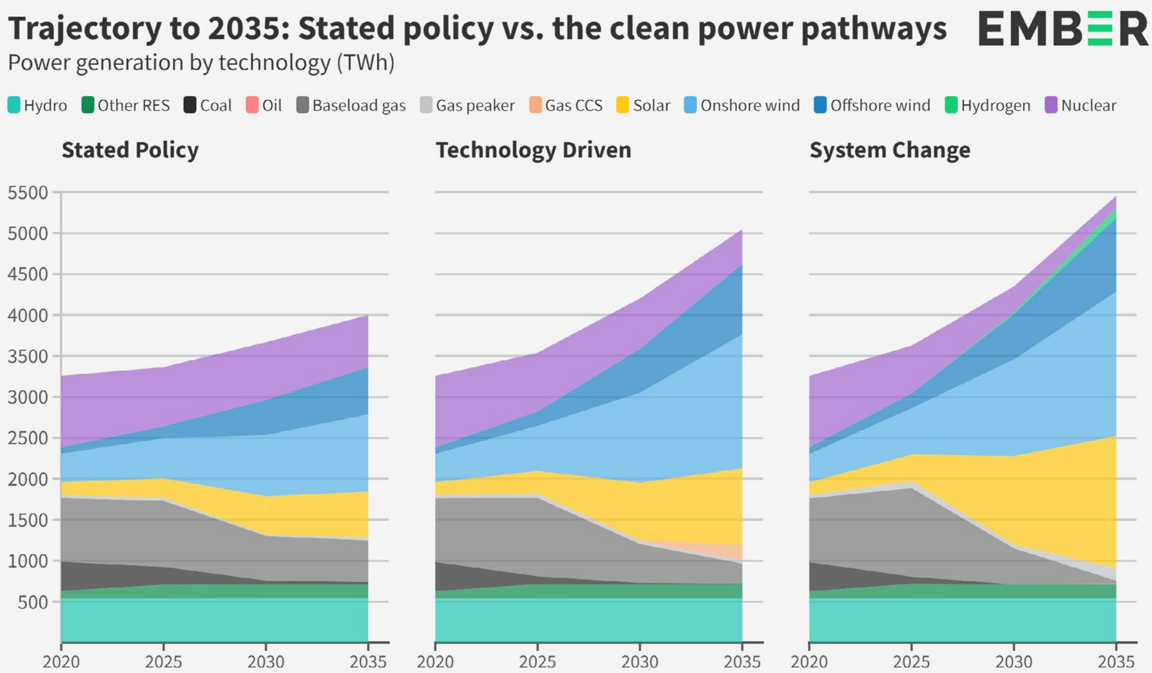



**Figure I:** Electricity generation by technology between 2020–2035 in the three modelled scenarios.

## The varied paths to a more flexible, reliable power system

**A clean and expanded power system, dominated by wind and solar, is reliable and resilient to extreme weather events.** Granular modelling reveals that Europe can operate a 95% clean power system by 2035 without compromising reliability and that the weather-dependent, intermittent nature of wind and solar does not pose a threat to the resilience of the grid, even when faced with unfavourable climatic conditions.

**Enhancing system flexibility through a varied portfolio of technologies is key to cost-effectively integrating wind and solar, while maintaining the power system's ability to supply growing demand.** As the power supply transforms into one dominated by wind and solar, a parallel system transformation is required to provide for their distinct flexibility needs, and to efficiently integrate new types of power demand. Maximising system flexibility reduces dependence on thermal (gas) capacities for balancing. Enhancing system flexibility ensures that – if adequate wind and solar can be deployed – fossil assets can be phased out without compromising system reliability.

**Fully leveraging demand flexibility enables the cost-efficient operation of the future power system.** Electrification provides challenges but also opportunities if demand-side flexibility (such as smart charging EVs and flexible heat pumps) and battery storage, including that carried by electric vehicles, can be activated. This is particularly important for the integration of solar power, as shifting demand by a few hours can boost the alignment of demand with daylight hours. These flexibility services also enable peak shaving, a key tool supporting grid resilience and managing the growth of demand peaks.

**Three key technologies emerge as the cornerstones of flexibility in a clean power system, maintaining system balance over a range of temporal scales: electrolysers, interconnections, and clean dispatchable generation.**

By 2035, wind and solar output frequently exceed demand, at which point **electrolysers** convert excess supply into green hydrogen. The electrolyser fleet grows to 200–400 GW by 2035 and supplies 14–27Mt of green hydrogen, enough to cover the majority of estimated European domestic demand while maximising the value of renewables output. The REPowerEU plan broadly puts the EU27 on track for this by 2030, aiming for more than 65 GW of electrolyser capacity and 10Mt of hydrogen production. If green hydrogen is instead imported or produced off-grid, it is found that a smaller fleet of ~100 GW by 2035 would still provide sufficient flexibility to the clean power system.

Exchange over **interconnectors** enables system balancing when mismatch between supply and demand is geographic. The least-cost path for the European grid sees interconnections at least double by 2035 compared to 2020, enabling the cost-efficient expansion of wind and solar capacities by allowing their deployment in countries with the most favourable conditions.

**New clean dispatchable power sources** enter the system by 2035, but the complete replacement of declining fossil and nuclear capacities is not required. As such, the general trend in all modelled pathways is towards a smaller and cleaner fleet of dispatchable sources by 2035, despite increases in electricity demand (and peak demand). Maintaining the existing hydropower fleet through continued investment and modernisation is strongly recommended.

New, clean, dispatchable capacities can take a variety of forms. Differences in system cost are small, but each technology has a unique risk profile which decision makers must consider.

The wind and solar deployment levels are unaffected by choices between dispatchable capacity options, which have bigger implications for Europe's dependency on fossil gas. This reinforces that accelerating wind and solar deployment is the central challenge for power sector decarbonisation, as it remains essential across a range of possible system configurations.

**Gas with CCS only plays a small role by 2035 in pathways that include it.** The role of this technology becomes larger if interconnection expansion is limited, as wind power cannot be as effectively moved across the grid. This would compound two risk factors: the possibility that CCS technology will not reach maturity before 2035, and a prolonged gas dependence. Conversely, the need for gas CCS can be entirely replaced, at minimal additional cost, by a combination of additional solar, earlier deployment of hydrogen turbines, and some additional unabated gas capacity.

**Bringing forward investment in clean dispatchable technologies can remove the need for any new unabated gas deployment after 2025.** Alternative flexibility options, such as hydrogen turbines, gas with CCS and utility-scale batteries can be used, at minimal additional cost, to build a resilient and clean power system by 2035.

**No new nuclear is found to be cost-competitive in modelled pathways, but sensitivity analysis reveals that developing new nuclear according to national plans does not incur significantly higher system costs.** Doing so would quicken the transition away from gas in the medium term, and lower long-term reliance on this fuel by providing an alternative form of clean generation to abated gas. These benefits of course need to be weighed against safety risks and the issue of nuclear waste disposal.

# Clean power at the core of credible net zero pathways

The power sector will play an increasingly central role in Europe's energy system as the continent seeks to reach net zero emissions by 2050. This is because the tools that will enable most of the sector's decarbonisation – wind and solar power – are already mature, cheap, and able to draw on plentiful resources. The decarbonisation of Europe's power system is already well under way. The carbon intensity of electricity[3] in the EU27 fell 30% in the ten years to 2020, and in the same year, renewables overtook fossil fuels as the number one power source.[4]

The growth of clean power[5] isn't only about decarbonising the power sector. Clean electricity can and will unlock the decarbonisation of swathes energy demand in transport, industry, and buildings. For this reason, an increase in electricity demand is a near-ubiquitous feature of decarbonised energy pathways. The direct application of electricity is often the most efficient means to replace fossil fuels. Electric heat pumps are typically three to four times more efficient at delivering space heating than gas boilers.

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[3] As reported by the EEA

[4] As revealed by Ember's European power sector review 2020

[5] See Box 1.1 for a definition of the sources that this report collectively refers to as 'clean' power.

Electric Vehicles (EVs) typically have a tank-to-wheel efficiency three to four times higher than internal combustion engine vehicles. These represent the low-hanging fruit for decarbonisation through electrification.

Some end-uses require a higher energy density than direct electrification can easily provide (e.g., heavy transport) or higher temperature heat than heat pumps can deliver (e.g., industrial processes). For these end-uses, hydrogen and derivatives such as ammonia and synthetic hydrocarbons are emerging as the leading decarbonisation solutions. Producing hydrogen via the electrolysis of water powered by renewables (so-called green hydrogen) is forecast to become the cheapest production route as early as 2030.[6] This again will require clean electricity as an input.

A clear consensus is emerging within advanced economies around the need to decarbonise electricity systems in the 2030s. In 2021 the IEA released its 1.5C-compatible Net Zero (by 2050) pathway for the global energy sector. Citing reductions in the cost of renewables, the key recommendations included a zero emissions power sector in advanced economies by 2035. This finding was echoed by the sixth assessment round of the IPCC, which identified wind and solar as the technologies with the largest mitigation potential. In pathways assessed by the IPCC for 1.5C, unabated fossil sources contribute only 3% to the global power supply by 2040.[7]

Political commitments have started to align with this new clean power milestone on the route to net zero. The UK government has pledged a decarbonised electricity system by 2035,[8] after phasing-out coal by 2024. The German coalition government has also pledged net-zero power by 2035, and a target of 80% renewable electricity by 2030. The Biden administration in the US has pledged to create a carbon pollution-free[9] electricity sector no later than 2035.

These pledges to fully decarbonise power systems – which only a decade ago would have seemed unthinkable – have been made possible by remarkable cost reductions in wind and solar power over the last 10–15 years. Cost reductions to date were largely galvanised by public funding which accelerated early stage deployment.

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[6] **BNEF**: "'Green' Hydrogen to Outcompete 'Blue' Everywhere by 2030."

[7] Based on Ember analysis of the median of **IPCC AR6 pathways** with 1.5C low overshoot.

[8] **UK Government announcement**

[9] The **Executive Order** doesn't define what qualifies as "carbon pollution-free". It is expected to include a wide range of technologies with zero or supposedly near-zero CO2 emissions, including bioenergy and fossil generation with carbon capture and storage.

The cost of crystalline solar PV modules sold in Europe declined by around 93% between December 2009 and December 2020.[10] Between 2010 and 2020, the total installed costs of onshore and offshore wind in Europe fell by 38% and 28% respectively, as offshore capacity expanded eleven-fold.

So impressive are these cost reductions that in 2021 the levelised costs of **new** solar and wind were cheaper than the marginal cost of operating **existing** coal and gas power in many European countries.[11] Spiralling fossil fuel prices since the end of 2021 have only exacerbated this trend. The long decline in wind and solar costs has been halted in 2022 due to high global energy and commodity prices, but the IEA recently concluded that this has not hampered their competitiveness, as fossil fuels and electricity prices have risen much faster since the last quarter of 2021.[12]

Not only are wind and solar the most competitive sources of electricity, there is evidence that they are widely popular. Recent polling revealed that 86% of Europeans would support new wind and solar projects being built near to where they live.[13] But while social barriers show signs of disappearing, there remain regulatory barriers to wind and solar deployment. Recent in-depth barrier analysis[14] concluded that no EU country has effective policies in place that would ensure the necessary deployment of wind and solar. The most serious problems are linked to permitting, "**especially the high complexity, long duration and low transparency of administrative procedures**."

[10] According to renewable cost trends reported by **IRENA: Renewable power generation costs 2020**

[11] The BNEF H1 2021 LCOE update showed that new wind and solar was cheaper than existing coal and gas in countries that represent 46% of the world's population. In Europe, new solar was cheaper than existing fossil capacity in Germany, France, and Spain. Similarly, new wind was cheaper in the UK and Poland.

[12] IEA Renewable Energy Market update 2022 (May 2022)

[13] YouGov **polling** commissioned by the European Climate Foundation (2021)

[14] **RES Policy Monitoring Database**, Final report, eClarion (2022)

Advances in wind and solar come at a time when it is increasingly clear that fossil fuels must be rapidly phased out of power production, starting with advanced economies but soon followed by the rest of the world. The IPCC's 5th assessment round provided evidence that coal must be phased out in the power sector in advanced economies by 2030[15] to meet the Paris Agreement Climate goals, and the 6th assessment round confirmed that gas must soon follow.[16] In this context, and with gas prices spiralling, the economics of gas power in Europe is growing increasingly fragile,[17] and the case for new investments weakening.

This study explores least-cost pathways to clean power in Europe[18] compatible with the Paris Agreement climate goals (1.5C). The analysis provides detailed, country-by-country, hour-by-hour power system modelling to confirm the feasibility of this milestone for Europe. Key metrics are quantified in order to benchmark progress, while accounting for a range of uncertainties. Crucially, the costs of competing routes are assessed, including the costs of developing the power system according to current plans.

### Box 1.1: On the use of 'clean power' in this report

Clean power is used as a broad category to group together low-emissions sources of electricity. This includes sources that have zero emissions at the point of generation, like wind, solar, hydro, and nuclear. Unabated fossil fuels, such as coal and gas, are excluded. The definition of clean power used here also includes less mature renewables (tidal, geothermal, wave) and sources that have the potential to be low-emissions, but where there remains a risk of significant emissions (hydrogen, bioenergy, waste and fossil fuels with CCS). There is no perfectly 'clean' source of electricity, as no electricity source is yet zero emissions on a lifecycle basis, nor can any source be operationalised without any environmental impacts.

[15] Climate Analytics (2019): Global and regional coal phase-out requirements of the Paris Agreement: Insights from the IPCC Special Report on 1.5°C.

[16] Based on Ember analysis of the median of IPCC AR6 pathways with 1.5C low overshoot.

[17] Carbon tracker report 'Put gas on hold' found that more than a fifth of European gas-fired power plants were loss making in 2021, before the unprecedented increases in gas prices.

[18] The term Europe is used to refer to the countries included in the modelling: EU27 + UK + Norway + Switzerland + the Western Balkan six (AL, BA, KX, ME, MK, RS). Turkey and Ukraine are not included.

# Three pathways for Europe

This report summarises the results of three modelled pathways for the European power sector. The **Stated Policy** pathway is aligned with stated national policies[19] until 2035.

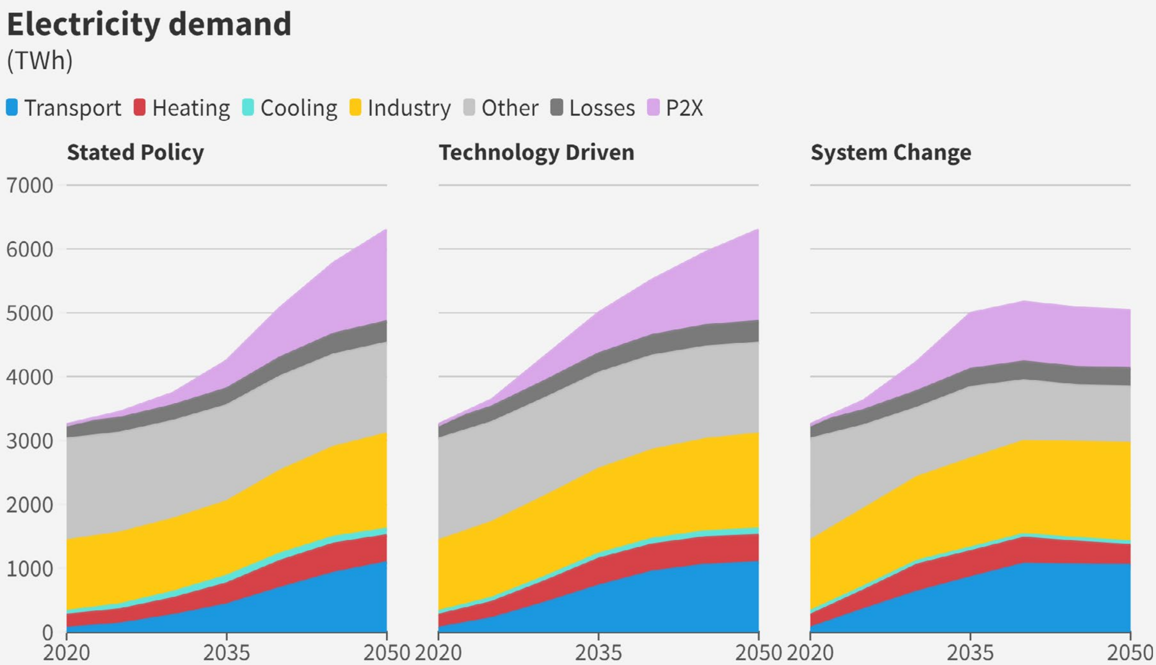



**Figure 2.1:** Electricity demand by pathway and sector, including estimated electricity demand for P2X. Underlying demand data is provided in the Technical Report.

[19] As at end October 2021

The other two pathways – **Technology Driven** and **System Change** – are computed to minimise cost while remaining within a carbon budget compatible with the Paris Agreement climate goals. The latter two pathways expand clean electrification, but differ in their assumptions about available technologies and the levels of energy savings resulting from societal change.

All pathways show a large increase in electricity demand by 2050 (Figure 2.1), despite energy efficiency measures, because of increases in clean electrification (to decarbonise space heating and light transport) and power-to-X (P2X) (to decarbonise industry and heavy transport). Pathways differ the extent to which these changes occur by 2035, and the wider assumptions dictating energy demand as a whole. Another important distinction is the technologies available to supply electricity (and hydrogen). Key pathway storylines and assumptions are elaborated below, and summarised in Table 2.1. Detailed demand and supply (technology) assumptions are provided in a separate Technical report.

## 2.1 Stated Policy pathway

The **Stated Policy** pathway represents the power and energy system as described by existing government plans[20] until 2035. This is the lowest ambition pathway. The power system in this pathway is unrestrained after 2035 due to a lack of detail in official plans. Instead, it evolves in order to reach zero emissions in the power sector[21] at least cost by 2050.

[20] Accurate as of October 2021. The main source of power sector data is the TYNDP 2020 National Trends scenario, which is informed by NECP documents. Ember updated this data with significant energy policy updates since 2019, notably the Polish 2040 energy plan and the German coalition agreement (November 2021) (see Technical Report).

[21] Negative emissions in the power sector are not considered due to model limitations. Therefore by 2050 (and 2040 in System Change) the pathways are designed to reach absolute zero emissions in the power sector. This is expected to have limited impact on the conclusions because the study is focused on 2035. The full trajectory until 2050 is included mainly to provide a longer time horizon over which to weigh investment decisions. The absence of negative emissions in the power sector should have limited impact by 2035 because the technologies required to decarbonise the power system (mainly wind and solar) are mature. Residual emissions from gas CCS generation are an exception to the zero emissions requirement. The gas CCS capacity which is on the system in 2045 is allowed to remain online in 2050, which mitigates against radical power system interventions to abate the final few percent of emissions.

Assumptions about the wider energy sector (e.g., energy demand, electrification) gradually converge with the Technology Driven pathway between 2035 and 2050. As such, these two pathways share a common endpoint in 2050. The objective of economy-wide net zero emissions by 2050 is viewed as consistent with the Stated Policy storyline because every country in scope has signified an intention to achieve this.

**Final energy demand** is estimated to reduce by only 8% by 2035 (compared to 2019). Two thirds of these savings originate from the buildings sector, as a result of renovations, while the remaining third are in transport, resulting from electrification, despite increased activity. **Electricity demand** (excluding P2X) increases by 17% to 3800 TWh by 2035, driven by the transport sector. Growth accelerates post-2035, reaching 4850 TWh by 2050.

Hydrogen production can be blue or green, but electrolyser electrolyser capacity is capped at 5 GW by 2025 and 60 GW by 2030 in line with the EU hydrogen strategy (2021). Estimated **hydrogen demand**[22] reaches 350 TWh by 2035, the majority of which is for industry.

## 2.2 Technology Driven pathway

The **Technology Driven** pathway remains within a carbon budget compatible with warming of 1.5C (see Box 2.1) and is consistent with a net-zero energy system by 2050, by which point power sector emissions must fall to zero. This is the medium ambition pathway. Energy savings are higher than in Stated Policy, but electrification proceeds faster and further, resulting in higher electricity demand by 2035.

Unlike the System Change pathway, the modelling of this pathway includes the option to invest in new nuclear power, and power generation equipped with carbon capture technology. Technology trajectories are determined by economic optimisation, with no phase-out dates or renewables targets mandated.

[22] Demand figures here exclude demand from the power sector, which is determined self-consistently by the power system modelling, and added to these amounts. These hydrogen demand figures include hydrogen to produce other fuels, namely ammonia for (domestic) shipping, synthetic methane for industry, and synthetic kerosine for (domestic) aviation.

Assumptions about the wider energy sector in this pathway by 2050 are used to guide The Stated Policy between 2035 and 2050, such that the pathways share a common endpoint (but not total emissions over the period), simplifying the comparison of pathway costs.

**Final energy demand** reduces 20% by 2035 and 43% by 2050. Transport and buildings dominate reductions by 2035, as efficient electric vehicles increase market share and more action is taken to renovate buildings and roll out efficient electric heat pumps. **Electricity demand** (excluding P2X) grows by 34% to 4350 TWh by 2035, driven by transport but with sizable contributions from heating and industry. Growth slows post-2035, reaching 4850 TWh by 2050, with direct electrification at an estimated 62%.

Hydrogen production can be blue or green, but like Stated Policy, electrolyser capacity is capped 5 GW by 2025 and 60 GW by 2030. Estimated **hydrogen demand** reaches 510 TWh by 2035, 70% of which is for industry and the rest transport.

## 2.3 System Change pathway

The **System Change** pathway remains within a carbon budget compatible with 1.5C and is consistent with a net-zero energy system by 2040. This is the highest ambition pathway.

Assumptions about the wider energy system and society are aligned with CAN Europe's Paris Agreement Compatible (PAC) scenario – an energy scenario built in a participatory manner that embodies the energy policy demands of civil society in Europe. As such, energy savings – resulting from behavioural change and the implementation of a circular economy – are the highest of any pathway. In the power sector, coal is phased out by 2030, and other fossil fuels predominantly[23] by 2035.

**Final energy demand** reduces 35% by 2035 and 54% by 2050, driven by the buildings sector, with an acceleration of increasingly deep renovations. Transport electrification also proceeds faster, increasing efficiency. **Electricity demand** (excluding P2X) grows by 27% reaching 4100 TWh by 2035.

[23] In the power sector, baseload gas power is phased out before 2035, while gas CHP and gas peakers are phased out between 2035 and 2040.

<table>
<tr><th></th><th colspan="2">Stated Policy</th><th colspan="2">Technology Driven</th><th colspan="2">System Change</th></tr>
<tr><td rowspan="2">Storyline</td><td colspan="2" rowspan="2">Represents the power system as described by national plans until 2035 after which assumptions converge with Technology Driven pathway.</td><td colspan="4">Clean power (2035) pathways</td></tr>
<tr><td colspan="2">Least-cost optimised pathway compatible with the Paris Agreement climate goals ( 1.5C), and consistent with a net-zero energy system by 2050.</td><td colspan="2">A pathway aligned with the assumptions of CAN Europe's Paris Agreement Compatible scenario. Consistent with a net-zero energy sector by 2040.</td></tr>
<tr><td>Carbon emissions</td><td colspan="2">Total unrestricted. Zero power sector emissions by 2050.</td><td colspan="2">Total power sector emissions less than 9 $GtCO_2$ (2020–2050). Zero power sector emissions by 2050.</td><td colspan="2">Total power sector emissions less than 8 $GtCO_2$ (2020–2050). Zero power sector emissions by 2040.</td></tr>
<tr><td rowspan="2">Direct electricity demand / power generation (TWh)</td><td>2035</td><td>2050</td><td>2035</td><td>2050</td><td>2035</td><td>2050</td></tr>
<tr><td>3540/4000</td><td>4520/6640</td><td>4050/5050</td><td>4520/6620</td><td>3830/5450</td><td>3840/5640</td></tr>
<tr><td rowspan="2">Direct electrification</td><td>2035</td><td>2050</td><td>2035</td><td>2050</td><td>2035</td><td>2050</td></tr>
<tr><td>30%</td><td>62%</td><td>40%</td><td>62%</td><td>47%</td><td>66%</td></tr>
<tr><td colspan="7">Demand assumptions</td></tr>
<tr><td>Transport</td><td colspan="2">Increased car activity by 2035. 100% of new cars are BEVs from 2040. Car fleet electrification: 15% by 2035, 100% by 2050. Road freight electrification: 4% by 2035, 33% by 2050.</td><td colspan="2">Unchanged car activity by 2035. 100% of new cars are BEVs from 2035. Car fleet electrification: 30% by 2035, 100% by 2050. Road freight electrification: 21% by 2035, 33% by 2050.</td><td colspan="2">Modal shift reduces car activity by 2035. Share of BEVs in new passenger vehicles reaches 100% in 2025. Passenger car fleet electrification: 45% by 2035, 100% by 2040. Road freight electrification: 33% by 2035, 57% by 2050.</td></tr>
<tr><td>Buildings</td><td colspan="2">Announced efficiency measures reduce heating and cooling demand by 9% by 2035. Electric heat pumps cover all space-heating requirements by 2050. Large heat pumps account for 40% of District Heating by 2050.</td><td colspan="2">An average 2% renovation rate reduces heating and cooling demand by 20% by 2035. Electric heat pumps cover all space-heating requirements by 2050. Large heat pumps account for 40% of District Heating by 2050.</td><td colspan="2">An average 3% renovation rate reduces heating and cooling demand by 45% by 2035 Electric heat pumps cover all space-heating requirements by 2040. Large heat pumps account for 40% of District Heating by 2040.</td></tr>
<tr><td>Industry</td><td colspan="2">Energy demand unchanged by 2035. Direct and indirect electrification: 36% and 8% by 2035</td><td colspan="2">Energy demand reduced 9% by 2035. Direct and indirect electrification: 46% and 12% by 2035</td><td colspan="2">Energy demand reduced 14% by 2035. Direct and indirect electrification: 51% and 14% by 2035</td></tr>
<tr><td>Supply assumptions</td><td>+</td><td>All generation technologies</td><td>+</td><td>All generation technologies</td><td>−</td><td>No new nuclear or gas CCS</td></tr>
<tr><td>Storage</td><td colspan="6">Deployment of pumped storage (and hydropower) is not cost-optimised, but follows expected pathways. Deployment of utility scale batteries is determined by cost optimisation. Development of the hydrogen system is determined by cost optimisation (electrolysers and hydrogen-burning turbines).</td></tr>
<tr><td>Interconnection</td><td colspan="2">Growth restricted to planned projects, allowing maximum expansion by a factor of 1.5 by 2035. After 2035, as Technology Driven.</td><td colspan="2">Expansion determined by cost optimisation, up to a maximum potential on each border, informed by the TYNDP candidate project list.</td><td colspan="2">As Technology Driven</td></tr>
</table>

**Table 2.1:** Key pathway storylines and their defining assumptions for the three main pathways: Stated Policy, Technology Driven and System Change.

This is less than Technology Driven, as increased energy savings outweigh higher electrification. Continued energy saving measures cause power demand to plateau post-2035, never exceeding 4250 TWh, while electrification proceeds further than Technology Driven by 2050, reaching an estimated 66% (direct).

Hydrogen production is 100% by (green) electrolysis. Electrolysis capacity is uncapped in all timesteps. Estimated **hydrogen demand** reaches 690 TWh by 2035, the highest of any pathway, 60% of which is for industry and the rest transport.

## 2.4 Sensitivity scenarios

In addition to these three main pathways, a set of 10 **sensitivity scenarios** are provided. Using the Technology Driven pathway as a basis;[24] these pathways explore the consequences of varying key input assumptions or the availability of power system technologies or services. All sensitivities are briefly described in Table 2.2, and described further in the Annex. Some sensitivities are intended to reflect the consequences of policy failure (e.g. Delayed interconnection). Others are intended to capture important economic or political uncertainties that affect input assumptions (e.g. High fossil prices, Alternative hydrogen). Another category represents the reality that system development is not dictated by cost-optimisation alone, and that social attitudes and politics often weigh heavily on decisions (e.g. Resistance to RES, Nuclear plus, No CCS). Insights from these sensitivities are shared throughout the remainder of the report, in particular to support the main findings.

[24] All sensitivities use the Technology Driven pathway as a basis, with the exception of System Change-B which adds extra utility scale battery capacity to the System Change pathway.

| Sensitivity scenario | Basic storyline |
|---|---|
| **Resistance to RES** | Social acceptance issues limit the land available, and hence the technical potential of onshore wind and utility-scale solar. |
| **Delayed interconnection** | A combination of lack of preparedness, excessive bureaucracy, or social resistance delay and limit interconnection projects. |
| **No gas + CCS** | Power plants equipped with carbon capture technology are not available for investment. |
| **Nuclear plus** | Nuclear plant lifetimes are widely extended to 60 years (unless already stated to close by a specific date), and all planned new nuclear goes ahead (both conventional and Small Modular Reactor units). |
| **Lower demand flex** | Governments and regulators fail to incentivise and enable the uptake of consumer technologies and behaviours required to deliver the assumed demand-side flexibility. |
| **Alternative H2 supply** | The power system is only required to supply half as much hydrogen, with the shortfall supplied by alternative sources (dedicated off-grid electrolysis or imports from outside of Europe). |
| **High fossil prices** | Fossil fuel prices are increased between 2025 to 2050. |
| **Limited new gas** | No new unabated gas capacity (either baseload or peaking) is deployed after 2025. |
| **Technology Driven B** | Additional utility-scale battery capacity is added to the system throughout the pathways – linked to installed solar capacity – to address the bias against battery projects resulting from the wholesale market-only modelling approach. |
| **System Change B** | |

**Table 2.2:** Sensitivity storylines. For further details, see the Annex and Technical Report.

### Box 2.1: Carbon budget assumptions

This analysis takes a carbon budget approach in order to avoid pre-defining emissions levels in certain years, with the exception of 2050 when emissions must be zero. Key assumptions are summarised here, and further details are provided in the accompanying technical report. Through a combination of external energy scenarios for Europe and data from integrated assessment models, it was deduced that the remaining carbon budget for Europe's energy sector – for a better than even chance of restricting global heating to 1.5C – is approximately 40–50GtCO2. Within this, a budget is allocated to sectors within scope of the model using a combination of existing emissions data, and this is verified by comparison to existing power system modelling studies, including the EU Commission's modelling for the Fit for 55% package. As a result, the Technology Driven pathway is constrained by a 2020–2050 budget for the power (and centralised heating) system of 9GtCO2. The System Change pathway is constrained by a smaller budget of 8GtCO2, corresponding to a higher chance of limiting warming to 1.5C.

### Box 2.2: The energy crisis and the war in Ukraine: implications for the results of this study

Global market pressures, exacerbated by the Russian invasion of Ukraine, have caused fossil fuel prices to soar throughout the second half of 2021 and into 2022. These cost pressures, coupled with a determined effort to wean Europe of Russian fossil fuel supplies, have increased the urgency of Europe's energy transition, the security dimension of which has never been more apparent. Europe is highly dependent on imported fossil fuels of all types, but the specific configuration of Europe's gas infrastructure – historically geared towards Russian imports – presents a particularly difficult challenge. The high price of gas combined with the threat of losing Russian gas supplies with little or no warning has sparked a rush for alternative gas supplies. In response, the EU's REPowerEU plan directs EUR 290 billion towards clean energy, with EUR 10 billion for alternative gas supplies, to cut Russian fossil gas imports by two-thirds by the end of 2022.

In the short term, market dynamics have shifted in favour of coal, which has halted a long-term decline, increasing generation by 20% in 2021 compared to 2020.[25]

The Stated Policy pathway is based on national policies at the end of October 2021, so does not capture any policy announcements since the invasion of Ukraine, such as accelerated renewables targets or any decisions regarding gas infrastructure. It's important to note however that announcements such as REPowerEU, while important, only set out increased ambition, which will require translation into European and national policy and planning. Seen this way, the Stated Policy pathway remains a relevant indication of committed national plans.

The three main pathways reported here do not take into account the recent cost increases in fossil fuels or renewables. Fossil fuel prices are taken from the IEA's World Energy Outlook 2021 Announced Pledges scenario, which projects a smooth evolution to lower costs over time as demand is assumed to reduce. Renewable technology costs are also based on pre-war trajectories of decreasing cost over time. The IEA estimates that higher renewable costs will persist throughout 2022 and 2023, but despite this, the competitiveness of wind and solar has not been hampered,[26] as fossil fuels and electricity prices have risen much faster since the last quarter of 2021.

Finally, short-term gas-related pressures are not considered by the modelling. It is assumed that gas supplies are available and secure. As a result of this and changes in power sector market dynamics, gas power generation is likely overly competitive in the modelling, especially in the short term. At the same time, despite cost increases in reality, it is possible that renewables are undervalued in early years in the trajectories.

In general, higher fossil fuel prices will only exacerbate the benefits of transitioning to a clean power system. The system costs calculations presented in this report will underestimate the cost of business as usual, particularly in the short term.

To partially address these limitations, specific sensitivity scenarios were developed. The results of this sensitivity analysis are shared in the relevant main findings, and summarised in the Annex.

[25] Ember (2022) European Electricity Review 2022

[26] IEA Renewable Energy Market update 2022 (May 2022)

3 Overview of results

# Pathway outcomes

In this section, the features of the three modelled pathways are summarised. The main conclusions drawn from pathway comparison and sensitivity analysis are presented in the next section.

| | | Stated Policy | Technology Driven | System Change |
|---|---|---|---|---|
| Power generation | TWh | 3,823 | 5,047 | 5,454 |
| Generation mix | Clean % | 86 | 94 | 96 |
| | W&S % | 52 | 68 | 78 |
| | Fossil % | 14 | 6 | 4 |
| Onshore wind | GW | 369 | 584 | 632 |
| | TWh | 940 | 1,640 | 1,760 |
| | % | 24 | 32 | 32 |
| Offshore wind | GW | 142 | 200 | 213 |
| | TWh | 580 | 855 | 905 |
| | % | 14 | 17 | 17 |
| Solar | GW | 530 | 802 | 1,424 |
| | TWh | 555 | 933 | 1,616 |
| | % | 14 | 18 | 30 |
| Unabated gas | GW | 310 | 228 | 118 |
| | TWh | 545 | 283 | 188 |
| | % | 14 | 6 | 4 |
| Gas CCS | GW | – | 34 | – |
| | TWh | – | 190 | – |
| | % | – | 4 | – |
| Hydrogen | GW | – | – | 131 |
| | TWh | – | – | 115 |
| | % | – | – | 2 |
| Nuclear | GW | 90 | 62 | 21 |
| | TWh | 635 | 425 | 150 |
| | % | 16 | 8 | 3 |
| Hydro (and pumped storage) | GW | 246 | 246 | 246 |
| | TWh | 540 | 540 | 540 |
| | % | 13 | 11 | 10 |
| Electrolysers | GW | 84 | 192 | 415 |
| Green H2 production | TWh | 109 | 480 | 920 |
| Battery storage | GWh | 148 | 246 | 842 |
| Interconnectors | 2020=1 | 1.5 | 2.1 | 2.4 |
| Flexibility from clean sources | % | 67 | 82 | 92 |
| Total cost saved by 2035 vs. Stated Policy | €bn | – | 529 | 975 |

**Table 3.0.1:** Summary of key results of the modelled pathways in 2035.

## 3.1 Power generation

Total power generation increases by 55% and 67% by 2035 in Technology Driven and System Change, respectively, to meet higher assumed demand. The Stated Policy pathway only sees a 19% increase.

The share of clean power[27] in Europe's electricity supply was 50% in 2010 and had risen to 62% by 2019.[28] The Stated Policy pathway sees some acceleration of this trend, with the clean power share increasing to 86% by 2035. This is largely driven by ambitious renewables targets announced by large countries such as Germany, the UK, and Spain. The modelled clean power pathways make faster progress. The Technology Driven pathway reaches 94% clean power by 2035, and the System Change pathway is almost entirely clean (96%).

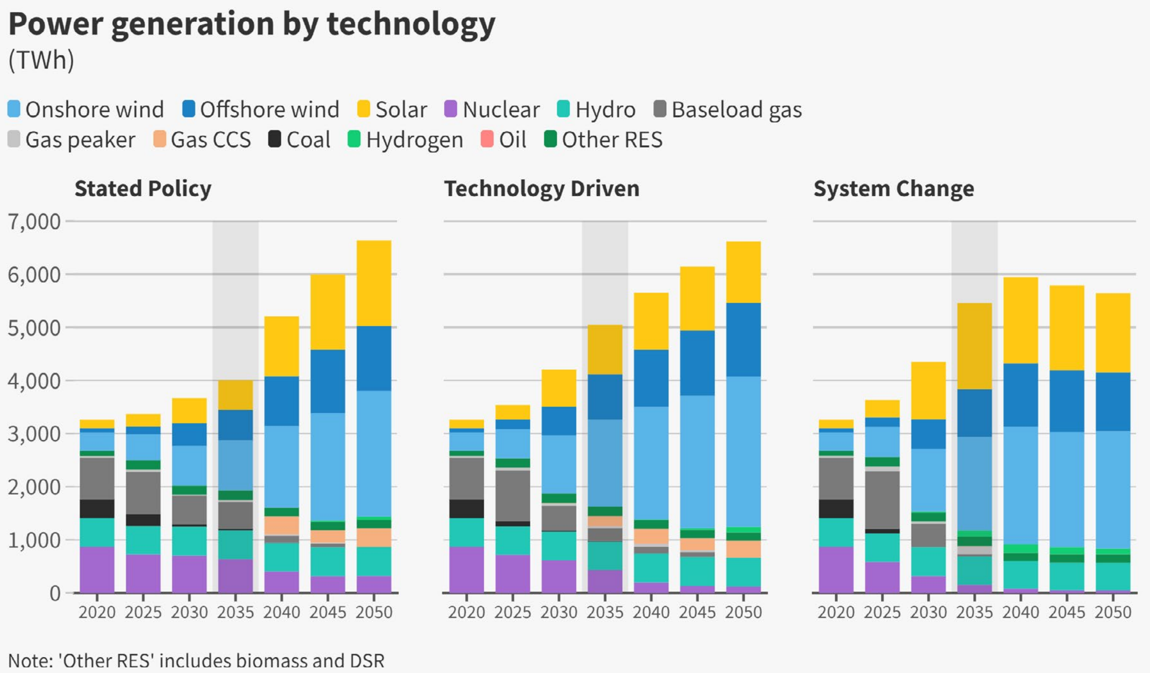


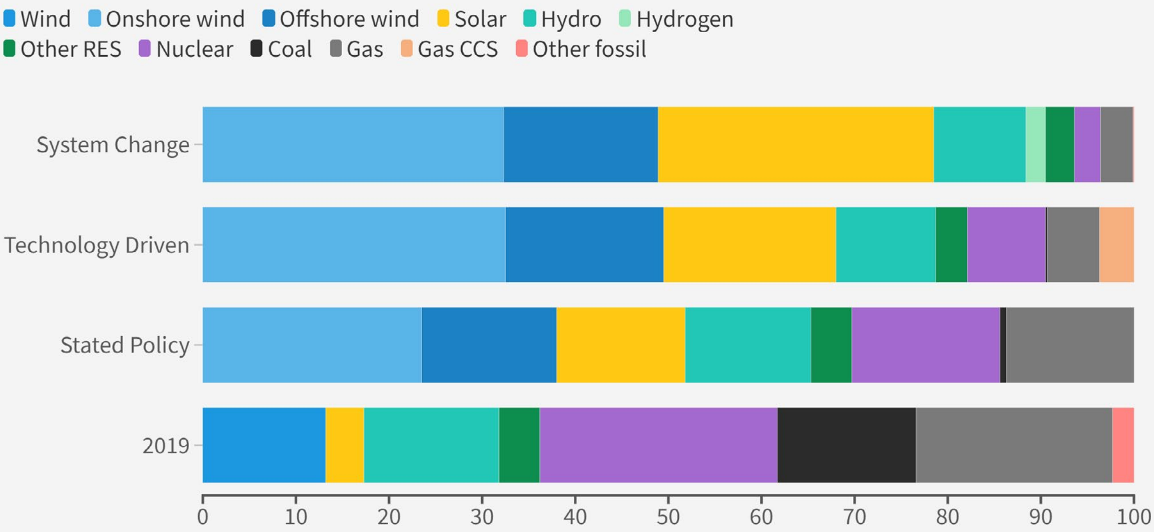

**Figure 3.1.1:** Electricity generation by technology between 2020–2050 in the three modelled scenarios.

[27] See Box 1.1 for a definition of the sources that this report collectively refers to as 'clean' power.

[28] According to data gathered for Ember's Global Electricity review 2021.

**Wind and solar eventually become the dominant source of electricity supply in all least-cost pathways.** The main difference between the pathways is the extent of penetration, and speed with which it is achieved. From a combined share of 17% in 2019, wind and solar provide over half of power supply (52%) by 2035 in the Stated Policy pathway. The Technology Driven and System Change pathways reach higher shares of 68% and 78% respectively.

**Generation mix in 2035**
(%)




Note: At present 2019 data aggregates on- and offshore wind into the single technology category 'Wind'

**Figure 3.1.2:** The share of power generation by technology in 2035 in all three modelled pathways, compared with the European generation mix in 2019.

The contribution of fossil generation varies by country in 2035; some countries fall short of ~95% clean power, while others are closer to 100%. In the Technology Driven pathway, 18 out of 35 countries have >95% clean power, rising to 26 countries in System Change. The contribution of wind and solar also varies substantially by country, reflecting natural variations in resources. The countries with the highest shares across all pathways (including Stated Policy) are Denmark, Ireland, and Spain. Large differences between the Stated Policy pathway and the clean power pathways indicate cases where national plans make poor use of the available energy resources. This is observed, for example, in Greece, Bulgaria, and Hungary.

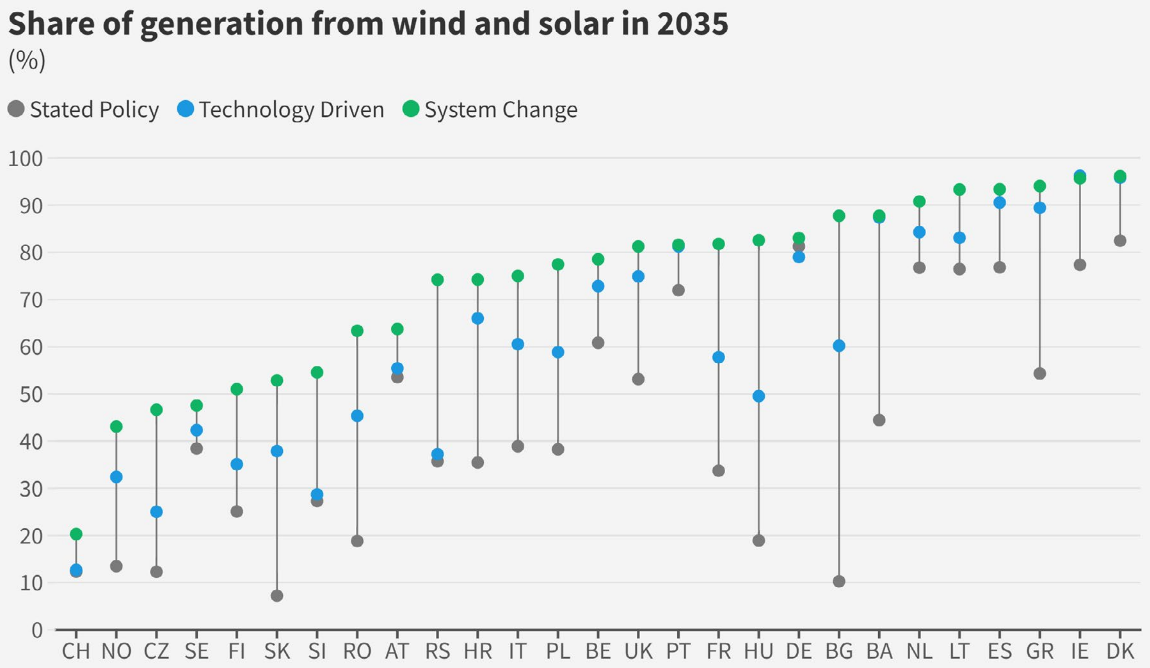



**Figure 3.1.3:** The combined share of wind and solar in annual electricity generation in all modelled countries across three pathways, in an average climate year.

**Unabated fossil fuels make a decreasing contribution to Europe's power supply over time, with coal effectively phased-out by 2030, and unabated gas around 5% or less by 2035**. In the Stated Policy pathway, coal generation falls to 43 TWh (1.2% of supply) in 2030, a 92% reduction compared with 2019. No carbon constraints apply to the Stated Policy pathway, so this result is driven by the worsening economics of coal generation. The decline of coal is even more dramatic in the clean power pathways, which deploy wind and solar faster. In Technology Driven only 17 TWh (0.4%) is supplied by coal in 2030, while phase-out is complete in System Change by definition.

All pathways display a temporary increase in generation from unabated gas in 2025, followed by varying degrees of decline. Broadly this is the result of the poor economics of coal generation given assumed fossil fuel and carbon prices (see Box 4.2.1 for a discussion of how more realistic near-term fossil fuel prices might affect the coal-gas generation balance). Crucially, the short-lived increase in gas generation does not result from a significant expansion of the unabated gas fleet. By 2030 in the Stated Policy pathway, unabated gas generation is 20% lower than 2019 levels, but continued development of the fleet means similar output is maintained until 2035. The Technology Driven and System Change pathways see greater reductions of 28% and 31% by 2030, and unabated gas only supplies 6% and 3% of total generation by 2035.

An increasing share of renewables in recent years has put the carbon intensity of European electricity on a downward trajectory. The carbon intensity of EU27[29] electricity supply fell by 30% between 2010 and 2020, from approximately 330 to 230gCO2/kWh. However, electricity demand remained flat over this period, meaning new wind and solar essentially replaced fossil sources. The challenge for this decade will be ramping up renewables such that fossils can continue to be displaced while also supplying increasing demand arising from electrification in the wider economy. The modelled clean power pathways achieve this, with a grid carbon intensity of 20–30gCO2/kWh in 2035, and a 55–67% increase in power supply.

The remaining fossil fuel generation in 2035 is concentrated into relatively brief periods to make up the shortfall when power demand is greater than the available clean supply. In the Technology Driven pathway in 2035, more than 70% of fossil generation occurs in just 20% of hours in a typical year across the whole system.

## 3.2 Generation capacity and utilisation

### Wind and solar

Europe's installed capacity of wind and solar has grown inconsistently over the last decade as a result of unstable policy incentives. Between 2010 and 2020, combined growth in wind and solar capacity in the countries in scope averaged 24 GW per year.[30] The modelled clean power pathways show that, over the 2025–2035 period, annual wind and solar growth must quadruple to put Europe on track for the least-cost clean power system by 2035. This is substantially more than would be delivered by Stated Policy.

In the clean power pathways, Europe's onshore wind fleet reaches 580–630 GW by 2035, and the offshore fleet grows to 200–210 GW. The resulting combined wind fleet (790–850 GW) is approximately four times the fleet in 2020, and 1.6 times larger than that in the Stated Policy pathway (511 GW).

[29] Accurate data for EU27 power supply is reported by the European Environmental Agency.

[30] Net capacity additions. Source: IRENA renewable energy statistics (2021).

Solar shows more variation between the clean power pathways. Most of the additional clean electricity in the System Change pathway is from solar. Between the two scenarios, the fleet grows to 800–1400 GW by 2035 from just 153 GW in 2020. Compared to the Stated Policy pathway in 2035, the solar fleet is 1.5–2.6 times larger.

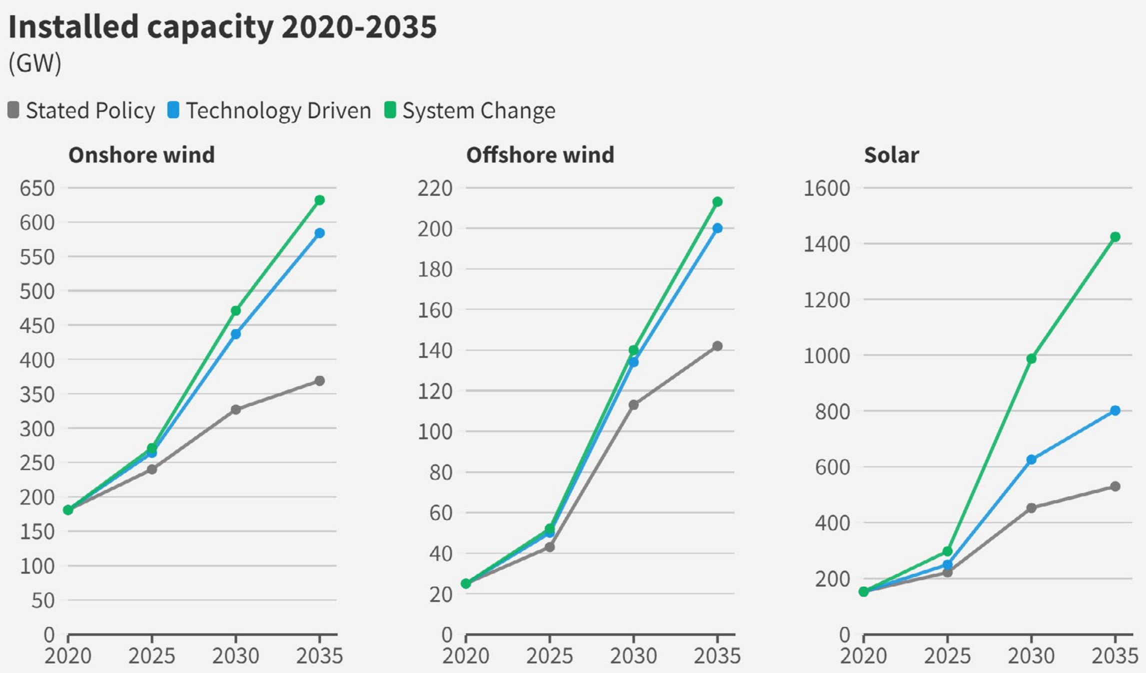



**Figure 3.2.1:** Installed capacity of the wind and solar fleet in the three modelled pathways between 2020 and 2035.

## Wind and solar capacity growth across Europe in the Technology Driven scenario between 2020 and 2035

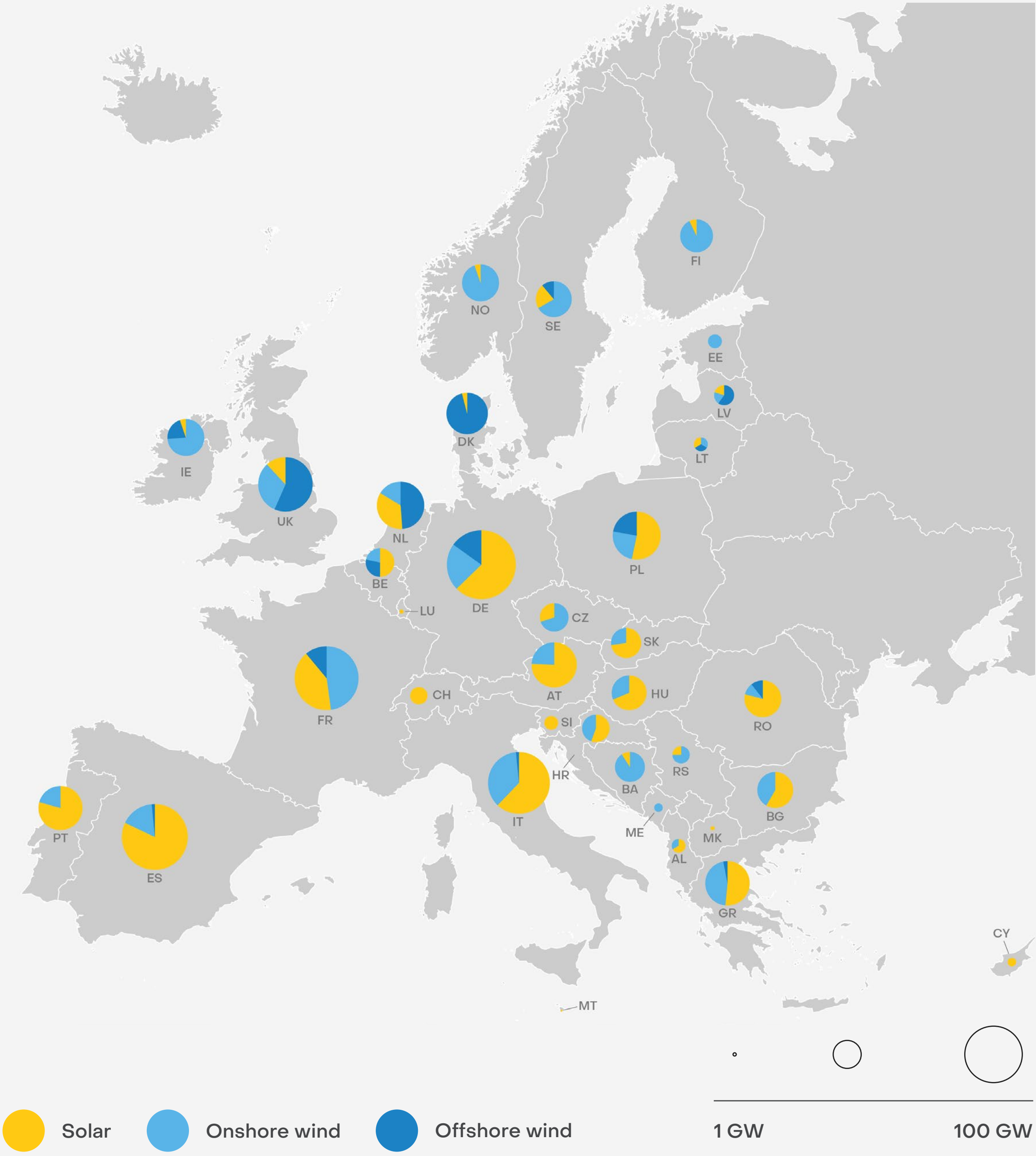



**Figure 3.2.2a:** Wind and solar capacity additions by country between 2020 and 2035 in the TD pathway.

## Wind and solar capacity growth across Europe in the System Change scenario between 2020 and 2035

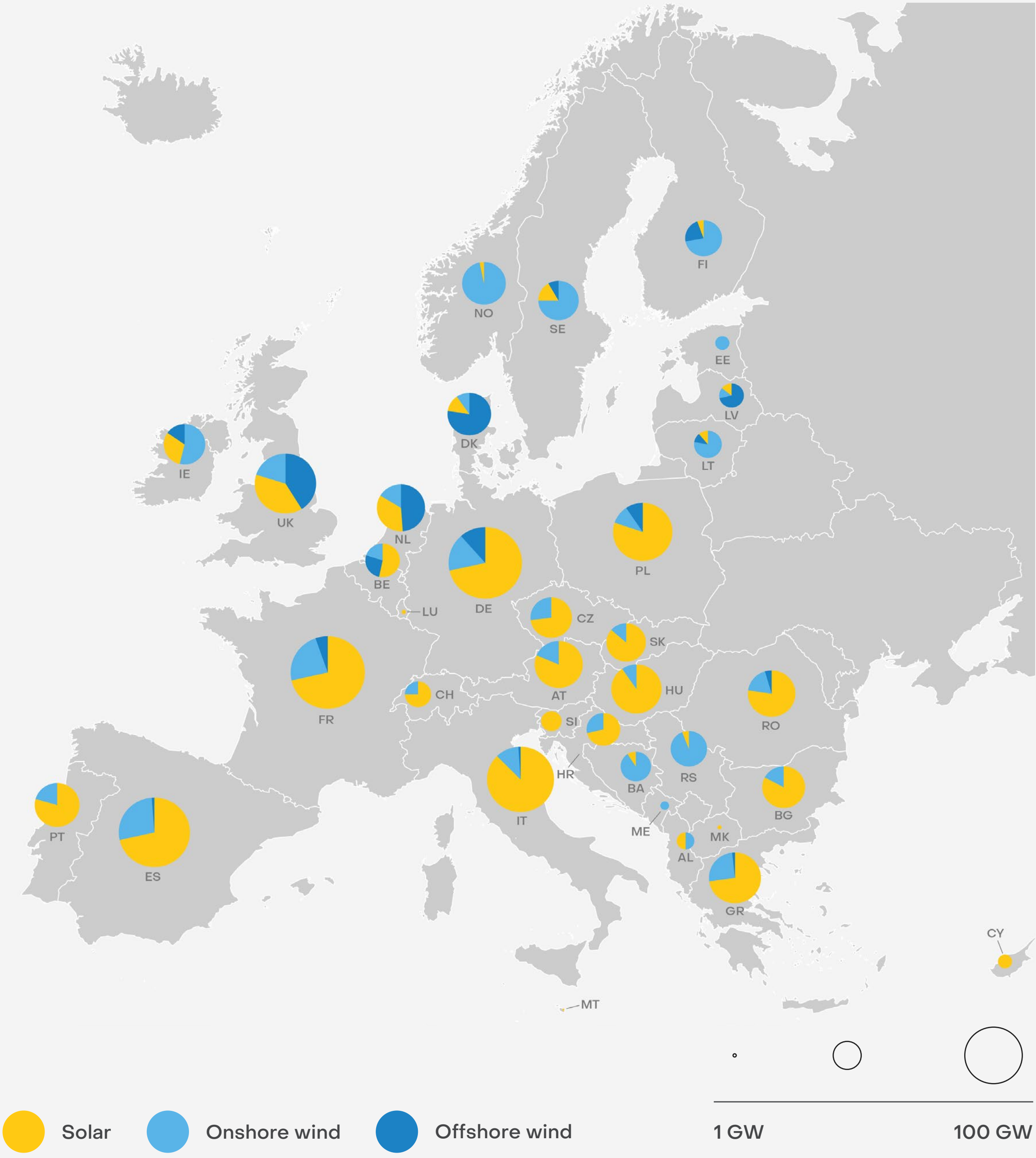



**Figure 3.2.2b:** Wind and solar capacity additions by country between 2020 and 2035 in the SC pathway.

## Dispatchable (firm) generation

Both Technology Driven and System Change pathways show a steady decline in the size of the dispatchable fleet required to provide a secure power supply. In contrast – despite showing slower electricity demand growth by 2035 – the Stated Policy pathway maintains a larger dispatchable fleet.[31] This alone is evidence that system planning at the national level is still guided by a baseload doctrine, which unless challenged will result in over-investment in dispatchable (fossil) capacities in the next decade.

Operational **coal capacity** in Europe stood at 140 GW in 2020 and is in decline. Europe may have seen the opening of its last new coal power plant in 2020. This trend continues and accelerates in the modelled clean power pathways. Both clean power pathways see early retirement of coal capacity, with the fleet shrinking to 28 GW by 2030 in the Technology Driven pathway and phased out entirely in the System Change pathway. The Stated Policy pathway sees some new coal investment in countries without phase-out plans, mainly in the Western Balkans. Even so, total installed capacity declines by 75% to 35 GW by 2035.

The total **unabated gas capacity** in each scenario also decreases over time, but more slowly than coal. Lower stack emissions and a younger average fleet age dictate that the unabated gas fleet has more of a role to play in the medium term (2030s). In all pathways and countries, the 2025 baseload[32] gas fleet is capped according to the outlook of ENTSO-E.[33] This is in recognition of the fact that typical lead times for large gas projects exceed the 2025 time horizon, meaning new capacities will largely already be foreseen by the latest datasets provided by TSOs.[34] After 2025, the expansion of unabated baseload gas capacity is unrestricted. Even so, neither clean power pathway sees investment beyond what is expected by 2025.

[31] Technologies Included in the 'dispatchable' fleet are: unabated gas (baseload and peaker), coal, oil, hydropower, pumped storage, biomass, other renewables (marine, geothermal, renewable waste), nuclear, gas CCS, hydrogen. All but unabated gas, coal, and oil qualify as 'clean dispatchable'.

[32] The category 'unabated baseload gas' used in this report comprises large Combined Cycle Gas Turbines (CCGTs) and Combined Heat and Power (CHP) units. Broadly speaking, the category captures all gas generation assets that are not specifically designed for operation in low-utilisation (peaking) mode. While several distinct generation technologies can fulfil the peaking role, to reduce complexity this modelling only considers Open Cycle Gas Turbines (OCGTs).

[33] Using the National Trends scenario of the TYNDP 2020.

[34] For consistency, a similar approach is followed for wind and solar capacities, using near-term industry forecasts to limit deployment by 2025.

The resulting deployment pattern sees the fleet peak in size in 2025, before shrinking as retiring plants are not replaced. By 2030, the total fleet size is reduced by more than a fifth in both clean power pathways. The decline is primarily driven by reductions in Italy, Spain and the UK. The fleet in Technology Driven almost halves by 2035 compared to 2025, whereas in System Change all but 15 GW (all CHP) is closed, in accordance with the pathway storyline.

In contrast, the Stated Policy pathway envisages an excess of baseload gas capacity relative to the least-cost clean power pathways, with more than 60 GW estimated to be commissioned between 2026–2035, costing an estimated €60 billion.

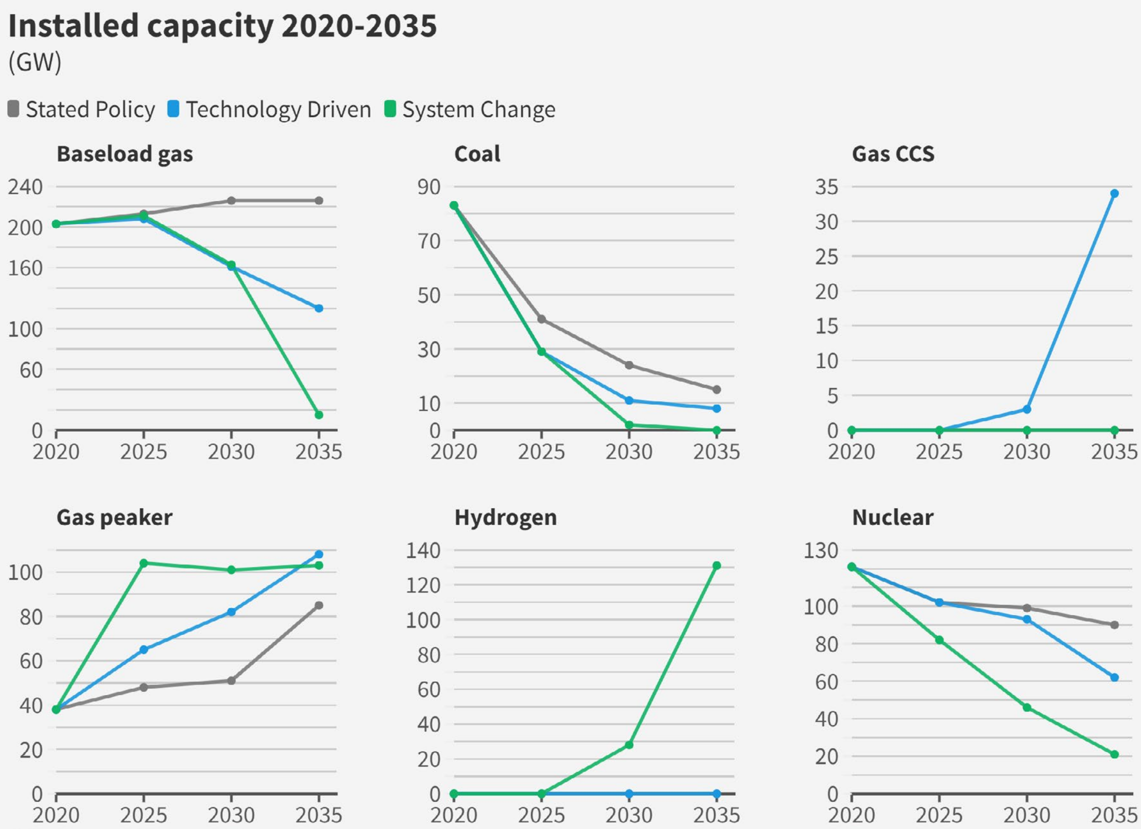



**Figure 3.2.3:** Installed capacity of the main dispatchable generation technologies in the three modelled pathways between 2020 and 2035. Hydropower (not shown) is the same in all pathways.

In least-cost pathways, gas peakers are prefered to baseload assets as a flexible balancing solution. Investment in peakers is unconstrained in the modelling, as a reflection of relatively short construction times and low capital requirements. They fill a gap in supply-side flexibility until new clean firm generation technologies are available in the 2030s. Deployment of flexible gas peakers in the clean power pathways outpaces the Stated Policy pathway. In the Technology Driven pathway, gas peaker capacity grows by 40 GW by 2030 which is enough to offset reductions in baseload capacity. The System Change pathway deploys yet more peaking capacity over this timescale, adding 60 GW.

Two factors drive this difference between clean power pathways. Firstly, although electricity demand in 2030 is lower in System Change than Technology Driven, the electrification of 'new' demand sectors with highly variable load profiles proceeds faster. By 2030, electricity demand from transport and heating totals 660 TWh (18% of demand) in System Change, compared with 420 TWh (11% of demand) in Technology Driven. Secondly, the coal fleet closes more quickly in System Change. Only 6 GW of coal remains open (all CHP) in System Change in 2030, whereas 28 GW remains open (with very low utilisation) in Technology Driven.

Sensitivity analysis reveals that this large deployment in flexible gas peakers is not the only way to ensure system security (see main findings 4.7 and 4.8 for a more in depth discussion of the need for gas capacities versus alternatives dispatchable capacities).

Neither clean power pathway sees any investment in **new nuclear capacity**, meaning that (with current cost assumptions) new nuclear is not cost-competitive. There may however be other reasons to invest in nuclear, relating to its impact on gas consumption and the extent to which it can ameliorate the wind and solar deployment challenge (see section 4.8).

The size of the nuclear fleet in 2020 was 121 GW. By 2035 the fleet size varies in modelled pathways owing to different assumptions about expected plant lifetimes and investment in new capacities. The fleet is largest in Stated Policy, but still reduced at 90 GW. Where a phase-out date is set by law, or a lifetime extension has already been granted, the resulting closure date is respected in all pathways. Where the situation is less clear, the Technology Driven scenario assumes a default lifetime of 50 years, whereas the System Change scenario assumes 40 years. As a result, the 2035 fleet is 62 GW in Technology Driven and 21 GW in System Change.

**New clean dispatchable** generation technologies are available as investment options in the model. In the Technology Driven pathway, **Hydrogen turbines** and **CCS** technology are assumed to become available in 2030 onwards.

The System Change pathway does not use CCS technology, as the storyline places a greater emphasis on proven technology. The Technology Driven pathway sees deployment of a 34 GW gas CCS fleet by 2035 – less than a fifth the size of the unabated baseload gas fleet in 2020. Hydrogen turbines are used later, with no deployment by 2035, but over 180 GW required to reach zero emissions in 2050. Multiple factors combine to promote much earlier investment in hydrogen turbines in the System Change pathway by 2035. These are: almost complete phase-out of the fossil fleet, an absence of CCS technology, and a faster decline in the nuclear fleet. The pathway therefore uses a fleet of 130 GW of hydrogen turbines by 2035, rising to approximately 200 GW in later years.

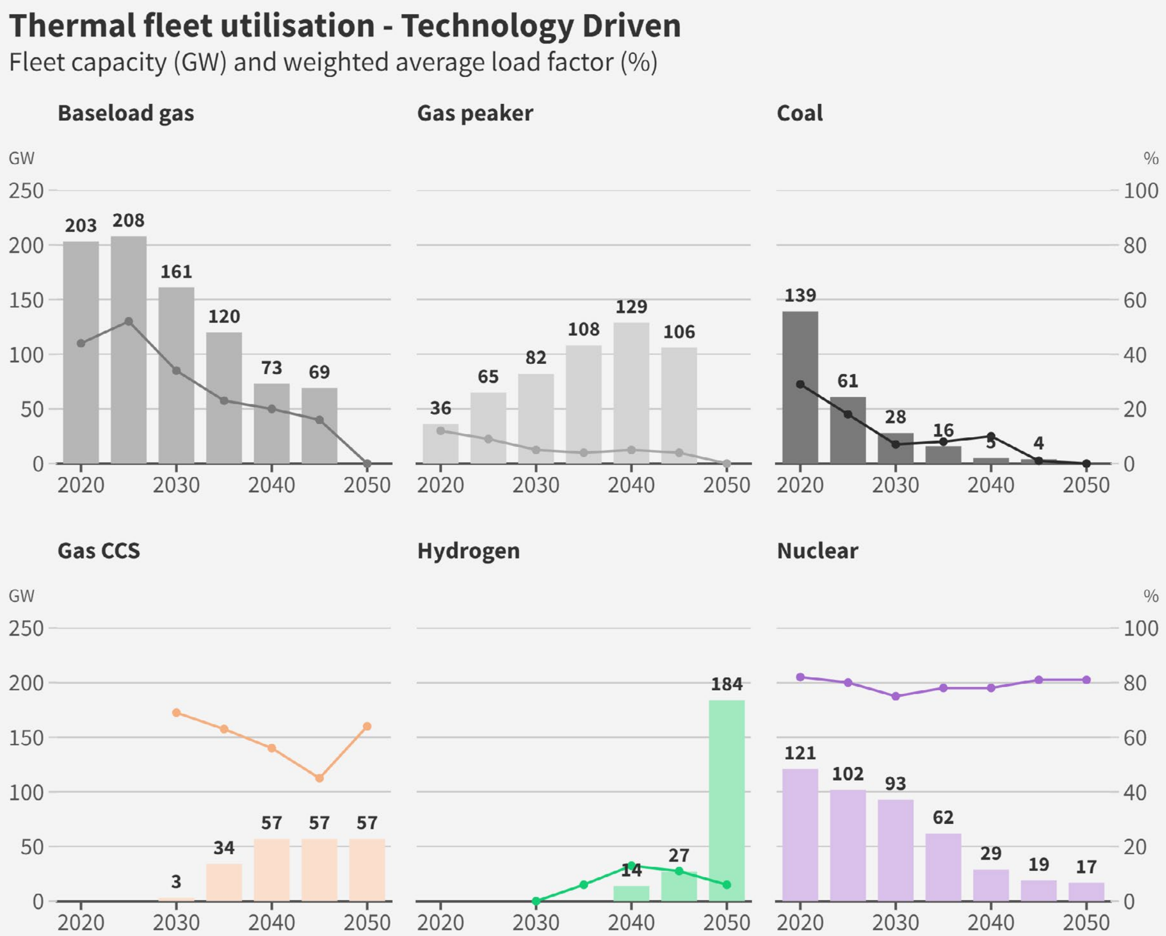



**Figure 3.2.4a:** Fleet capacity and weighted average utilisation (load factor) of thermal generation. Technology Driven pathway.

The utilisation of the unabated thermal fleet changes over time, in parallel to the fleet shrinking. A common trend to both clean power pathways is for decreasing utilisation of baseload coal and gas plants. The average utilisation of baseload gas drops from approximately 45% in 2019 to 25% or less by 2035 in both clean power pathways. The drop in coal utilisation is much steeper, as coal generation is more severely limited by the assumed carbon budget. In the Technology Driven scenario, a small amount of capacity with very low utilisation (less than 10%) is retained until 2035, mainly in Germany and Poland, behaving effectively as a reserve. Gas CCS in the Technology Driven scenario operates in a baseload mode, with average utilisation ranging from 45–65%. Hydrogen turbines in all pathways function as peaking capacity, with country-level capacity factors ranging from 7–15% in 2040.

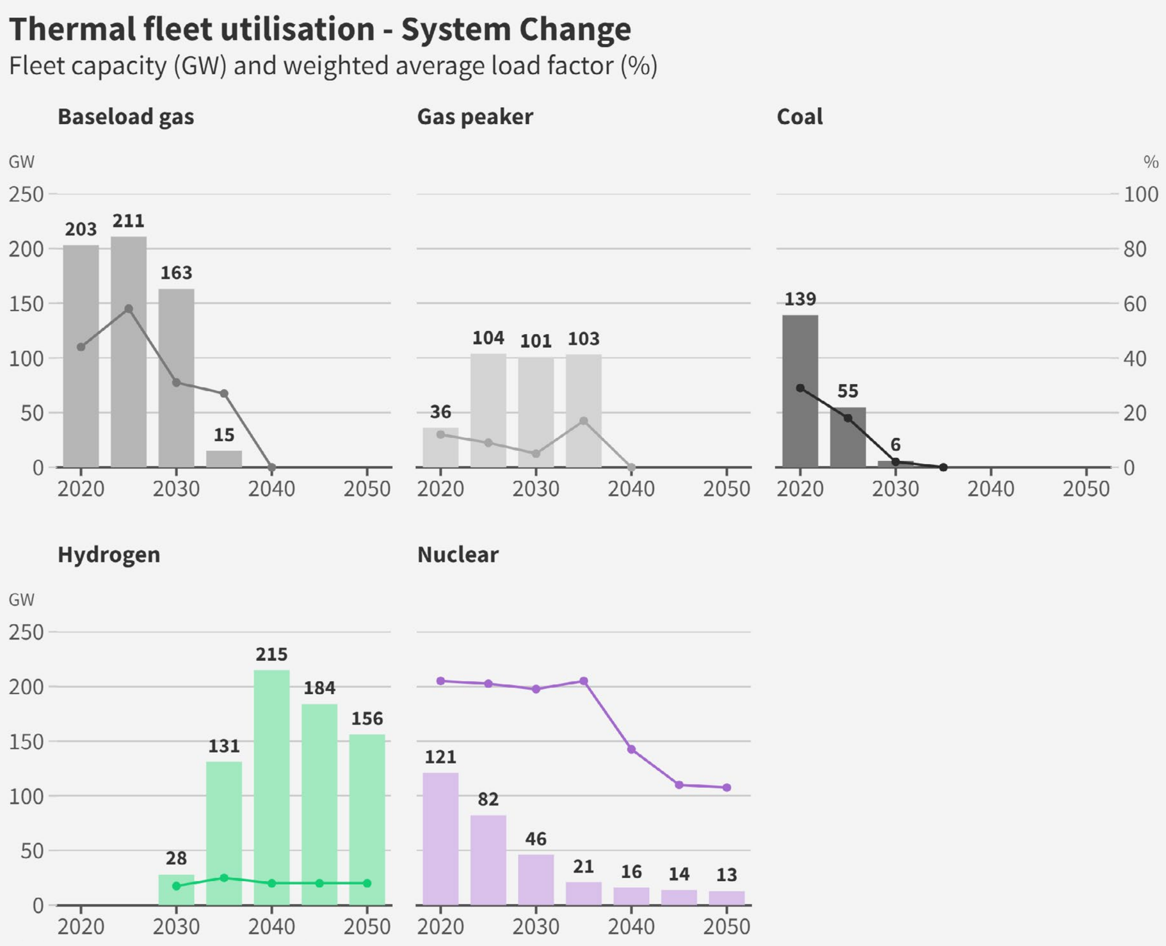



**Figure 3.2.4b:** Fleet capacity and weighted average utilisation (load factor) of thermal generation. System Change pathway.

# 3.3 Interconnection

The System Change pathway sees the fastest growth in interconnection capacity[35] resulting in the most well connected system by 2035. Net transfer capacity increases by a factor of 2.4 by 2035 relative to 2020, whereas the Technology Driven pathway expands interconnection by a factor of 2.1.
All pathways expand to the same extent by 2025, according to the ENTSO-E reference grid. After this, a maximum potential growth in each timestep is defined on each border.[36]

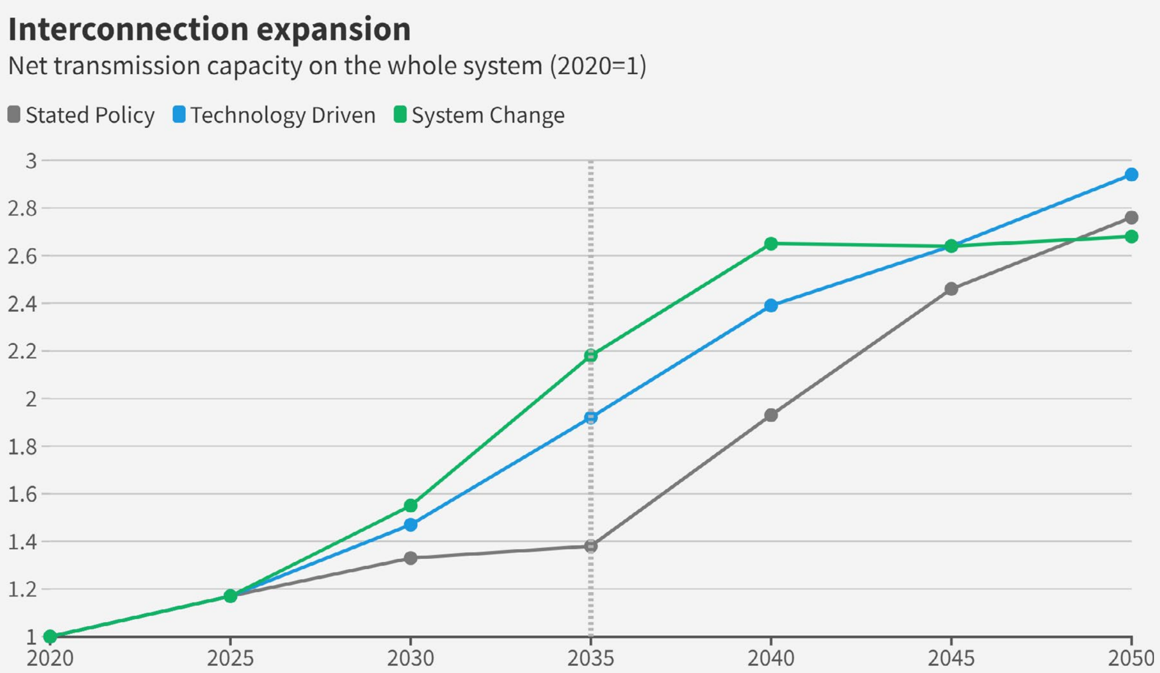



**Figure 3.3.1:** Evolution of total net transfer capacity (interconnection) in the three main pathways, relative to ENTSO-E's 2025 reference grid (common to all pathways).

[35] 'Interconnection capacity' and 'net transfer capacity' are used interchangeably.

[36] This potential is based on the list of candidate projects in the TYNDP 2020 power system needs study, which ensures a level of technical feasibility while still allowing room for significant expansion above existing plans.

Both clean power pathways see higher expansion than the Stated Policy pathway which is confined to planned projects[37] and expands by a factor of 1.5 by 2035 (compared to 2020). After 2035 – driven by economic optimisation – the Stated Policy pathway invests heavily in interconnection, reaching parity with other pathways by 2050. This behaviour indicates that there is high value in early investment in this infrastructure.

The cost of increasing interconnection is considerable, but small compared to other investments in the power system. In the System Change pathway, interconnection accounts for 5% of investments between 2020 and 2035. In the Technology Driven and Stated Policy pathways, the investment share is 4% and 3% respectively.

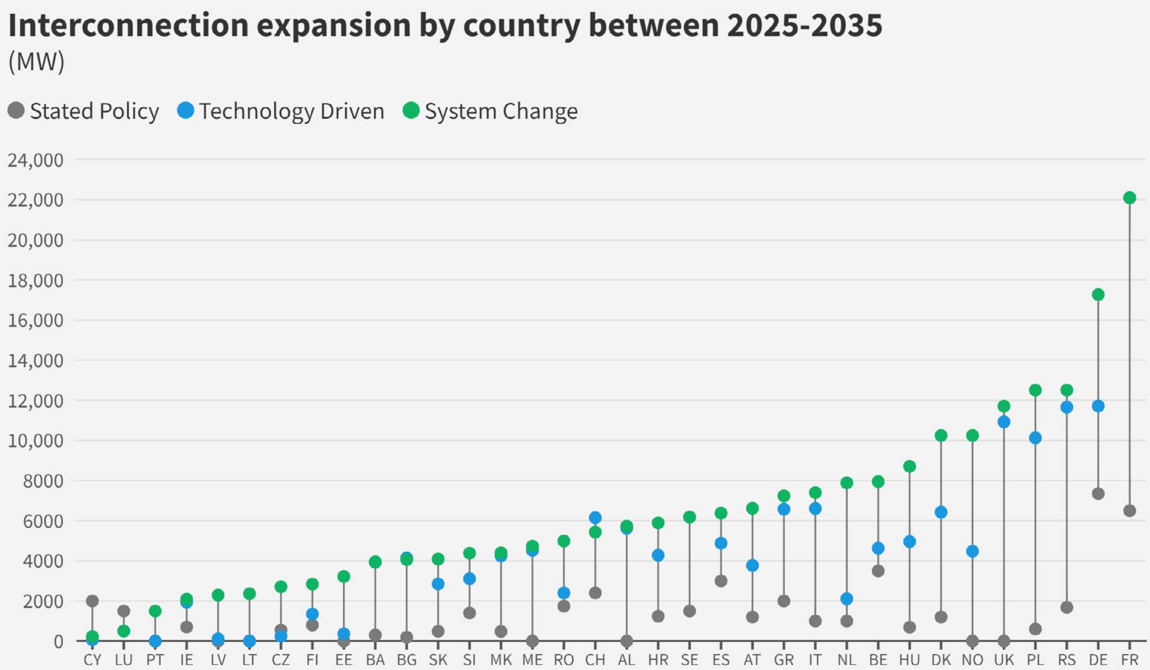



**Figure 3.3.2:** Interconnection expansion by country between 2025 and 2035 (all expansion involving each country is included).

[37] The list of projects and their details are sourced from the TYNDP 2020 Project Sheets provided by ENTSO-E.

In the Stated Policy pathway approximately 50% of expansion between 2025 and 2035 involves countries in West Europe, and a further 30% involve countries in Southern Europe. The proportions are notably different in the clean power pathways where the share of expansion across the four quarters of Europe is more even. While every region in Europe sees additional expansion compared with Stated Policy, approximately 30% of expansion involves countries in West Europe and 30% in South Europe. North and East Europe see significantly higher expansion of interconnection in clean power pathways compared to Stated Policy.

**Interconnector expansion in the Technology Driven scenario between 2025 and 2035, (MW)**

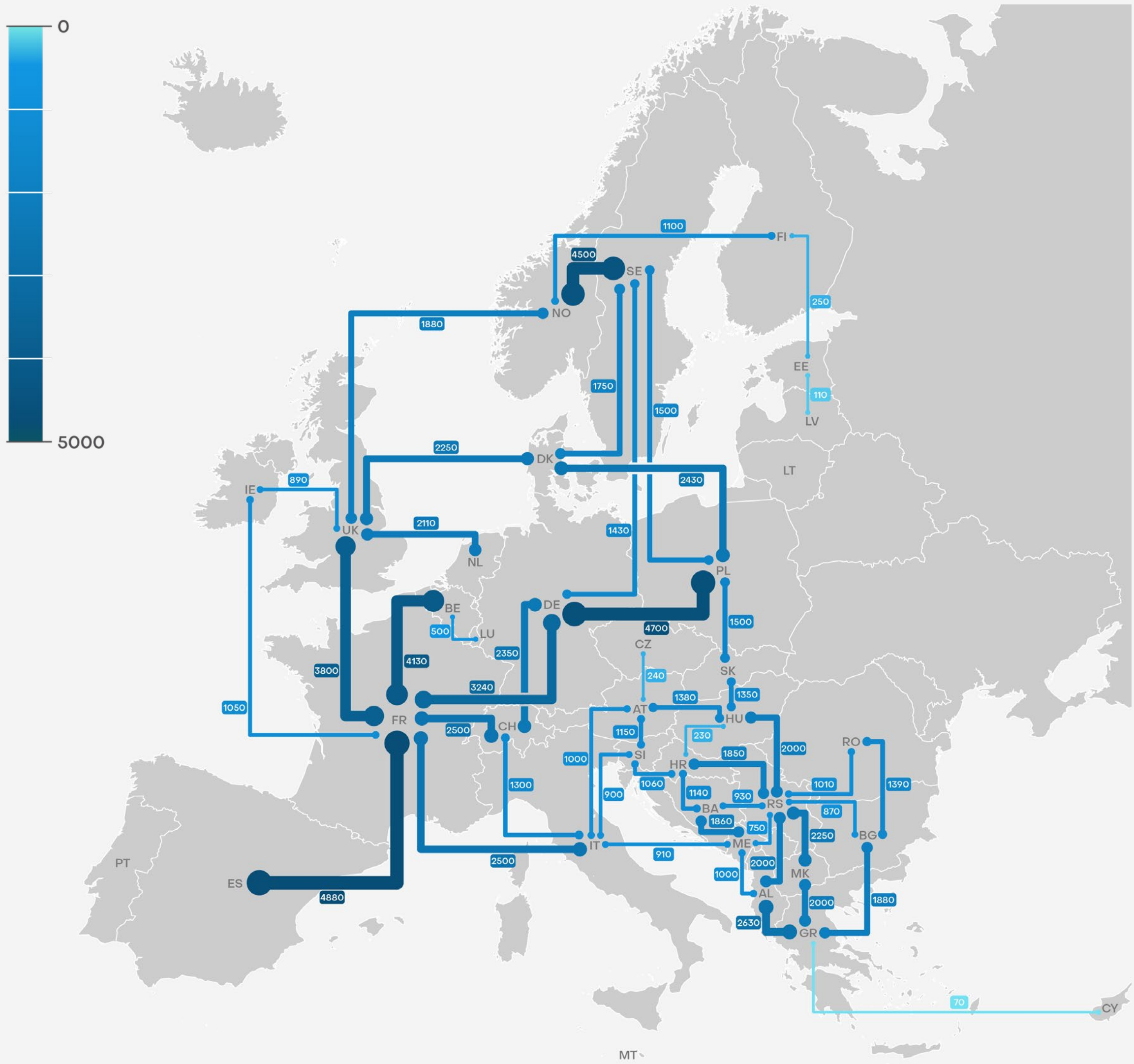



**Figure 3.3.3a:** Map of interconnection expansion on each border, between 2025 and 2035 in the TD pathways.

## Interconnector expansion in the System Change scenario between 2025 and 2035, (MW)

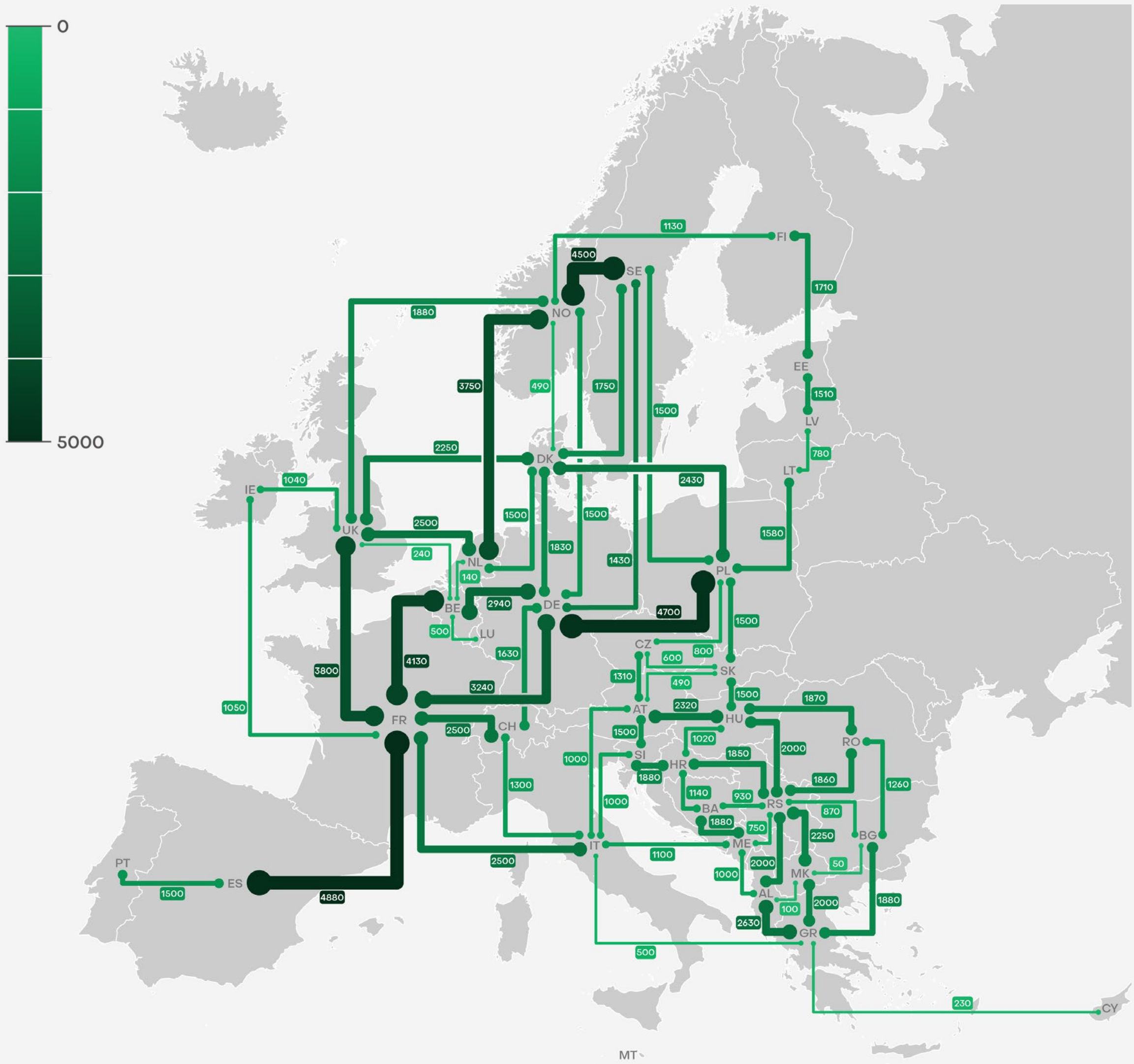



**Figure 3.3.3b:** Map of interconnection expansion on each border, between 2025 and 2035 in the SC pathways.

# 3.4 Storage and hydrogen

Storage technologies play an increasingly vital role in system balancing as the penetration of variable sources of generation increases. The modelled pathways make use of a range of technologies capable of providing storage over timescales of hours (batteries, including vehicle-to-grid), days (pumped hydro), and months (hydrogen).

The capacity of pumped hydro follows national plans, with a fleet of 61 GW in 2035, up 14 GW from 2020, capable of storing an estimated 485 GWh in all pathways.

The deployment of utility-scale batteries is determined by economic optimisation. This leads to an underestimation of deployment because the modelling approach exclusively considers the wholesale electricity market – missing potentially significant revenue streams available to battery projects in grid-supporting markets. To address this bias, higher deployment is explored in sub-scenarios **Technology Driven-B** and **System Change-B** (see Box 3.4.1).

### Box 3.4.1: Modelling of utility-scale battery storage

A two-stage approach was taken to grid-scale batteries. In the core scenarios, the level of battery storage is optimised economically, as are most other key technologies. However, this leads to what is likely an underestimation of battery capacity on the system. This is because the modelling approach, which exclusively considers the wholesale electricity market, does not capture the full value chain available to battery projects. Batteries are not the only technology to provide grid services, but this model limitation disproportionately affects potential battery deployment as the full range of their grid services, including unique functions such as fast frequency response, is not taken into account. This issue was addressed through the introduction of two further scenarios – referred to as Technology Driven-B and System Change-B – in which the deployment levels of battery storage is scaled up. In each case, the size of the battery fleet (assuming a 2-hour duration) is linked to the deployment of solar PV, used as a proxy for the expansion of renewables and thus the likely investment in grid-scale batteries; solar PV was also selected due to the emerging trend of joint solar and storage projects.

A ratio of 10% of battery to solar capacity was chosen, informed by the 2022 TYNDP Distributed energy scenario which shows a similar relationship and takes a similar modelling approach. The results presented in this report are those of the economically optimised case, unless stated. See the technical report for more details.

The impact of adding extra battery storage – a situation which arguably more accurately reflects expected future grid development – is explored in later sections. In summary, the effect of adding almost 100 GW of utility-scale batteries to the Technology Driven pathway by 2035 is a 25 GW (10%) reduction in the gas fleet (abated and unabated), including a 15 GW reduction in unabated gas peakers. These additional batteries also bias capacity deployment in favour of solar over wind, with solar installed capacity increasing by 53 GW (7%) in 2035. In view of this evidence, it is likely the main pathways represent a mild overestimate of thermal capacity requirements, on the order of 10%.

In addition to utility-scale batteries, a fraction of the EV fleet is assumed to provide vehicle-to-grid services (V2G), whereby car batteries can discharge to the grid as well as charge. The resulting storage capacity typically exceeds grid-scale battery capacity in all pathways – even those with additional utility-scale deployment.

The System Change pathway assumes the fastest transition from internal combustion engine to EVs, and the largest proportion of V2G-ready EVs due to high levels of consumer engagement. By 2035, total battery storage available to the model is 842 GWh (1158 GWh in System Change-B), corresponding to 7% (10%) of average daily electricity demand. In the Technology Driven pathway, EV adoption is slower and consumer engagement levels are lower than those in the System Change pathway. This results in a total battery storage capacity of 246 GWh (446 GWh in Technology Driven-B) corresponding to 2% (4%) of average daily electricity demand. The Stated Policy pathway, with battery deployment following the TYNDP 2020 National Trends pathway, and the slowest EV uptake, reaches a combined 148 GWh of battery storage by 2035.

[37] The list of projects and their details are sourced from the TYNDP 2020 Project Sheets provided by ENTSO-E.

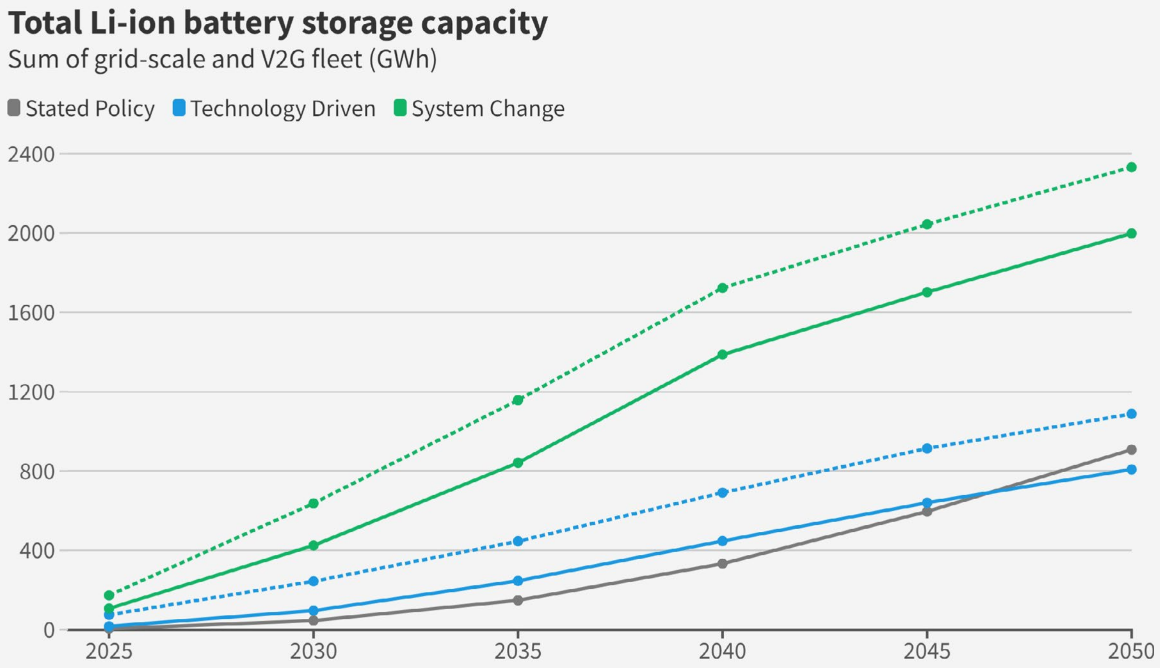



**Figure 3.4.1:** Total battery storage capacity over time, by pathway (utility scale assets and V2G). Dashed lines refer to Technology Driven-B and System Change-B sub scenarios.

The energy storage technology offering the longest storage duration in the model is hydrogen. Electrolysers are modelled as off-takers from the grid, and hydrogen turbines are modelled as generation sources. The deployment of both technologies in modelled pathways is determined by economic optimisation, within limits.[38] This combination allows excess renewable electricity to be stored, and used flexibly on demand.

[38] The deployment of electrolysers is capped at 60 GW in Sated Policy and Technology Driven pathways, in line with the ambition set out in the EU hydrogen strategy.
There are no such restrictions in the System Change pathway. Hydrogen-burning turbines are available in the model from 2030, reflecting the emerging status of this technology.

An external hydrogen demand[39] for the rest of the energy system is estimated (excluding international aviation and shipping), and the modelling supplies this demand through either blue or green production.[40] In the System Change pathway, only green production is used, as the storyline does not foresee commercialisation of CCS technology. Alternative sources of hydrogen, such as extra-European imports, are not included, hence the hydrogen supply is by default 100% domestic and grid-connected in all pathways. Gas networks are not explicitly modelled. To minimise the impact of this limitation, it is mandated that each country must produce 50% of its own demand domestically.
The potential system impact of alternative hydrogen supplies (imports or off-grid production), and relaxing the domestic supply criterion, are explored in a sensitivity scenario (see Box 4.3.2).

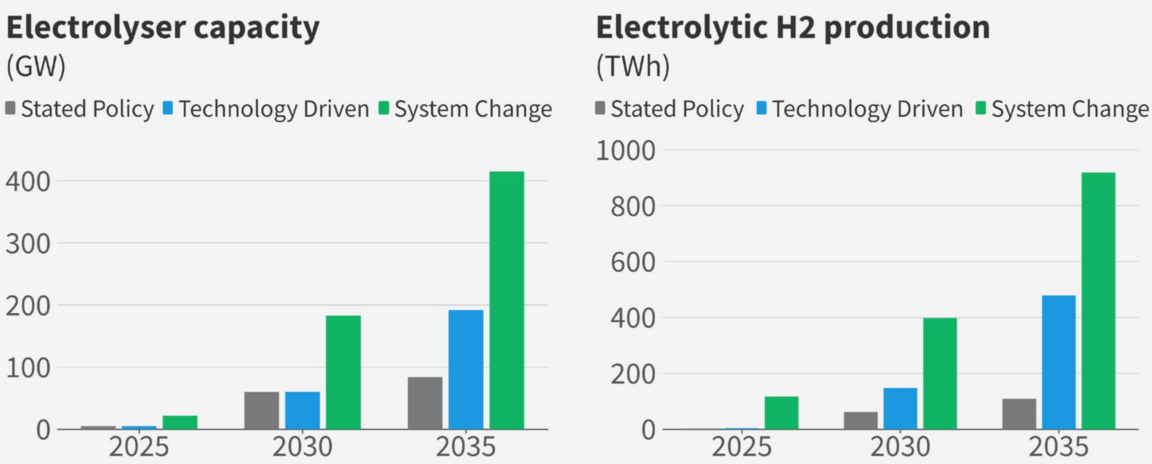



**Figure 3.4.2:** Electrolyser capacity and electrolytic hydrogen production in all modelled pathways.

[39] See the technical report for more details on the assumptions underpinning the estimated external hydrogen demand.

[40] Blue and green hydrogen routes are available to the Stated Policy and Technology Driven scenarios. Green production is explicitly modelled via electrolysis. Blue hydrogen is assumed to be available at a fixed price set to match forecasts in the IEA World Energy outlook (2021). Only green hydrogen is available to the System Change pathway, as the storyline does not see commercialisation of CCS technology, this is why electrolysis capacity is also not capped.

The electrolyser fleet in the Technology Driven pathway reaches 60 GW by 2030, and operates with a ~25% capacity factor to produce 150 TWh or 5Mt per year, supplying approximately half of estimated European hydrogen demand. This amount of green hydrogen is less than the EU27 target set out in the REPowerEU plan of 10Mt domestic renewable hydrogen, plus a further 10Mt of imports. By 2035, however, a fleet of 190 GW produces 480 TWh (14Mt) of green hydrogen annually. This cost of green hydrogen quickly falls as electrolysers become cheaper and cheap (excess) wind and solar power becomes abundant. Correspondingly, the share of blue hydrogen in total supply falls from 50% in 2030 to 4% by 2035. By 2050, a fleet of 380 GW is producing 1200 TWh annually, of which 200 TWh is consumed by hydrogen turbines in the power sector, supplying peak power as the thermal fleet is decarbonised.

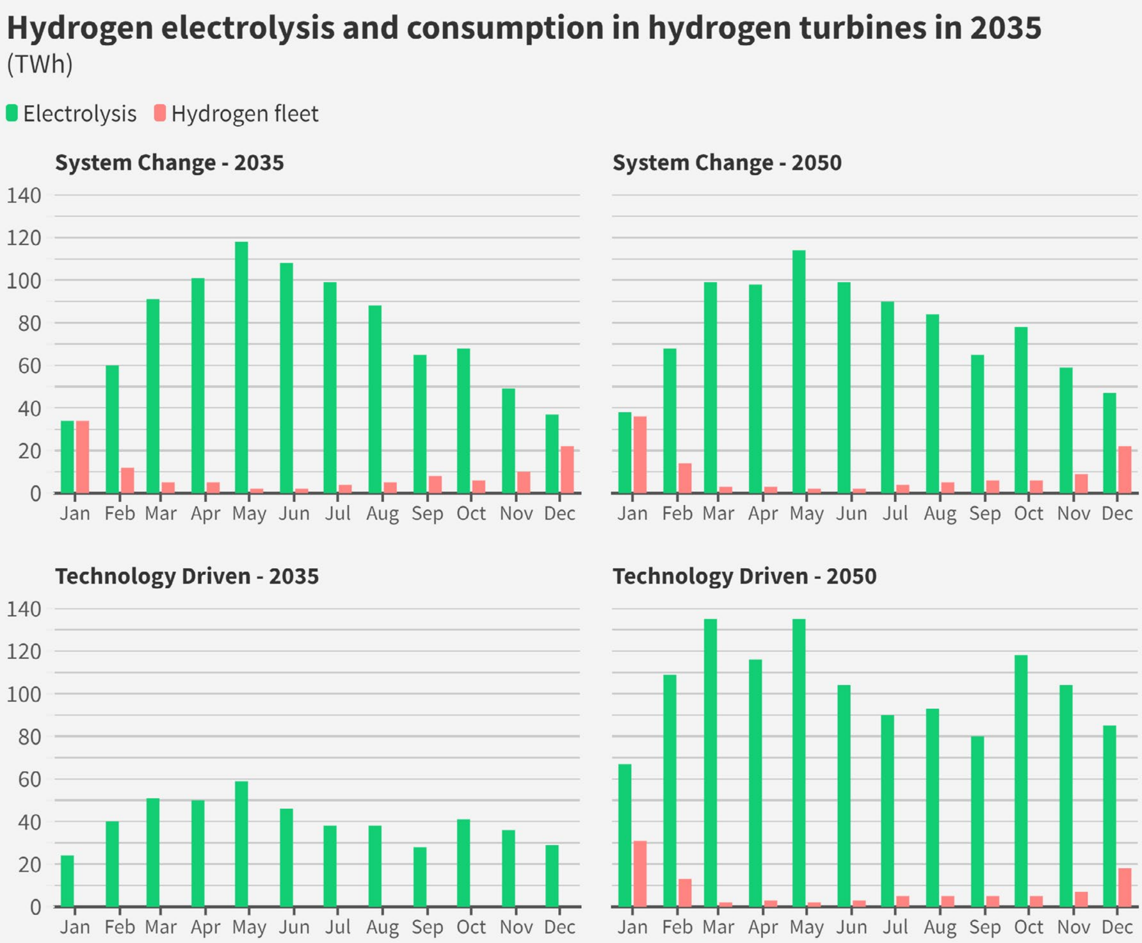



**Figure 3.4.3:** Monthly production of green hydrogen and monthly consumption in hydrogen turbines, in System Change (top) and Technology Driven (bottom) pathways, in 2035 (left) and 2050 (right).

Consumption of hydrogen for power production occurs primarily in the winter months to support the power system through high demand peaks. In contrast, hydrogen production peaks in summer, when solar power is more abundant.

In the System Change pathway, a green hydrogen system develops more rapidly, driven by a larger hydrogen demand, faster deployment of renewables, and a need for clean dispatchable capacity as unabated fossil generation is phased out earlier. By 2030, electrolyser deployment reaches 183 GW, a figure which exceeds current EU27 targets, but can still be considered reasonable in the short-term; Aurora's global electrolyser database has identified a 142 GW pipeline of electrolyser projects in Europe expected to be completed by 2030.[41] This fleet in 2030 produces 400 TWh (12.5Mt) per year, exceeding the EU27 target of 10Mt by 2030. By 2035, an electrolyser fleet of 415 GW produces 900 TWh (27Mt) of green hydrogen annually, one quarter of which is consumed by hydrogen turbines in the power sector.

## 3.5 System costs and investment

Cost considerations are a crucial component of the modelling. In conjunction with the carbon budget they inform investment decisions in new power system infrastructure and its utilisation. System development in the Technology Driven and System Change pathways is computed following cost-minimising principles (within the framework of each storyline). In contrast, system development in the Stated Policy pathway is pre-determined until 2035, and dictated by cost minimisation after this date.

The cost calculations presented here include **power system costs** as well as other energy supply costs, to account for different levels of electrification (and hence avoided fossil fuel costs). Where these are combined they are referred to as **total system costs**; a metric that covers the same scope of energy services between pathways, not just the power system. See Box 3.5.1 for definitions and an overview of the system cost methodology. Table 3.5.1 provides an overview of the cost results.

[41] auroraer.com/media/companies-are-developing-over-200-gw-of-hydrogen-electrolyser-projects-globally-85-of-which-are-in-europe

The total system cost calculations reveal that the clean power pathways described in this study can be delivered at a lower overall cost than the Stated Policy pathway. By 2035, total savings in the clean power pathways relative to Stated Policy amount to between **€530–1010 billion**. This is likely an underestimate as high fossil fuel prices in 2022 and likely following years are not taken into account.

### Box 3.5.1: System cost methodology

The pathways in this report explore a range in the level of power system decarbonisation, electrification, efficiency measures, and energy savings. Costs are a critical component of the modelling. The main objective of power system modelling is to match supply with demand at least cost, therefore minimising power system costs within each pathway and within the constraints of each storyline. However, comparison of costs between pathways is more difficult. A larger power system in one pathway implies cost savings elsewhere (i.e., avoided fuel costs), which are not captured by considering power system costs alone. In order to capture these trade-offs, cost calculations are provided at two levels:

**Power system costs:** includes operational and investment costs relating to electricity supply and transmission (interconnection). No adjustment is made for the fact that the power system reaches different sizes (total supply) at different times across the three pathways. These costs are used to calculate the average (unit) cost of electricity supply.

**Total system costs:** includes power system costs, plus operational and investment costs relating to hydrogen supply, plus costs associated with selected energy supply outside of the power sector. These other energy supplies are counted in sectors where electrification is increased in the clean power pathways, namely industry, transport, and buildings (space heating). Total system costs are therefore more comparable across pathways, as they capture the avoided (mainly fossil fuel) costs arising from increased (direct and indirect) electrification, as well as the impact of energy saving and efficiency measures in the pathway storylines.

Further details on cost calculations are provided in the accompanying technical report.

| €2020 billion | Stated Policy | Technology Driven | System Change |
|---|---|---|---|
| Power systems costs* until 2035 | 4,660 | 4,610 | 4,560 |
| Energy systems costs until 2035 | 8,150 | 7,620 | 7,140 |
| Energy systems cost savings by 2035 | – | 530 | 1,010 |
| Investment requirements** before 2035 | 1,330 | 1,630 | 2,080 |
| Additional investments by 2035 | – | 300 | 750 |

*Both power system and energy system costs are given as a cumulative sum of annualised costs between 2020 and 2035. **Investment requirements are the sum of overnight investment in the power system between 2020 and 2035.

**Table 3.5.1:** Summary of pathway  costs in the clean power pathways versus Stated Policy.

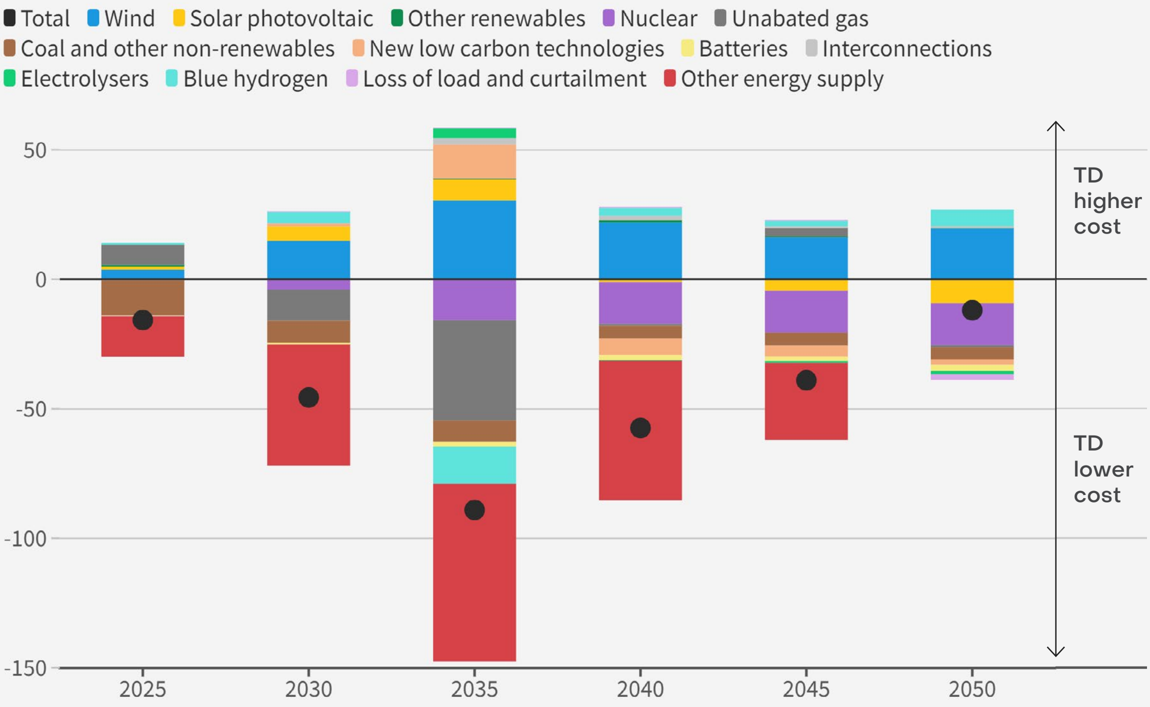
## System costs: Technology Driven (1.5C) vs Stated Policy

**Power system costs** in the Technology Driven remain comparable to the Stated Policy pathways, despite Technology Driven supplying 26% more electricity by 2035. Larger upfront capital costs for wind and solar in the power system are offset by avoided carbon costs and avoided costs associated with new nuclear and fossil capacities.

Annual coal power costs are €8–10 billion lower in the Technology Driven pathway between 2025–2035, with savings split equally across capital and operational costs.

## Difference in annualised system costs between Stated Policy and Technology Driven pathways

Technology Driven - Stated Policy (€bn/year)




Notes: Annualised system costs include investment costs, fixed operating costs, variable operating costs, fuel costs, and carbon costs. The 'Other energy supply' estimates the cost savings resulting from reduced fossil fuel supply outside of the power sector, as a result of electrification or reduced energy consumption.

**Figure 3.5.1:** Difference in annualised system costs between the Technology Driven and Stated Policy pathways. (cost as presented as Technology Driven minus Stated Policy, meaning positive values represent additional costs of the Technology Driven pathway, and negative values represent cost savings).

By 2035 the coal fleet is half that of the Stated Policy pathway, and it generates only a third as much electricity, resulting in much lower fuel and CO2 costs.

In 2035 a significant difference in nuclear costs emerges as the Technology Driven pathway avoids the investment costs required to maintain a larger nuclear fleet, which falls to 62 GW compared to 90 GW in Stated Policy.

Unabated gas costs are temporarily higher in 2025 driven by investment in gas peakers, but savings accrue thereafter, reaching €12 billion per year by 2030 and €39 billion per year by 2035.

Avoided $CO_2$ costs deliver the bulk of this €39 billion annual saving in 2035 (€15 billion), while a smaller unabated gas fleet results in lower annualised capex (€10 billion) and reduced fuel costs (€10 billion). This demonstrates that the investments in unabated baseload gas in Stated Policy after 2025 are neither cost efficient nor required to achieve clean power by 2035.

In 2030 and 2035 the largest excess cost is wind power, adding €30 billion per year by 2035, stemming mostly from increased capital costs. The next largest sources of excess costs are gas CCS and solar. However, these additional costs to the power system are more than offset by reduced coal, gas, and nuclear costs previously described.

While costs to the power system are approximately balanced, the additional supply provided in Technology Driven is used to further electrify, which in combination with additional energy savings creates a bigger cost difference between the pathways in terms of **total system costs**. Annual cost savings from avoided fossil fuel consumption peak at €90 billion in 2035. Cumulative savings over the period 2020–2035 amount to €530 billion (or 6% of Stated Policy costs).

After 2035, the margin of difference in annual costs gradually reduces as the Stated Policy pathway sees increased deployment of wind and solar, displacing fossil fuels on the path to zero emissions by 2050. Nuclear costs continue to be higher in the Stated Policy pathway as this technology is locked in by investments made pre-2035. Wind costs remain higher in the Technology Driven pathway and a higher wind dependency persists, with the fleet reaching 1.2TW by 2050 compared to 1TW in Stated Policy. The opposite is true for solar, with the Stated Policy pathway showing a larger fleet after 2040, resulting in higher investment costs.

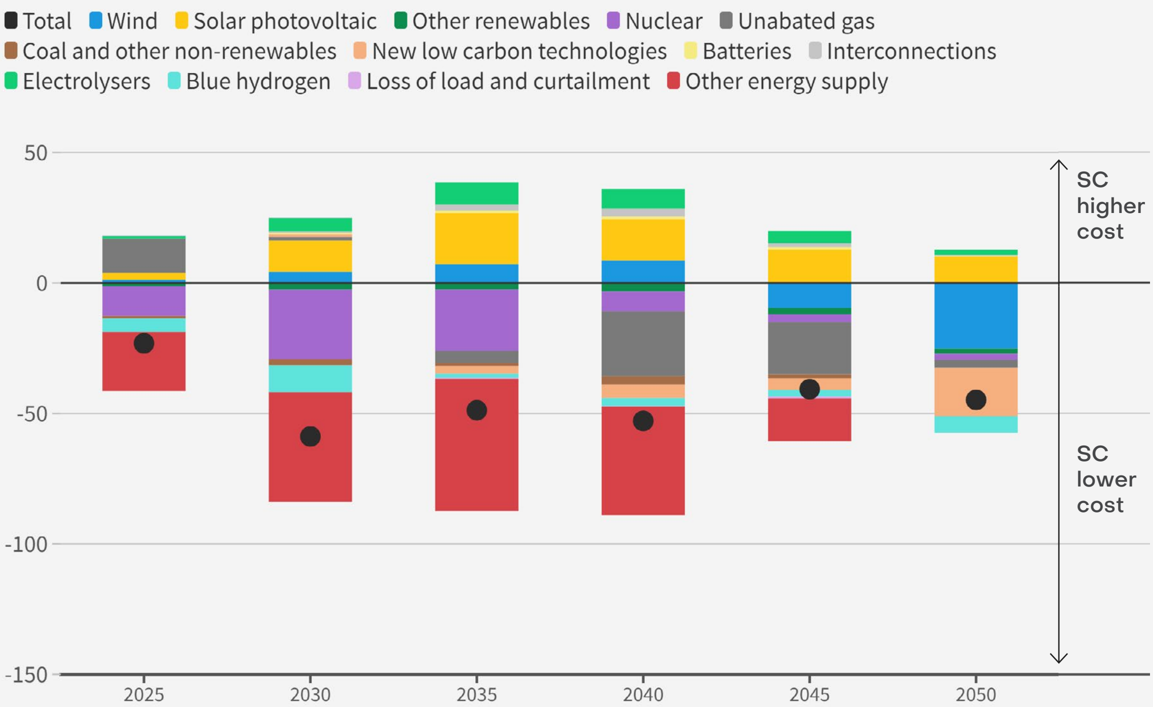
In summary, power system costs in the Technology Driven scenario are consistently lower but similar to Stated Policy. This is because Stated Policy prolongs reliance on costly fossil fuels and continues to invest in expensive and unnecessary new nuclear assets, while limiting deployment of cheap wind and solar. The annual costs eventually equalise towards 2050 as the pathways converge the most cost-efficient, renewables-led configuration. However, across the whole pathway, the cost of delayed action encapsulated by the Stated Policy pathway is an 8% increase in total system costs, or €820 billion (€530 billion by 2035). The unprecedented increases in fossil fuel prices seen in 2021–2022 are not accounted for in these calculations, meaning the cost of a delayed transition is likely even higher than this estimate.

## System costs: System Change vs Technology Driven

The System Change pathway represents an increase in ambition relative to the Technology Driven pathway. Specifically, societal change and a shift to a more circular economy enable energy consumption savings, and delivery of clean technologies is accelerated.

**Difference in annualised system costs between Technology Driven and System Change pathways**

System Change - Technology Driven (€bn/year)




Notes: annualised system costs include investment costs, fixed operating costs, variable operating costs, fuel costs, and carbon costs. The 'Other energy supply' estimates the cost savings resulting from reduced fossil fuel supply outside of the power sector, as a result of electrification or reduced energy consumption.

**Figure 3.5.2:** Difference in annualised system costs between the System Change and Technology Driven pathways: alternative routes to achieve clean power by 2035. (cost as presented as System Change minus Technology Driven, meaning positive values represent additional costs of the System Change pathway, and negative values represent cost savings).

This faster transition delivers further **total system cost** reductions compared to Technology Driven, amounting to €480 billion (6%) by 2035. Compared to the Stated Policy scenario, cumulative savings amount to €1010 billion (12%) by 2035.

**Power system costs** remain similar throughout the main phase of the transition (2020–2035), while total electricity supply is 8% higher by 2035 due to higher demand from P2X. Power system costs in System Change become cheaper after 2035 as continued energy savings result in a relatively smaller power system. By 2050, total electricity supply is 15% smaller than Technology Driven, and annual power system costs are 13% lower.

Until 2035, the System Change pathway is characterised by higher capital costs for wind and solar, gas peakers (in 2025) and electrolysis. These are balanced by the lower costs of a smaller nuclear fleet and the avoided costs of sourcing alternative (not green) hydrogen.[42]

Cost reductions resulting from faster fossil phase-out in the power system can also be seen. The System Change pathway uses a 50% smaller unabated gas fleet in 2035, delivering significant savings in operational costs, as a fleet of low-utilisation unabated gas is not maintained. Annual savings peak in 2040, when CO2 cost savings are €13 billion per year, and €8 billion is saved in fuel costs.

These savings in nuclear and fossil are balanced by the higher capital costs associated with a larger wind and solar fleet and further expansion of interconnection, meaning total power system costs remain comparable.

Despite deploying a large fleet of hydrogen turbines from 2035 (130 GW), the annual costs for clean firm generation are lower in the System Change pathway. For upside flexibility, from 2035, the Technology Driven pathway uses a comparatively small gas CCS fleet (34 GW) in combination with low-utilisation unabated gas (228 GW), with hydrogen turbines introduced in the 2040s. The reason for this cost pattern is that while capital and fixed operating costs in clean firm capacities are higher in System Change, variable operational costs are lower. The avoided cost of fossil gas for CCS plants is the main reason, as well as CO2 costs for residual emissions. The System Change scenario sees additional costs from electrolysis (partly to fuel the hydrogen fleet), but these are comparable on an annual basis to the cost savings in the clean dispatchable fleet.

In summary, **power system costs** in the System Change pathway are comparable but consistently lower than the Technology Driven and Stated Policy pathways until 2035, despite delivering the largest electricity supply in 2035. Up to 2035 these cost trends can be explained by an even faster phase-out of fossil fuels and nuclear power in favour of cheap wind and solar.

[42] All hydrogen production in the System Change scenario is green hydrogen.

Considering the wider energy system, higher electrification and further energy savings mean that **total system cost** savings over 2020–2035 add up to €480 billion relative to Technology Driven and €1010 billion relative to Stated Policy.

### Box 3.5.2: System cost scope: estimating the impact of missing costs

There is no agreed upon scope by which to calculate the total 'cost' of an energy system. This study focuses on the power system, but the pathways created produce different amounts of electricity and green hydrogen. This has an obvious impact beyond the power system, as more end-uses can be electrified with a larger power supply, saving fuel costs. For this reason, the system cost calculations attempt to cover the same scope of energy services when comparing pathways (i.e., all the fuel costs for cars, not just electric cars).

In addition to these considerations around scope of energy supply, the modelling apparatus that is used – like all models – is a simplification of the power system. The European network is represented as a connected network of connected 'nodes', with each country represented by a single point. This captures the important exchanges between countries, but neglects power system infrastructure internal to countries (national transmission and distribution systems). Moreover, gas grids are not included – it is assumed that each country can access a gas supply at a given price, free from supply constraints. Similarly, any costs resulting from the need to repurpose or redeploy gas infrastructure for use with hydrogen are not captured.

This study only presents **comparative** system costs between pathways. This ensures that any neglected costs that are comparable in size between pathways will be cancelled out, leaving only the cost differences of the energy services that are in scope. As a result of this approach, misleading cost patterns will only result from cases where a neglected cost is significantly different between the pathways. For this reason, costs associated with interventions that happen in all pathways are not considered to have a big impact on system costs. An example would be infrastructure to electrify the car fleet, e.g., charging points, as all pathways end with a fully electrified fleet.

Potentially significant missing costs, i.e., ones that might differ between pathways include:

- Hydrogen storage and transmission,
- Intra-national electricity transmission and distribution grids,
- Efficiency measures (building renovation)

Hydrogen plays a different sized role in each pathway, and estimated consumption grows at different rates. By 2035, total consumption is estimated to be 340 TWh in Stated Policy, 500 TWh in Technology Driven, and 920 TWh in System Change. By 2050 consumption is more even, at 950–1200 TWh. As a result, total pathway costs should be relatively unaffected, as the system develops regardless, but storage costs will increase sooner for System Change than other pathways, which is relevant for upfront investment costs. If it is assumed that 25% of annual consumption is required in storage capacity, as suggested by Gas Infrastructure Europe (GIE),[43] the requirements in 2035 across pathways would be 85–230 TWh, or a difference of 4.5Mt. At an estimated capex of €27 per kgH2 (GIE), this amounts to an extra investment of €120bn, or 16% of the additional investments already estimated for the System Change pathway relative to Stated Policy by 2035.

In a similar way to hydrogen gas networks, transmission system reinforcement will be required in all pathways to cope with higher peak power demand. Peak power demand doubles in Technology Driven and Stated Policy by 2050, but the largest increase observed in System Change is 70%, implying less transmission expansion may be required in the latter pathway. However, different levels of activity at the distribution level, as a result of consumer (and prosumer) behaviour could imply different requirements for distribution grid strengthening.

[43] Gas Infrastructure Europe: Picturing the value of underground gas storage to the EU H2 system, 2021

The System Change pathway assumes the largest contribution of vehicle-to-grid services, implying costs could be systematically higher than presented. However, analysis of multiple case studies[44] has revealed that in total, transmission and distribution system costs typically only amount to 10–15% of whole system costs. Therefore, relative differences between pathways – given each will require development in this area – are likely to be small.

Finally, the System Change pathway reduces demand for space heating faster than Technology Driven or Stated Policy by assuming a higher building renovation rates are reached faster although all pathways eventually assume greatly improved building efficiency by 2050. The costs of such renovations will likely pay back over the duration of the modelled pathway, but this adds another source of upfront cost that is not accounted for. It is estimated that €275bn per year of extra finance until 2030 will be required to deliver the EU's proposed renovation wave.[45] This is substantially larger than the approximately €120bn per year required in power system investments in the System Change pathway to 2030. Similarly, the European commission estimates that annual additional investments to achieve the Fit-for-55 targets will be twice as high for buildings as for the power sector. It is not possible to estimate the scale of the difference in required building investments between pathways, but it is likely to represent a substantial additional investment in all pathways, peaking earlier in the System Change pathway than others.

## The cost of electricity supply

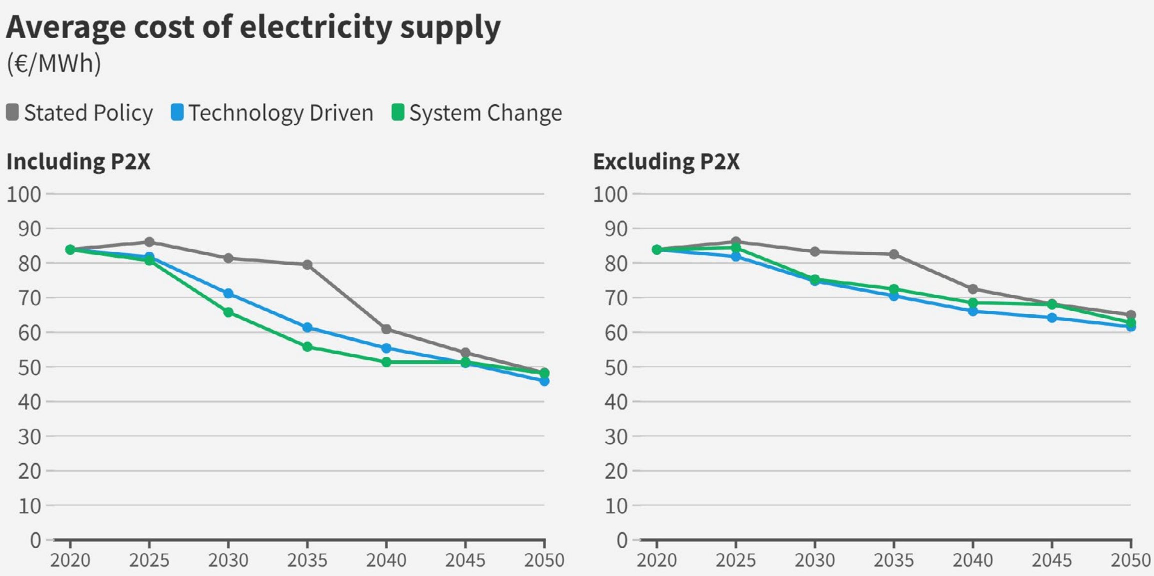
The average cost of electricity declines in all pathways as cheap wind and solar increasingly dominate the system. As explained above, the clean power pathways have comparable **power system costs** to Stated Policy until 2035, while delivering a larger supply of electricity. As a result, the clean power pathways deliver electricity at a lower unit cost.

[44] Brown et al. (2018): Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'.

[45] Estimate by the Green Finance Institute: Unlocking the trillions

The difference is largest in 2035, with clean power pathways supplying electricity at 23–30% lower cost per unit. This includes the power supply required to run P2X installations, which play a much larger role in the clean power pathways, and account for much of the additional electricity supply. However, If this supply is removed, the average cost of electricity supply for direct energy consumption is still lower in clean power pathways by 14–15% in 2035.

These results show that Europe's power supply can be decarbonised and expanded, and in doing so the cost of electricity will become cheaper. These calculations are based on a stable (and gradually decreasing) outlook fossil fuel prices.[46] The unprecedented increases in fossil fuel prices seen in 2021–2022 have only made renewable sources even more competitive on a cost basis, exacerbating the cost trends presented here.




Notes: These figures represent the annualised cost of the electricity system per unit of electricity supply (with and without counting the supply to operate power-to-X facilities). Annualised costs include investment and operational costs of electricity generation and interconnections assets (transmissions between countries).

**Figure 3.5.3:** The annualised cost of the electricity system per unit of electricity supply (including and excluding the supply to operate P2X facilities). Annualised costs include investment and operational costs of electricity generation and interconnections assets (transmissions between countries).

[46] From the IEA WEO 2021 Announced Policies scenario.

## Investment requirements

It has been demonstrated that clean power pathways can be delivered at comparable cost to the power system, and higher electrification plus energy savings can deliver total system cost savings of €530–1010 billion by 2035 relative to Stated Policy. However, each step up in ambition, from Stated Policy to Technology Driven to System Change, requires higher power system investments in the short term. These investments are evidently cost-effective, but nevertheless present a major policy and delivery challenge.

The Technology Driven pathway requires total power system investments of €1.6 trillion by 2035, which is €300 billion (23%) more than Stated Policy. This **additional** investment is equivalent to 0.1% of annual EU27 over the period (2020–2035). Lower investment in coal, gas, and nuclear capacities are not enough to offset the additional investments in wind and solar. The 'investment gap' grows until 2035, when additional investments in gas CCS, electrolysers and interconnection add to the difference (Figure 3.5.2). However after 2035, the pattern switches as investments in the Stated Policy pathway increase radically in order to reach zero emissions by 2050.

The System Change pathway requires total power system investments of €2.1 trillion by 2035. This is €450 billion (28%) more than the Technology Driven and €750 billion (56%) more than Stated Policy by 2035. The additional investment needs relative to Stated Policy are equivalent to 0.3% of annual EU27 GDP over the period 2020–2035. Investment needs equalise in the 2040s between System Change and Technology Driven, and become relatively smaller thereafter as ambitious energy savings continue, meaning the zero carbon system does not require further expansion after 2040.

In general, by 2035, investment in clean power pathways is dominated by wind and solar power, which require €1.3–1.6 trillion. Other significant investments include €50–100 billion for clean dispatchable capacities to support variable wind and solar generation. Investment of €75–100 billion is needed to expand interconnection by 2035, double the investment in this area in Stated Policy. €60–120 billion further investment in electrolysers by 2035, as seen in System Change, could supply all of Europe's estimated hydrogen demand with domestic green hydrogen.

Total cumulative investment in each pathway across 2020–2050 is similar at an estimated €2700–3000 billion, meaning that Technology Driven and System Change pathways represent different extents of front-loading, rather than total capital injection. There is evidently high value in front-loading investments in a clean expanded power system, with savings unlocked amounting to an estimated €1 trillion by 2035, and the cost of electricity reduced.

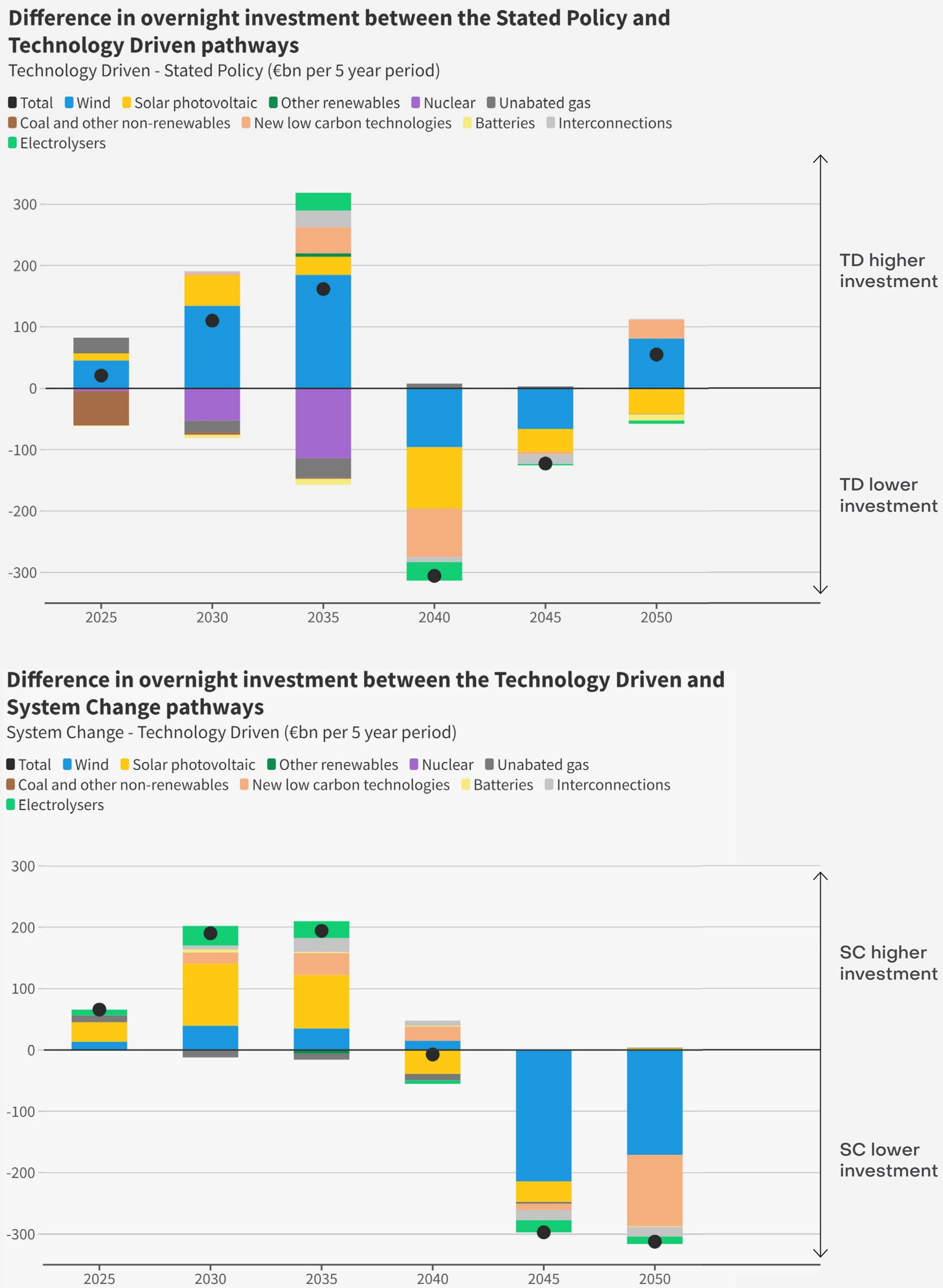



**Figure 3.5.4:** Difference in overnight investment costs (billion Euros per 5-year period). Top: Technology Driven minus Stated Policy pathway. Bottom: System Change minus Technology Driven pathway.

# Emergent themes

This section presents the main conclusions drawn from the modelled pathways. Each finding is accompanied by policy recommendations.

## 4.1 Clean power is cheaper than stated policies

**Reaching clean power by 2035 is not only necessary but can be achieved at no extra cost than stated policies.**

The clean power pathways in this report represent least-cost solutions to supplying an increased demand for electricity, within a carbon budget compatible with 1.5C. They achieve a 94–96% clean share of electricity by 2035, i.e. unabated fossil fuels provide only 4–6%. In contrast, the Stated Policy pathway reaches 86% clean power by 2035, and in doing so exceeds the estimated carbon budget for a 1.5C compatible pathway.[47]

While the System Change pathway mandates total fossil phase-out before 2040, the Technology Driven pathway does not – rather it represents a solution driven by economics using a wider range of technologies.

[47] Technology Driven and System Change pathways are computed within carbon budgets of 9 and 8 $GtCO_2$ respectively (for the power sector). Cumulative emissions in the Stated Policy pathway reach 10 $GtCO_2$ while delivering less electricity cumulatively and by 2035.

The emergence of ~88% clean power by 2030 and ~95% clean power by 2035 in both pathways is a clear indication that early decarbonisation of the power system constitutes a crucial milestone in cost-effective and 1.5C-compatible pathways.

The results presented here add to the growing consensus that advanced economies must largely decarbonise power systems by 2035, and such action is an essential feature of **credible and economic** pathways towards fully net zero energy systems by 2050 at the latest. The same conclusion is reached by the IEA, who in June 2021 recommended that advanced economies (such as those of Europe) reach net zero electricity emissions by 2035. The latest mitigation scenarios from the IPCC for 1.5C (low overshoot) also show that advanced economies achieve near-total power sector decarbonisation by 2035.[48]

The main driver behind this new benchmark is simple – wind and solar power provide a low cost, high potential form of emissions mitigation. Much of the emissions mitigation in the modelled pathways happens before 2030, by which point the clean share of electricity is 88–89%, highlighting this decade as critical for Europe's energy transition.

Analysis of costs in relation to the Stated Policy pathway reveals that an expanded clean power system can be created by 2035 at comparable cost to the power system. Larger upfront capital costs for wind and solar in the power system are offset by avoided carbon cost, and avoided capital and operational costs associated with fossil and new nuclear capacities.

### Additional electrification made possible by an expanded power supply delivers total cost savings of €530–1010 billion by 2035

The additional electricity (and green hydrogen) supply unlocks further electrification in the economy, leading to total cost savings of €530–1010 billion by 2035 as a result of avoided fossil fuel consumption in other sectors (transport, industry, buildings, see section 4.2). This is likely an underestimate as the unprecedented increase in fossil fuel prices in 2021–2022 are not accounted for. The expanded power supply in clean power pathways allows direct electrification to reach 40–47% by 2035, compared to 30% under Stated Policy. The clean power pathways achieve the triple feat of swiftly reducing emissions, boosting electrification, and lowering costs.

[48] As shown by Ember analysis of IPCC AR6 WGIII climate and energy pathways compatible with 1.5C with low overshoot.

**Building a clean, wind and solar dominated power system by 2035 will require an additional upfront investment of between €300–750bn above existing plans.**

While larger upfront investment is needed, cost savings are rapidly realised (as stated above). Extra investment needs are driven by wind and solar deployment, which see €460–720bn invested above existing plans by 2035. These additional capital requirements are partially offset by avoided investments in new nuclear capacities (€170bn by 2035) and unabated coal and gas (€100bn by 2035). Further investment is also required in infrastructure to increase system flexibility.

In other words, accelerating clean power will quickly pay for itself by lowering Europe's fossil fuel bill, without increasing the unit cost of electricity. Meanwhile, receipts to fossil fuel suppliers will be reduced and investment in the European economy will be enhanced. All this provides strong justification for unleashing additional upfront investment in clean power system infrastructure.

## Policy recommendations:

- Place a clean power system by 2035 (less than 5% fossil) at the centre of plans to transition Europe and the EU27 to a net-zero economy by mid century. Without this, the EU27 cannot credibly maintain its status as the leader of the global energy transition.
- Faster action is needed, starting today. In the modelled pathways, the period 2025 to 2030 sees major transformation of the power system, reaching more than 85% clean power. Now is the time to mobilise additional investment in clean power infrastructure for delivery by 2025.

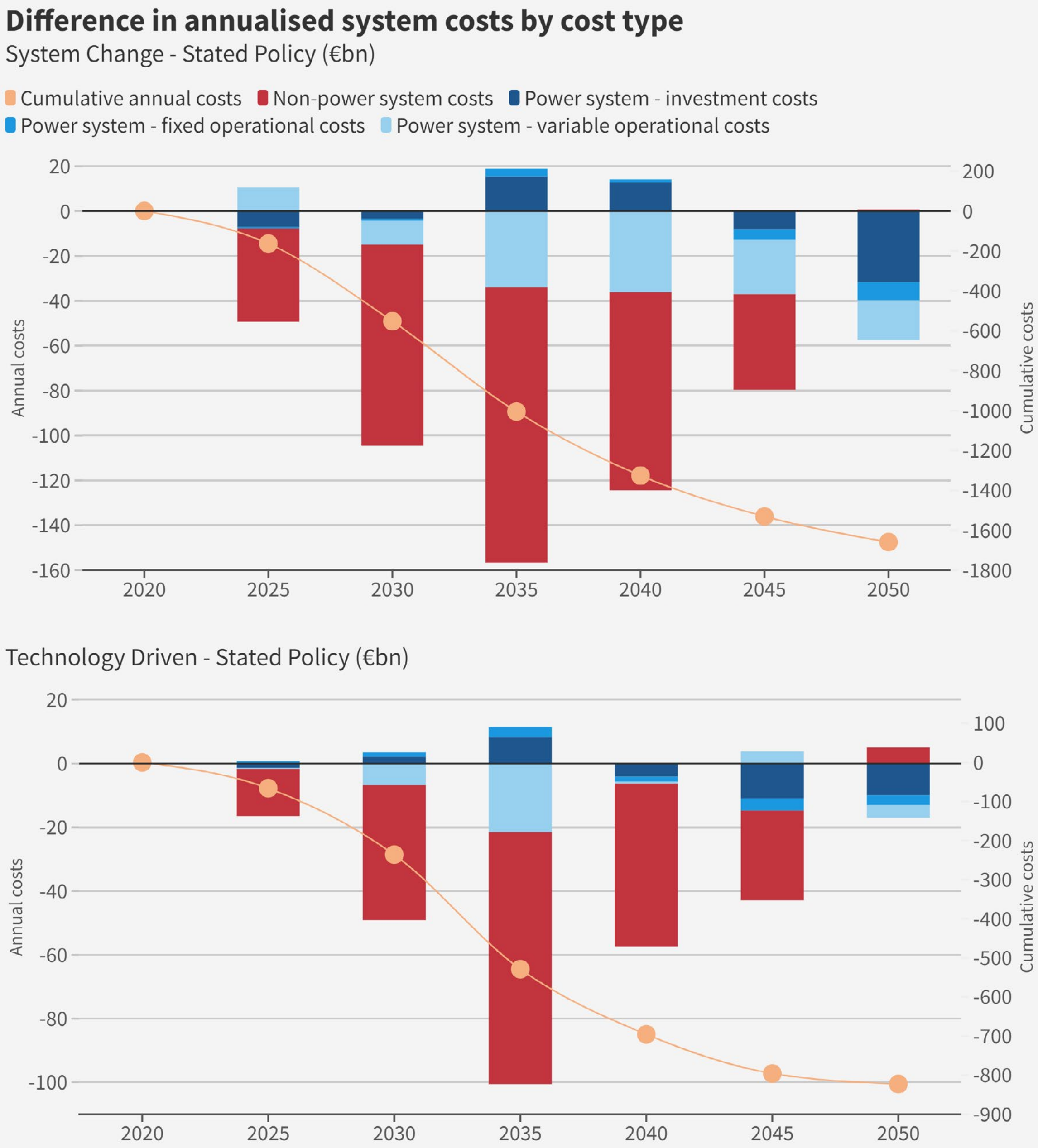



**Figure 4.1.1:** The difference in annualised system cost between the clean power pathways and Stated Policy pathway, displayed as SC minus SP (top) and TD minus SP (bottom). Power system investment costs include annualised capex for generation assets, interconnections, electricity storage, and grid-connected electrolysers. Power system fixed operational costs include maintenance of power generation assets. Power system variable operational costs include fuel and CO2 costs. Non-power system costs capture the estimated cost of fossil fuel supply that is saved by additional energy savings, electrification, and other renewable fuels relative to Stated Policy.

## 4.2 Fossil fuel consumption halves this decade

### A combination of clean electrification and energy savings can reduce Europe's fossil fuel consumption by up to 50% by 2030, improving energy sovereignty.

**Europe is highly dependent on imported fossil fuels.**

The EU27 imports 85% of its fossil gas, with imports from Russia covering 40% of consumption in 2019. Imports provide 64% of the EU's hard coal consumption, approximately half of which comes from Russia. The EU27 is also the world's second largest importer of oil. This state of high exposure to price-volatile energy sources poses a clear risk to the EU27's energy sovereignty and economic stability. Production of oil and gas in the EU27 is on a downward trajectory, and in wider Europe only Norway and the UK have significant production capacities today. New domestic production would take years to scale up, it would be insufficient to impact global prices, and would undermine Europe's climate targets. In this context, pursuing an energy system increasingly based on domestic renewables presents a lower risk path with better outcomes for European consumers, as well as the climate.

**Electrification, efficiency, and energy savings have the potential to reduce fossil fuel consumption in all sectors, unlocking decarbonisation.**

Wind and solar are domestic and plentiful sources of energy; unleashing their potential will be pivotal to protecting Europeans from the whims of fossil fuel exporters by reducing fossil dependency across the entire energy system. Direct electrification of end-uses often delivers major efficiency improvements compared to conventional use of fossil fuels. This is most obvious in the case of space heating and light-duty transport (e.g. cars and vans). Indirect electrification, i.e. replacing fossil fuels with green hydrogen (or derived fuels), is better suited to replace fossil fuels for energy intensive end-uses.

**Primary consumption of fossil fuels can be reduced by up to 50% by 2030.**

Primary consumption[49] of fossil fuels in Europe (and the EU27) is estimated to reduce 38–50% by 2030 in the clean power pathways, compared with an approximate 25% reduction in Stated Policy. The Fit-for-55 plan, if implemented, would reduce consumption by 33%, a smaller reduction than the clean power pathways in this report. Implementation of the REPowerEU plan, which targets gas consumption[50] with a view to ending Russian imports, would half gas consumption in 2030 compared to what it would be under the Fit-for-55 plan. However, this is at the expense of additional coal consumption in 2030, and little extra progress on oil reduction. In total, the REPowerEU plan reduces total fossil consumption by 40%.

Fossil fuel reductions in the clean power pathways are driven by a collapse of coal in the power sector. Total consumption of coal falls by 70–80% in clean power pathways, compared with 60% in Stated Policy. Oil consumption is reduced by 30–45%, driven by electrification of transport, saving 2–3 times more oil than Stated Policy. Finally, gas reductions reach 30–45% in clean power pathways, compared with 20% in Stated Policy. Half of the savings come from the buildings sector in all cases, as a result of increased renovation and deployment of heat pumps. Box 4.2.1 explains in more depth the implications for fossil gas consumption in the EU27. Table 4.2.1 summarises the changes in gas consumption observed in sensitivity scenarios.

**Electrification contributes to approximately 70% of fossil fuel reductions.**

Direct and indirect electrification, combined with the efficiency savings resulting from these technology switches, deliver approximately 70% of estimated fossil fuel reductions by 2030.

The remainder are delivered through energy savings, primarily from building renovation and modal shift in transport, showing that societal change also has a role to play in reducing Europe's fossil fuel dependency. Figure 4.2.2 shows the breakdown in reductions in fossil fuel consumption by type of measure.

[49] The definition used here is equivalent to Total Energy Supply. This includes final energy demand in all sectors, consumption by the energy sector, distribution losses, non-energy consumption, and net transformation inputs. International maritime bunkers and aviation are excluded.

[50] The pathways presented in this report were modelled before the invasion of Ukraine, and hence do not prioritise reduction of one fossil fuel over another.

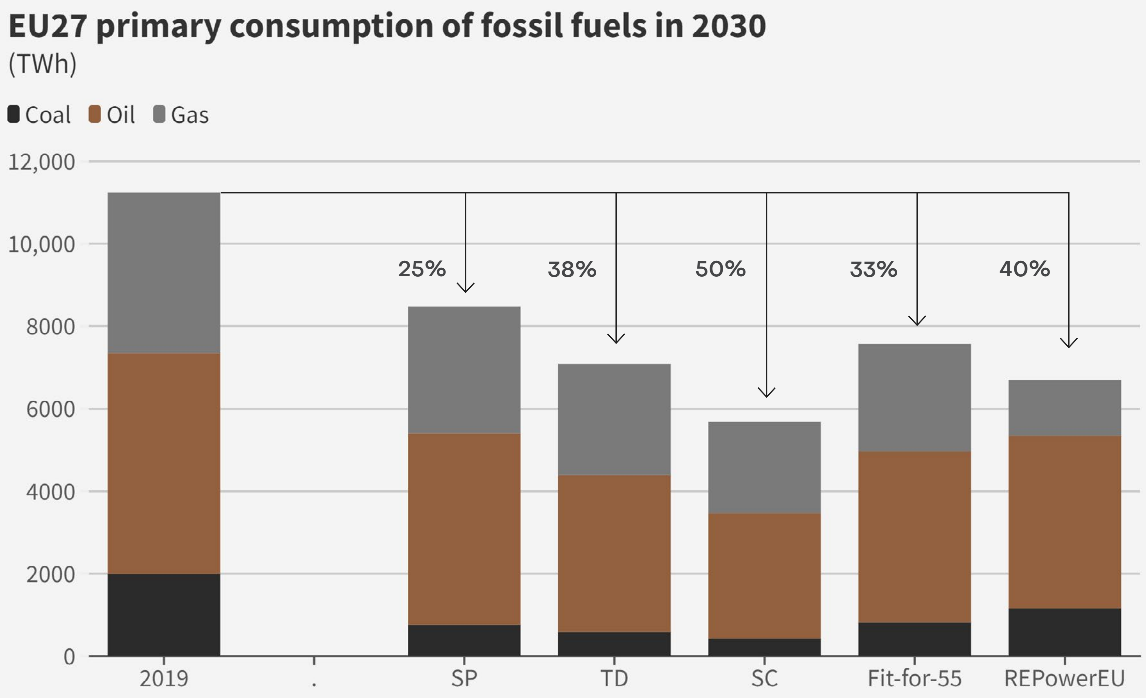



**Figure 4.2.1:** Estimated primary consumption of fossil fuels in modelled pathways in 2030 compared with 2019.

**Fossil fuels in transport.** The vast majority of reductions are either enabled or directly delivered by electrification in the clean power pathways. It is assumed passenger transport activity increases in Stated Policy and Technology Driven, albeit more slowly in the latter. Activity remains unchanged in System Change. However, increased modal shift and electrification in the clean power pathways ensure that any increases in activity do not translate into increased fossil fuel consumption. Electrification not only represents a switch to a cleaner fuel source, but it also unlocks substantial efficiency gains. The efficiency of battery electric vehicles is on average three times higher than internal combustion engine vehicles.

**Fossil fuels in buildings** (space heating). Renovation rates and subsequent energy savings are assumed to increase from Stated Policy to Technology Driven and System Change. In all pathways, this is the largest single source of fossil fuel reduction, delivering over half of the savings in System Change. The direct increase in electricity consumption is relatively small, and this is used to power electric heat pumps. This change in technology – and the associated boost in efficiency – unlocks the second largest share of fossil fuel savings.

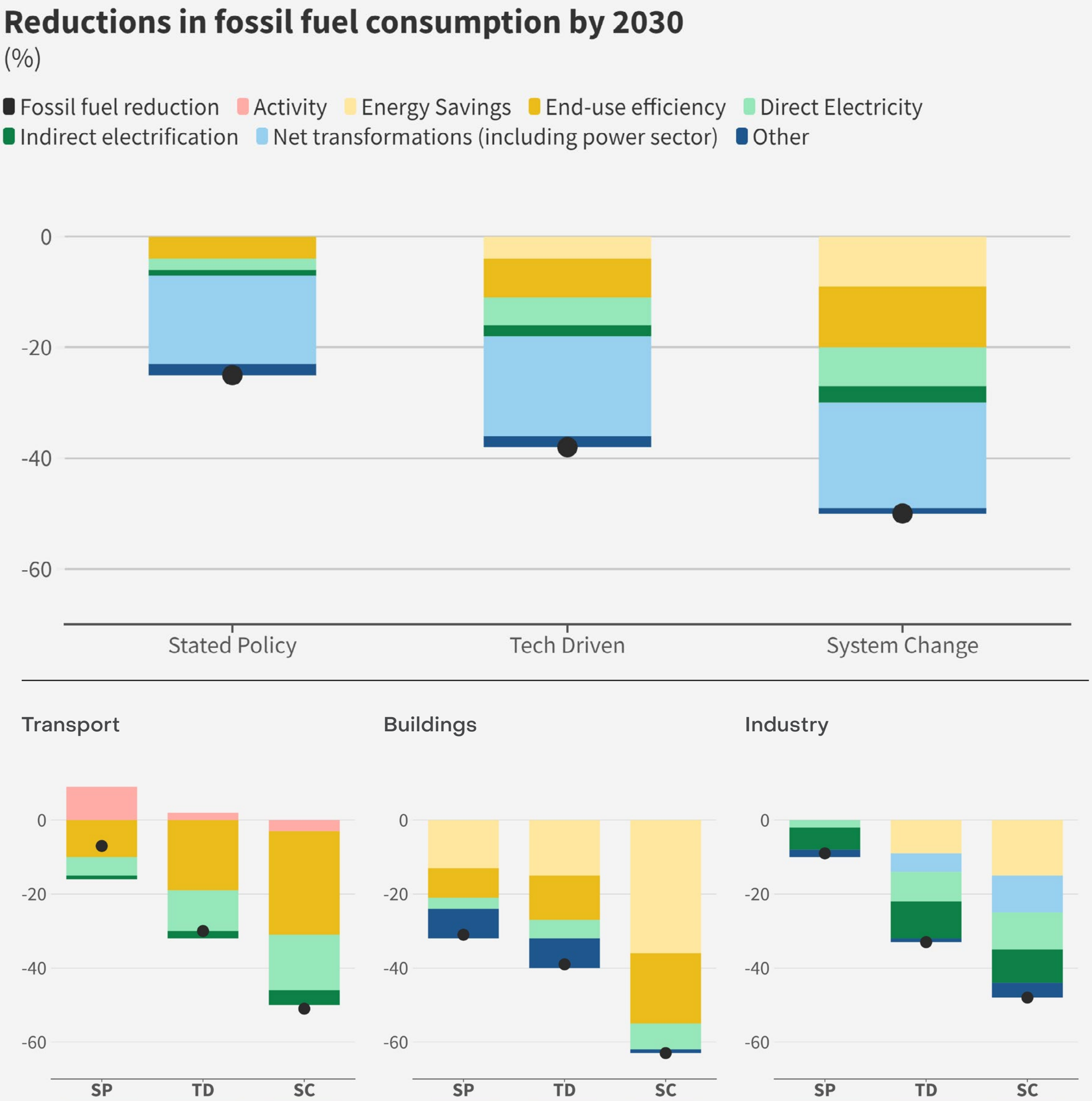



**Figure 4.2.2:** Reductions in estimated primary consumption of fossil fuels in modelled pathways by 2030 (difference from 2019), by the cause of reduction. The energy savings (or activity) category captures the effect of changes to consumption, before the impact of switching to more efficient end-uses (e.g. electric heat pumps). Both energy savings and efficiency improvements are considered before the impact of fuel substitution with electricity (direct electrification) or hydrogen and hydrogen-derived fuels (Indirect electrification). The other category includes changes in consumption of fuels other than fossil fuels, hydrogen, or hydrogen derived fuels, for example, renewable heat and bioenergy.

**Fossil fuels in Industry.** Through improved process efficiency and additional energy saving measures, it is assumed that industrial energy demand can be reduced by 6–9% by 2030 (on a path to 17–27%[51] by 2050). Direct electrification increases from approximately 35% in 2020 to 42–45% by 2030, while the use of hydrogen and synthetic fuels increases to account for about 7% of energy consumption, directly replacing fossil fuels. Coal input into steel-related transformation processes is also considered (blast furnaces and coke ovens). This is unchanged by 2030 in Stated Policy, but reduces by 17–37% in clean power pathways[52] (in Technology Driven and System Change, respectively).

**Fossil fuels in the power sector.** In every pathway, the power sector sees the largest relative and absolute reduction in fossil fuel consumption of all the energy sectors by 2030. Coal consumption collapses, reducing by 92% in Stated Policy, and 97–100% in the clean power pathways. The reduction in gas is less dramatic, decreasing by 25% in Stated Policy and 31–32% in the clean power pathways. By 2030, total fossil fuel consumption in the power sector falls by 60% in Stated Policy, 65% in Technology Driven, and 67% in System Change.

## Policy recommendations:

- Policies to reduce dependence on fossil fuel imports should focus on measures that will permanently reduce demand. The greatest potential is in direct electrification and building renovation. Diversification of fossil fuel supply should be strictly limited to the short-term, in order to address immediate needs while avoiding lock-in of new infrastructure incompatible with the energy transition.
- Wind and solar provide the tools to decarbonise and expand the power sector. Removing the barriers and scaling up deployment is the central challenge for European energy policy.
- Enable the uptake of electricity in more end-uses to unlock decarbonisation through clean electrification. Simultaneously enable smarter consumption, by ensuring adequate local infrastructure, price signals, consumer engagement, and digital tools.

[51] Estimates based on external studies. See the accompanying technical report for details sector by sector demand assumptions.

[52] Steel-related consumption is assumed to decrease in line with conventional steel production in pathways presented in Material Economics (2019), Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry. Specifically, Technology Driven follows the 'New Processes' pathway and System Change follows the 'Circular economy' pathway.

### Box 4.2.1: The clean power pathways deliver a reduction of 33–45% in EU27 gas consumption by 2030

The European Commission estimates that full implementation of the Fit-for-55 legislation would reduce the EU's current level of gas consumption by 116bcm or approximately 30% by 2030. This is less than annual gas imports from Russia, which were ~150bcm in 2020. The REPowerEU communication proposes a mixture of supply diversification and further measures to reduce gas consumption, with the aim of removing dependence on Russian imports entirely by 2027. The additional demand-reducing measures would save an further 155bcm[53] by 2030 on top of Fit-for-55, bringing the total reduction of gas consumption to an estimated ~65% by 2030.

In the Stated Policy Pathway, EU27 gas consumption falls 22% by 2030, significantly less than the Fit-for-55 proposals and the REPowerEU plan. This pathway is, however, based on assumptions and data gathered before the outbreak of war in Ukraine, and the catalytic effect this had on the global energy crisis. This also indicates that, at the time the data was gathered, national stated policies were not aligned with the Fit-for-55 goals.

Gas consumption falls much further in the clean power pathways, reducing by 33% in Technology Driven and 45% in System Change by 2030. Only the latter would remove the equivalent of Russian imports by 2030. However, unlike the REPowerEU plan, the decline in coal and nuclear is not halted in favour of gas savings, nor is biomethane considered as an alternative to fossil gas.

[53] The measures in addition to Fit-for-55 that would reduce consumption of fossil gas (methane) by 2030 included in this total are: energy efficiency and heat pumps (37bcm), biomethane supply (18bcm), increased coal use in the power sector (24bcm), extra wind and solar power (21bcm), renewable hydrogen (27bcm), reduced use in industry (12bcm), cancelled nuclear phase-out (7bcm), and fuel switching in buildings (9bcm). Estimated savings from efficiency in buildings (10bcm) are not counted towards fossil gas savings, because these are achieved by reducing building thermostat temperatures, and therefore do not equate to a permanent reduction, rather a temporary measure. Figures are taken from the REPowerEU communication (COM(2022) 108, page 6).

These options could deliver further gas savings. In both pathways, roughly half of the gas savings achieved are delivered by the buildings sector, emphasising the huge potential of energy efficiency and heat pumps to reduce gas consumption. Roughly a quarter of gas savings are delivered by fuel switching and energy savings in industry, and the final quarter comes from the power sector.

Substantial savings in gas consumption to not materialise in 2025 in the modelled pathways due to a combination of model constraints, limitations, and assumptions. Firstly, investment in wind and solar before this year is capped in accordance with (pre-war) estimates of the best case scenario, which have been superseded in recent months. Secondly, the unprecedented price increases in fossil fuels observed in 2021–22 and its knock-on effect on renewables do not feature in the model input data. Thirdly, gas grids and storage are not included; gas is always assumed to be available at any location at a fixed price, whereas in reality there are price variations and infrastructure-related supply limits.

Of all the modelled sensitivity scenarios, the only one that sees a significant change in gas consumption in 2025 in the power sector is **High Fossil Prices**. Power sector gas consumption is 13% lower compared to the same year in Technology Driven. The difference in power generation (135 TWh) is made up mostly by coal (93 TWh) and extra deployment of solar (25 TWh). By 2030, the power generation mix essentially returns to that in Technology Driven. The variations in total pathway gas consumption in sensitivity scenarios is described further in Table 4.2.1.

| Sensitivity scenario | Impact<br>on gas and coal consumption in the power sector, relative to the Technology Driven pathway | Basic storyline<br>over total pathway 2020–2050 [bcm]<br>(TD total pathway consumption = 3110bcm) |
|---|---|---|
| **Higher fossil fuel prices** | Fossil gas consumption in 2025 is reduced by 13%, with electricity generation down 110 TWh. This is counterbalanced by an increase in coal and biomass generation of a combined 80 TWh, and an increase in solar of 30 TWh, facilitated by additional capacity deployment. The generation mix in 2030 is far less affected. | –138<br>(–4%) |
| **Nuclear plus** | Gas consumption is lower every year, with the difference growing from 1% in 2025 to 15% by 2035. From 2030 this is mostly due to nuclear replacing gas CCS as a source of clean firm generation. | –311<br>(–10%) |
| **RES resistance** | From 2030 gas consumption is significantly higher, reaching +59% by 2035. The main dynamic is a replacement of onshore wind with gas CCS. | +510<br>(+16%) |
| **Low demand flexibility** | Consumption of gas is 5% higher in 2035 as a larger gas CCS fleet plays a greater role in supply-side flexibility. | +99<br>(+3%) |
| **No gas CCS** | Generation from gas CCS is partially replaced by unabated gas from 2030, and partially by additional renewables, resulting in a net reduction in gas consumption. | –361<br>(–12%) |
| **Battery (Tech Driven-B)** | A boost in solar generation results in lower gas capacities (abated and unabated) from 2030, and lower gas consumption (8% lower by 2035). | –109<br>(–4%) |

**Table 4.2.1:** Gas consumption in the sensitivity scenarios.

## 4.3 Wind and solar deployment quadruples

### Annual wind and solar deployment must quadruple compared to the last 10 years.

As the cheapest and most impactful tools in averting the climate crisis, wind and solar have the potential to provide the most extensive global emissions cuts required by 2030 for a 1.5C pathway.[54] Our analysis finds that in Europe, wind and solar will be the backbone of a clean power sector. This means that strong Europe-wide ambition in deploying sufficient generation capacity quickly enough is of the utmost importance.

**Annual growth in wind and solar must quadruple by 2025 compared to the last decade, and persist at these levels until 2035.**

This analysis finds that a clean European power system by 2035 requires 790–850 GW of wind and 800–1420 GW of solar capacity. In contrast, Stated Policy delivers only 511 GW of wind and 530 GW of solar by 2035 (Table 4.3.1).

Achieving required capacity levels by 2035 will require a combined wind and solar growth rate of 100–165 GW per year across the preceding decade (2025–2035). This means that by 2025 Europe must more than quadruple the average annual growth of 24 GW/yr seen in the last decade. There are signs of an acceleration, with deployment hitting a record 36 GW in 2021, but a big deployment challenge lies ahead. Quickly ramping up deployment is essential – each further year of inadequate growth not only delays the realisation of a cheaper and cleaner power system, but increases the delivery challenge in later years if the 2035 milestone is to be met.

[54] IPCC (2022) Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

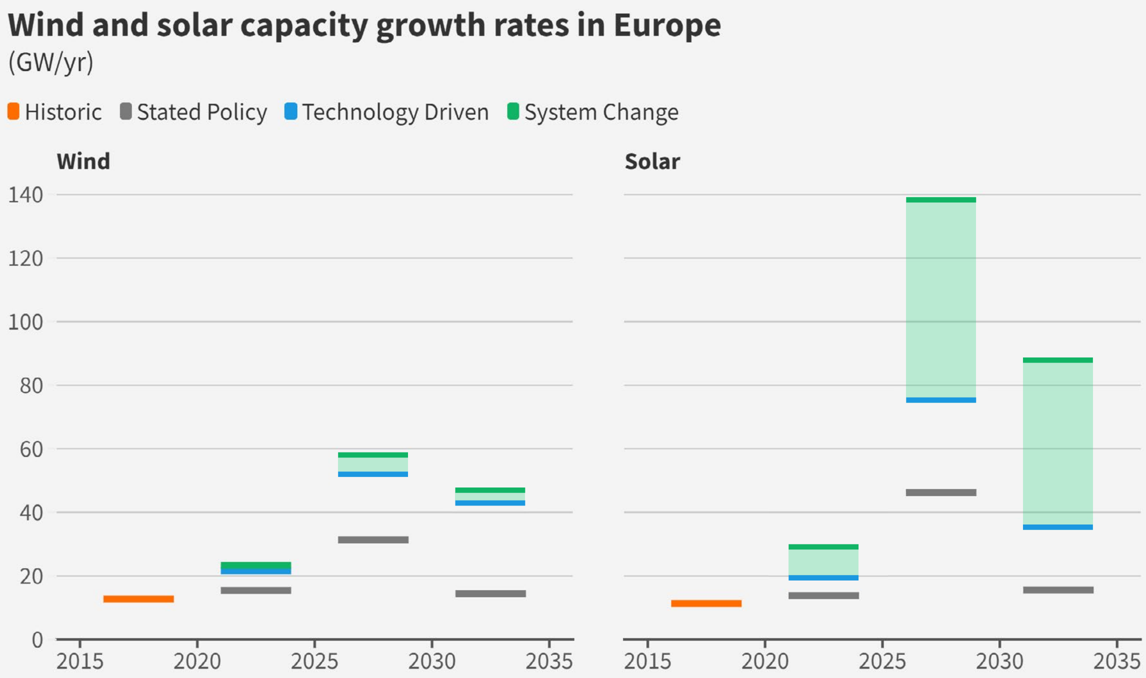



**Figure 4.3.1:** Deployment rate (GW per year net additions) of wind and solar in Europe over time in the three main modelled pathways.

| GW | | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Onshore wind | TD | 181 | 264 | 437 | 584 |
| | SC | 181 | 271 | 471 | 632 |
| Offshore wind | TD | 25 | 50 | 134 | 200 |
| | SC | 25 | 52 | 140 | 213 |
| Solar | TD | 153 | 250 | 626 | 802 |
| | SC | 153 | 298 | 987 | 1,424 |

**Table 4.3.1:** Installed capacity (GW) of wind and solar in Europe from 2020 to 2035.

**Unprecedented solar deployment levels must be reached by 2025, but this aligns with ambitious industry estimates.**

Over the past decade, the price of solar power has plummeted to make it one of the cheapest forms of power generation available.[55] Capitalising on this low cost energy source will be essential not only in creating a clean power sector but also in electrifying the wider European economy and cutting emissions.

Across Europe solar saw an average annual growth rate of 12 GW/yr over the 2010–2020 period.[56] The Technology Driven and System Change scenarios find that the 2025–2035 period will need to see growth rates of 55–115 GW/yr to reach a clean power sector by 2035. This means the European growth rate will have to at least quadruple this decade compared to the last. While this may appear to be a huge leap in expansion, it coincides with estimates of what is possible from the solar power industry. In Solar Power Europe's Raising Solar Ambition report,[57] the 'High' and 'Accelerated High' scenarios[58] would see annual EU27 capacity expansion reach 53–90 GW/yr by 2025.

Modelled solar expansion is not evenly spread across Europe,with 69–72% accounted for by just five countries: Germany, Italy, Spain, France and Poland. These countries all possess high levels of solar resource and/or land availability giving them very high potentials of cost-effective solar capacity.

The average solar growth rates in the clean power pathways are on a different scale to those achieved in the past ten years. However, on an annual basis, few countries have shown a precedent for the levels of expansion required. For example, of the five countries deploying most solar power by 2035 in clean power pathways, in the past decade only Poland has seen a year in isolation where capacity grew sufficiently to match the required rate by 2025. In the case of the remaining countries, Germany, Spain, Italy and France, a doubling or tripling of their previous records is required to surpass the minimum required average annual growth for 2025–2035.

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[55] IRENA (2021) Renewable Power Generation Costs in 2020

[56] Growth rate is found as the total change in capacity from 2010 to 2020 in Europe spread evenly across each of the 10 years.

[57] Solar Power Europe (2022) Raising Solar Ambition for the European Union's Energy Independence

[58] SPE's High Scenario forecasts solar growth based on a best optimal case in which policy support, financial conditions and other factors are enhanced in comparison to the current state of play of the market. The Accelerated High Scenario builds on this scenario with increased ambition to reduce fossil-fuel reliance in the EU27 following Russia's invasion of Ukraine.

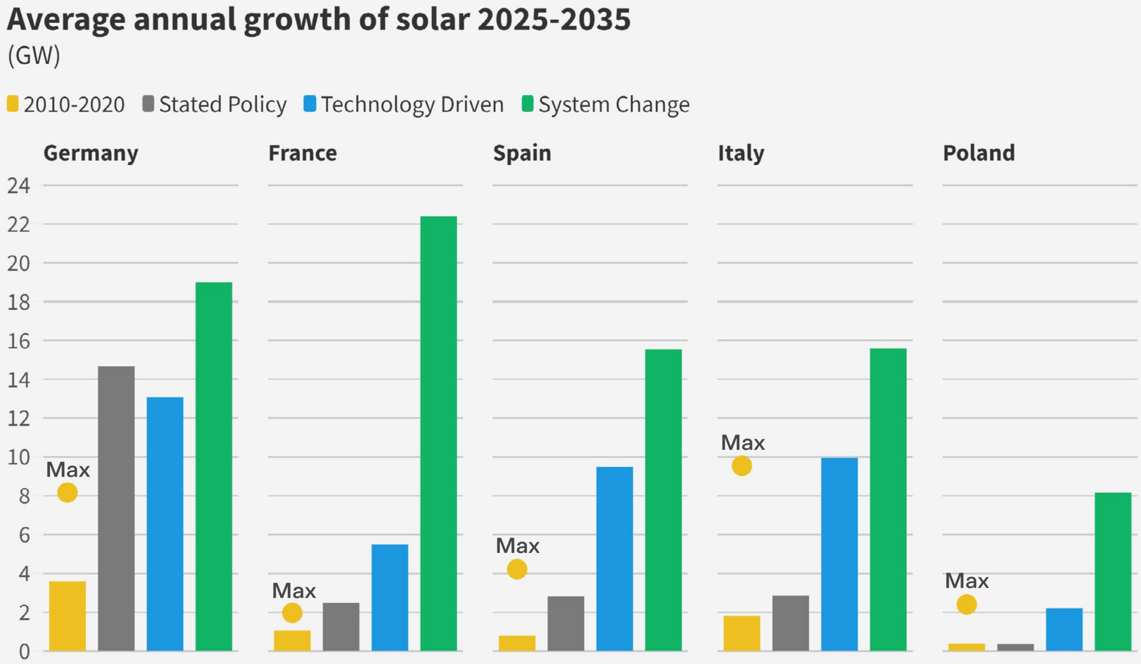


**Figure 4.3.2:** Deployment rate (GW per year net additions) of solar in the time periods 2010–2020 and 2025–2035 in selected countries. The maximum deployment in a single year between 2010–2020 in each country is labelled 'Max'.

### Wind deployment would need to exceed industry's best expectations.

Wind power is the second pillar of the clean power sector alongside solar. As a cheap and clean alternative to solar in countries with lower solar resources, and as a technology that compliments the seasonal variation in solar power output, wind power will also need to be dramatically scaled-up to achieve a clean power sector.

Across 2010–2020, wind power in Europe grew at an average rate of 12 GW/yr of which 2 GW/yr was offshore wind growth and 10 GW/yr was onshore wind growth. The clean power pathways see capacity grow at an average of 47–52 GW/yr between 2025–2035 (of which 32–36 GW/yr onshore and 15–16 GW/yr offshore) – a quadrupling of deployment rates compared with the previous decade. This ambition is matched by the position of the Global Wind Energy Council who in their 2022 Global Wind Report set out the need for global wind installations to quadruple in the decade to 2030 to limit global warming to 1.5°C by 2100.[59]

[59] GWEC (2022) 2022 Global Wind Report

The majority of modelled capacity expansion is concentrated in large Northern and Western countries with good wind resources. Four countries account for 54–59% of this capacity deployment: Germany, France, UK and Spain.

The annual record of wind deployment indicates a greater deployment challenge for wind than for solar. There has not been a year in the past decade in any of Europe's five largest economies in which the deployment of wind has matched the required 2025–2035 average annual deployment rate. Germany and Italy have recorded individual years of growth close to the required rate. In contrast, France, Spain and the UK would need to double or triple their annual growth records to match the modelled clean power pathways.

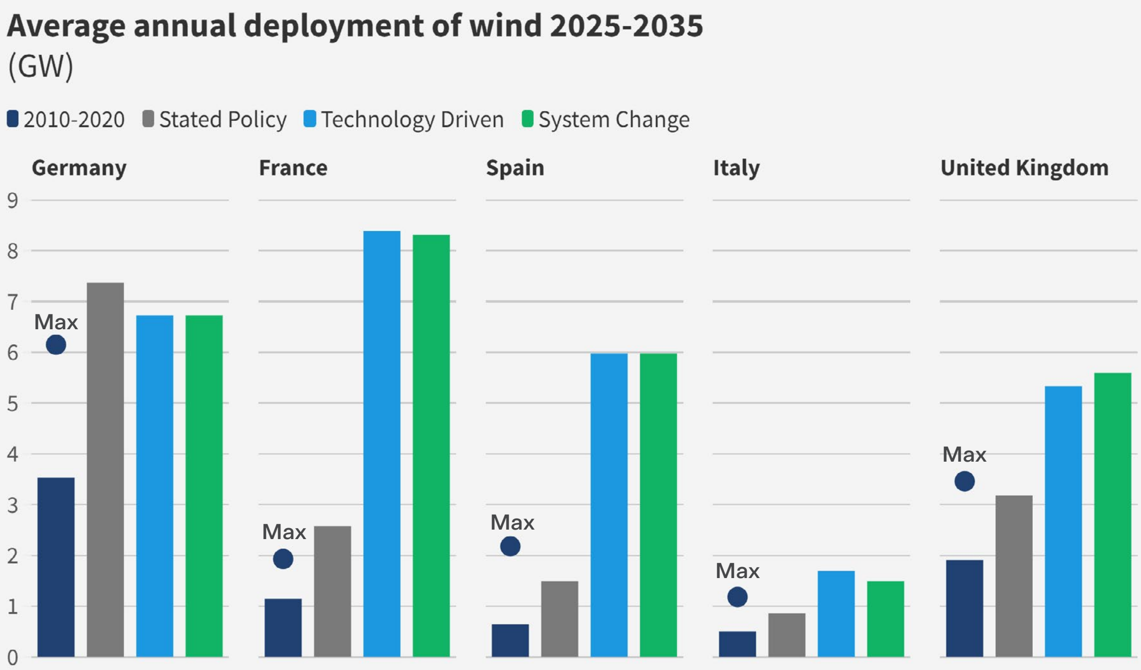


**Figure 4.3.3:** Deployment rate (GW per year net additions) of wind in the time periods 2010–2020 and 2025–2035 in selected countries. The maximum deployment in a single year between 2010–2020 in each country is labelled 'Max'.

In their outlook for 2022–2026, WindEurope note that over the period to 2026 wind deployment in the EU27 is likely to fall well short of what is required to meet the objectives of the "Fit for 55" policy package, which assumed an installed capacity of 453 GW by 2030. The Fit for 55 figure itself is lower than the modelled clean power scenarios (476–502 GW by 2030) suggesting that the current trajectory of wind deployment in the EU27 is significantly off-track to deliver Fit for 55 let alone a clean power sector by 2035.

### Box 4.3.1: Does REpowerEU get the EU27 on track for 2035 clean power?

By 2030 the clean power pathways see wind and solar capacities in the EU27 grow to 476–502 GW and 600–920 GW respectively. This is higher than the 453 GW of wind and 383 GW of solar capacity the EU27 Commission projected would be needed by 2030 to deliver the 'Fit For 55' package.[60] This suggests that meeting the targets of Fit for 55 would not put the EU27 on track to achieving a clean power sector by 2035.

In response to the invasion of Ukraine and the ensuing energy crisis, the EU27 built on the Fit for 55 proposals with the REpowerEU plan, which targets in particular a faster transition away from gas. The indicated ambition for wind and solar has subsequently increased to 510 GW of wind capacity and 600 GW of solar capacity by 2030.[61] These are ambitious goals that align with the clean power pathways presented here and if met would broadly put the EU27 on course to achieve a clean power sector by 2035.

However, achieving the wind and solar capacities set out in the clean power pathways and REpowerEU will require a rapid scaling-up of deployment, far exceeding national plans, and above levels foreseen in short-term market outlooks. For example, in their most recent market update[62] Solar Power Europe foresees current market trends failing to meet REpowerEU targets, delivering 538 GW of solar capacity by 2030. WindEurope[63] recently warned that growth in wind capacity will fall well short of what is required to meet the objectives of the Fit for 55 policy package, let alone the enhanced ambition of REpowerEU. Overcoming this deployment challenge will require the EU27 to put wind and solar growth at the centre of its near-term energy supply strategy (see policy recommendations for more details).

[60] The 'MIX' scenario from the EU Commission's Fit for 55 Impact Assessment model is used to provide capacity figures that align with the Fit for 55 targets.

[61] European Commission (2022) REPowerEU plan

[62] Solar Power Europe (2022) Solar-Powering EU Independence

[63] WindEurope (2022) Wind energy in Europe: 2021 Statistics and the outlook for 2022–2026

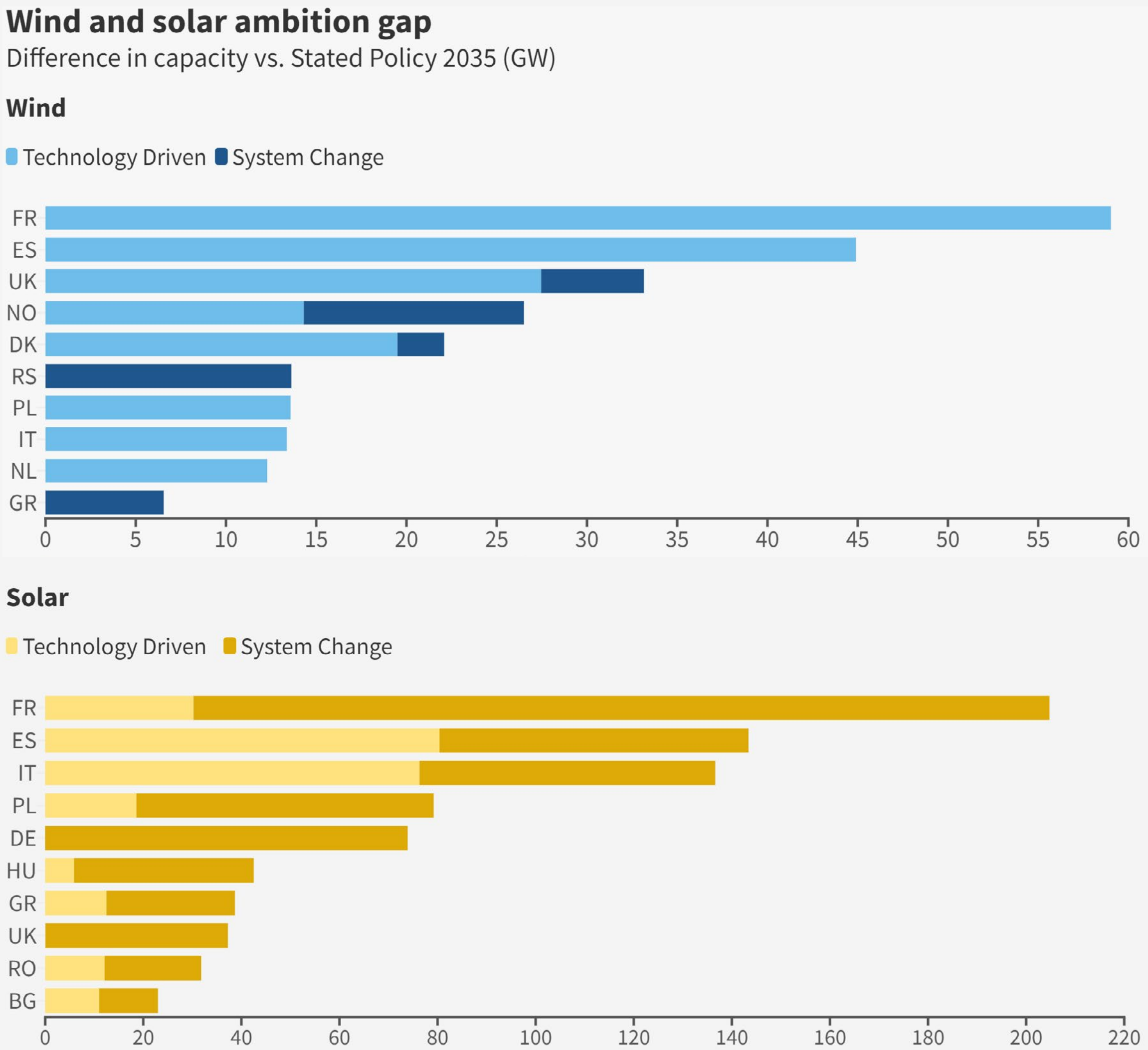


**Figure 4.3.4:** Difference in total installed capacity of wind and solar in 2035 between Technology Driven and Stated Policy pathways and System Change and Stated Policy pathways.

## Stated policies only deliver between a half and two-thirds of required wind and solar capacity by 2035.

By 2035, the Stated Policy pathway lags behind clean power pathways, delivering only 45–65% of the required combined wind and solar capacity.

Comparing the clean power pathways to the Stated Policy pathway provides an indication of the ambition gap in wind and solar expansion. This gap represents the difference between least-cost pathways and current plans. At the country level, a bigger gap indicates an undervaluation of national potential for wind or solar, highlighting the countries and regions with the strongest economic case for further expansion towards a clean power system by 2035.

The shortfall in capacity between Stated Policy and the clean power pathways is shown in Figure 4.3.4. The largest absolute shortfalls are observed in large countries with good renewable resources such as France, Spain, Italy, and the UK.

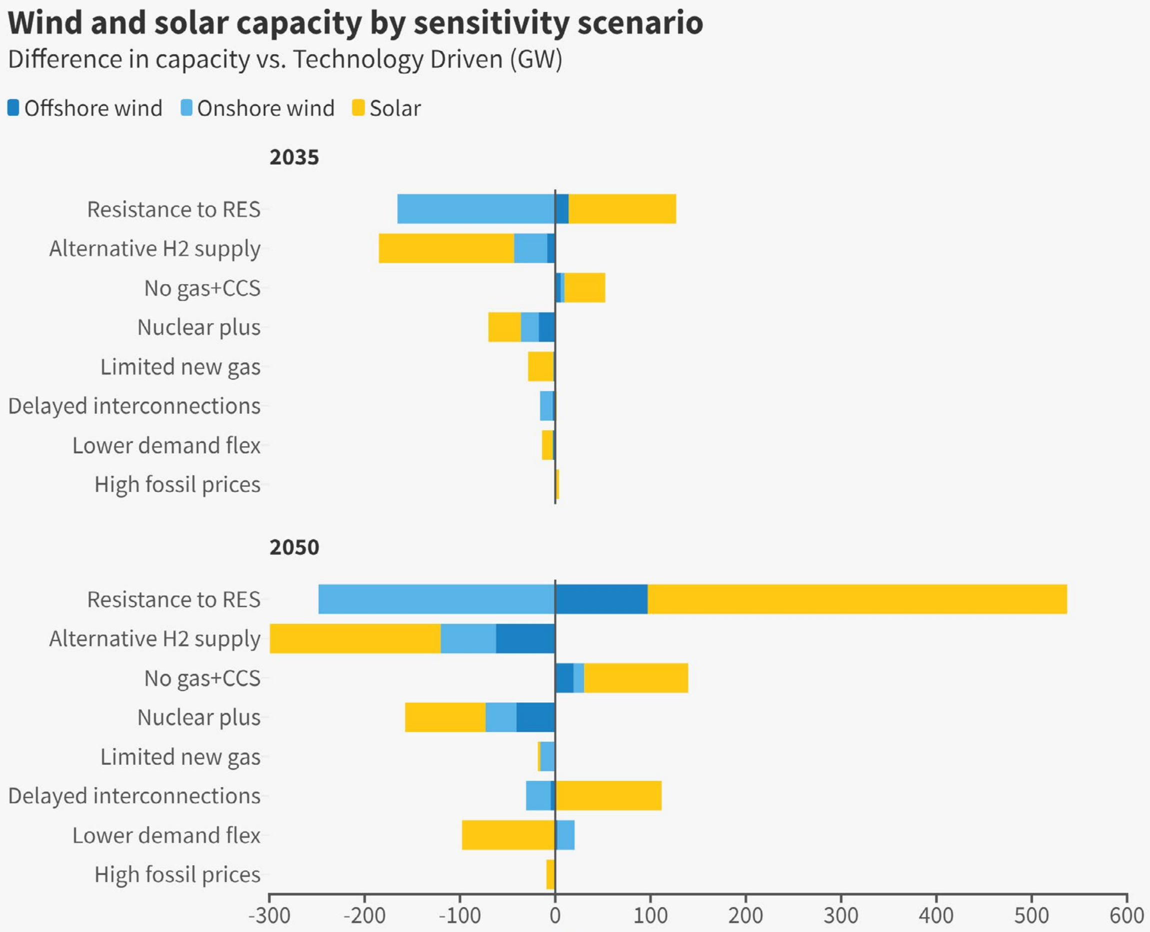


**Figure 4.3.5:** Difference in total installed capacity of wind and solar between sensitivity scenarios and Technology Driven pathway in 2035 and 2050.

### Sensitivity analysis: total wind and solar deployment levels are largely unaffected by key political and technological uncertainties.

Sensitivity analysis reveals potential impact that economic or political uncertainties might have on the required wind and solar deployment challenge. It is clear from this comparison that for the majority of the sensitivity scenarios, **wind and solar capacity is relatively unchanged by 2035**. The No gas CCS scenario results in the addition of 52 GW extra wind and solar capacity by 2035 (a 3% increase in the fleet), while combined deployment is 70 GW (4%) lower in the Nuclear plus scenario.

By 2050 most sensitivity scenarios still only differ in capacity from the Technology Driven pathway by small margins (less than 10%).

Only two sensitivity scenarios deviate substantially from the Technology Driven pathway by 2035. The Alternative H2 supply scenario sees a reduction in solar capacity of 142 GW (18%) and a reduction in wind capacity of 44 GW (6%) by 2035 while in the Resistance to RES scenario onshore wind capacity falls by 166 GW (28%) and solar capacity rises by 113 GW (14%).

In the case of Alternative H2 supply the reduction in wind and solar capacity reflects a reduction in overall system power demand as a result of lower demand for domestic (grid-connected) green hydrogen. However, it is still important to consider that in this scenario additional wind and solar capacity may still be required to provide power for off-grid hydrogen production, resulting in a similar deployment challenge in Europe to the clean power scenarios.

The Resistance to RES scenario shows the largest changes to wind and solar capacity. In this scenario, as a result of limited social acceptance, land availability for wind and solar is significantly reduced in comparison to the clean power pathways. As a result, in 2035 Resistance to RES sees a significant drop in onshore wind capacity, with the fleet size falling by 28%. This is partially compensated by a increase in solar capacity (14%) and additional offshore wind (7%), despite a reduction in the land available for utility-scale solar.[64] However, the lost generation from onshore wind (-488 TWh) is far from compensated by this extra solar and offshore wind (+61 TWh and +58 TWh). The extent to which solar can substitute is likely limited due to its lower load factor and different daily production profile. The largest source of replacement clean generation is Gas CCS, which contributes 460 TWh (+270 TWh). The same pattern in the wind and solar fleet is exacerbated by 2050.

These changes in deployment pattern reveal that, when cost-competitive onshore wind is prevented from expanding, the next best option from a cost perspective is to deploy additional solar (and to a lesser extent offshore wind) in locations where it was not previously considered cost-competitive. While doing this, additional gas CCS is needed, which replaces the bulk of clean generation. The combined deployment challenge of wind and solar is only marginally lowered before 2035, and the need for extra solar after 2035 actually increases the combined deployment challenge. The resulting system is one that is more reliant on gas, and on CCS technology which is yet unproven at scale.

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[64] The maximum European potential for utility-scale solar is far from reached in either the Technology Driven pathway or this sensitivity.

These comparisons show that Europe faces a significant and unavoidable wind and solar deployment challenge if the 2035 clean power milestone is to be achieved. This result is robust to key political, social, and economic uncertainties. If Europe fails to embrace cheap onshore wind, there is no suggestion the alternative paths are simpler to implement or carry less risk. Additional solar and offshore wind would be required in the medium term, while Europe's gas dependence may be prolonged by a turn to gas with CCS.

### Policy recommendations:

- Urgently facilitate a massive scaling of wind and solar deployment by streamlining the permitting process, as well as establishing best-practices in order to increase efficiency and minimise adverse social and environmental impacts.
- Ensure long-term supply chain security for the materials required to build wind and solar infrastructure in order to avoid high material costs and supply chain bottlenecks.
- Increase Europe's domestic wind and solar manufacturing capabilities to contribute to supply chain security and sustainability.

### Box 4.3.2: The power system impact of increasing non-domestic sources of hydrogen to meet European demand

The modelling approach, by default, assumes that European hydrogen demand is supplied by sources within Europe, and that all electrolysers are grid-connected. To test the impact of this assumption on power system dynamics and infrastructure needs, a sensitivity pathway (Alternative H2 supply) is provided in which only 50% of hydrogen demand is supplied within Europe from grid-connected sources. In this pathway, the domestic production requirement for each country (50%) is also relaxed. This sensitivity therefore represents a more open trade in hydrogen both within Europe and externally.

The **Alternative hydrogen** scenario sees lower electrolyser deployment (half by 2035) than Technology Driven, and lower wind and solar capacities, particularly solar which is 140 GW or 20% lower in 2035. The overall size of the thermal fleet is largely unchanged, as is the extent of interconnection expansion. All things considered, there is a limited impact on total pathway costs.

Reduced costs in the power system from lower deployment of electrolysers and renewables are balanced by the additional cost of sourcing alternative hydrogen at the assumed prices. Such a strategy would therefore ease the solar and wind deployment challenge in the medium-term, but at the cost of reduced energy self-sufficiency for Europe going forward.

## 4.4 Wind and solar become the backbone

### Wind and solar provide 70–80% of electricity by 2035 in least-cost pathways.

In the Technology Driven and System Change pathways, the share of wind and solar in annual power generation reaches 68% and 78% respectively, compared with 52% in Stated Policy. In only one of the modelled sensitivity scenarios does the wind and solar share fall below 65% in 2035: in the case of widespread resistance to renewables (lower potential) the share falls to 61% by 2035. The robustness of this outcome in cost-optimised pathways provides clear evidence to the cost benefit of maximising the contribution of wind and solar.

The results show that, with the expansion of wind and solar and supporting infrastructure, the European grid can provide an uninterrupted supply at a decreasing cost while ensuring grid balance and reliability. The required supporting infrastructure is discussed in the next section (4.5), and system resilience to adverse climatic conditions is explored further in section 4.6.

While the increasing penetration of wind and solar does present challenges to system operation, there are some important (and sometimes overlooked) complementarities between the technologies that reduce these.

**Wind and solar output are complementary to each other over a range of timescales.**

Studies have shown that a degree of complementarity exists between wind and solar output over timescales of hours to months, for many regions in Europe.[65] As a result, the aggregated variability of wind and solar is considerably less than that of each source in isolation. However, few countries have exceptional resources in both, and reliable output at the local or even country level at any one time cannot be guaranteed. This is a key reason why expanded capacity and utilisation of interconnection is critical to the efficient functioning of highly renewable systems. A better connected system allows deployment of wind and solar capacities in better alignment with available resources, minimising the total capacity required. This creates a more dynamic system capable of balancing temporal and geographic imbalances. For example, strong wind output in the North sea over winter can more easily be exported south and east, while strong solar output in Southern Europe over summer can more easily be sent to Northern Europe.

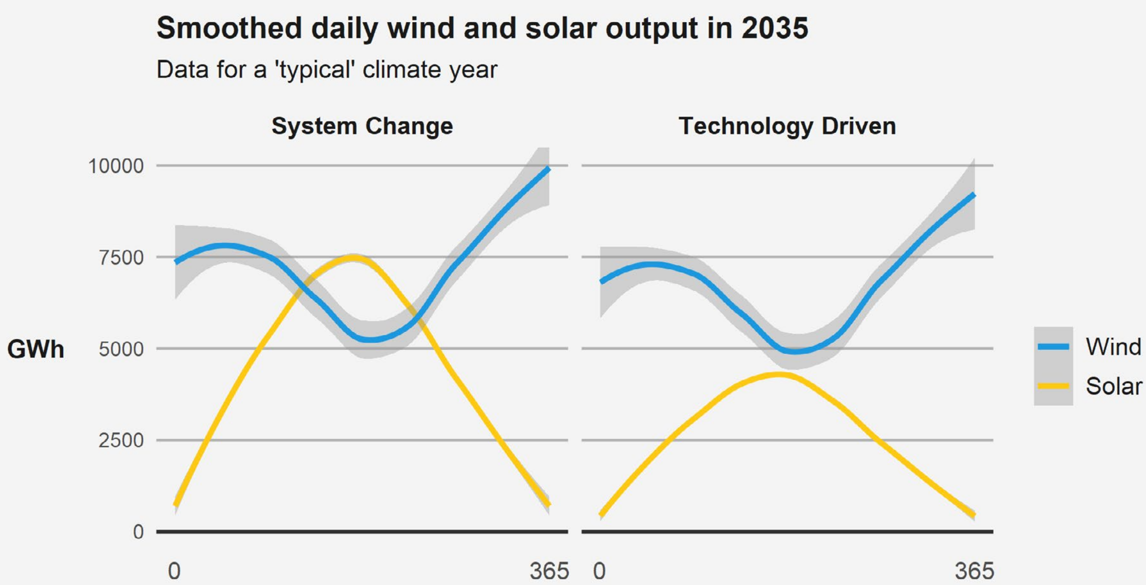


**Figure 4.4.1:** Daily output of wind and solar in a typical climate year, in Technology Driven (left) and System Change (right) pathways. Daily variations are smoothed to give a sense of the seasonal trend.

[65] For example, Jurasz et al. 2022 demonstrate complementarity using granular European generation data for 2020. Miglietta et al. 2017 find a correlation in hourly meteorological wind and solar data over three years in Europe (2012–14). Monforti et al. 2014 find favourable complementarity between wind and solar in Italy at high levels of spatial resolution.

### Wind and solar deliver across a large fraction of the year.

The contribution of wind and solar to the annual generation mix in 2035 is 68–78% in clean power pathways. However, due to variable weather conditions, there are many hours of the year where wind and solar greatly exceed or fall short of this share.

Figure 4.4.2 shows the distribution of hourly wind and solar generation in clean power pathways in 2035 as a fraction of electricity demand, at the whole system level. It shows that for between 25–50% of hours in a typical year, combined wind and solar production exceeds demand. At the other end of the scale, wind and solar only deliver less than 50% of demand in less than 20% of hours in Technology Driven, and less than 10% of hours in System Change. A similar pattern is observed at the country level. Figure 4.4.3 shows the same distribution of wind and solar output as a fraction of demand for four individual countries, chosen to represent a range of generation portfolios, demand profiles, and regions of Europe.

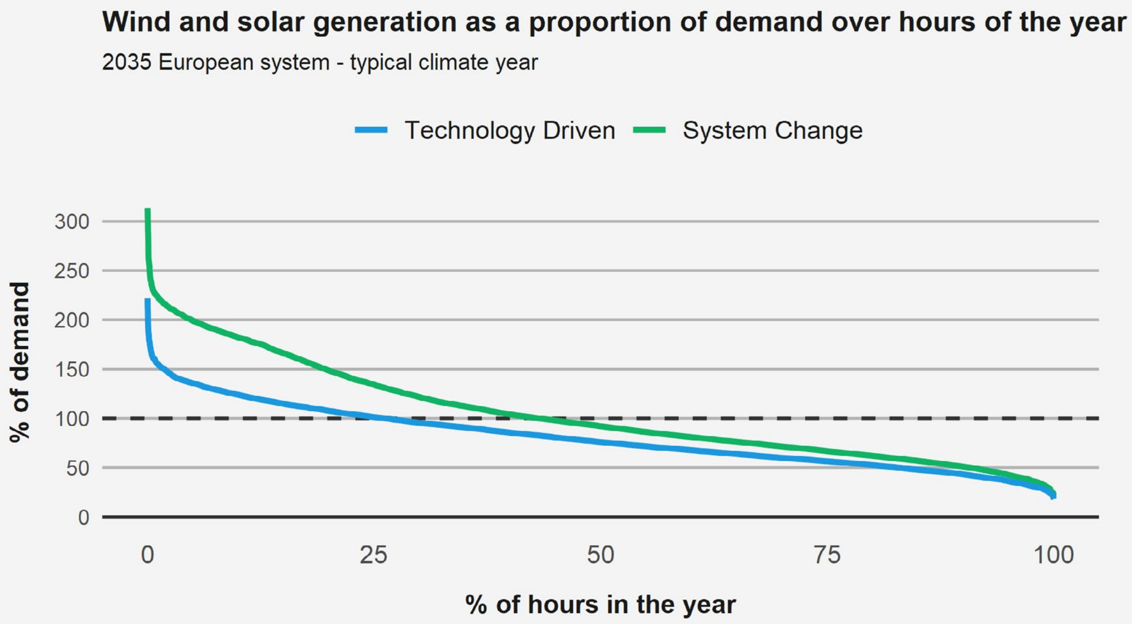


**Figure 4.4.2:** Hourly combined wind and solar output as a fraction of demand (without P2X) at the system level. This shows that the combined output of variable renewables exceeds direct electricity demand at the system level more than 25% of the time in the Technology Driven pathway, and approaching 50% of the time in System Change. At the other end of the distribution, wind and solar combined only deliver less than 50% of demand in less than 20% of hours in Technology Driven, and less than 10% of hours in System Change.

At times of excess, electricity can be shared between regions, converted into hydrogen through electrolysis, or stored for later use, with curtailment a last resort. The development of sufficient interconnection, flexible demand sources, and storage are therefore vital to maximising the value of renewables.

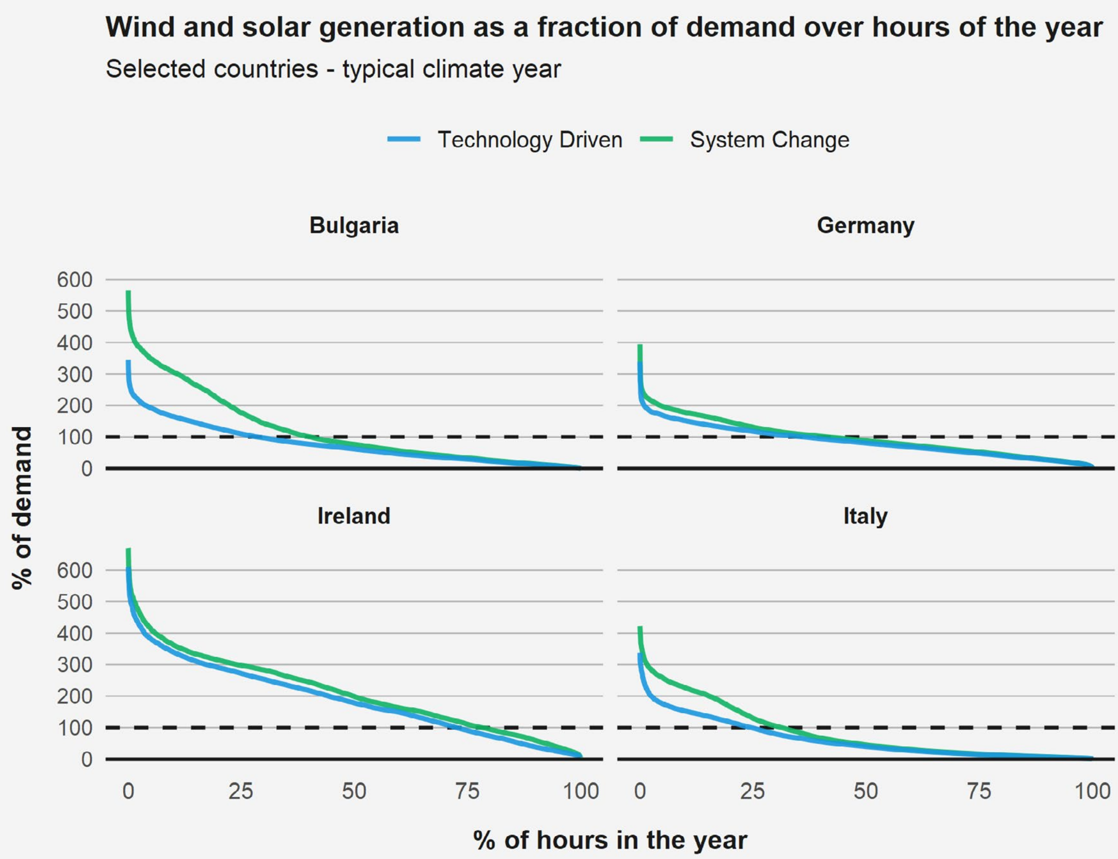


**Figure 4.4.3:** As Figure 4.4.2 but for selected individual countries. These countries represent power systems with a range of characteristics: generation portfolios, demand profiles, and regions of Europe. All reach more than 90% clean power in their national generation mix by 2035 in Technology Driven and System Change.

### System operators must start planning and adapting now for very high instantaneous shares of wind and solar.

A paradigm shift in power system operation is needed, as an increasing share of weather-dependent sources means the system must become more responsive to available supply rather than demand. Maintaining system stability will require new approaches, as unlike conventional generation, wind and solar are variable on short timescales and have a non-synchronous (inverter-based) interface with the grid.

Technical studies and real world experiences are accumulating, and the evidence suggests that engineering and technical challenges can be overcome using existing techniques and technologies. Important grid services such as maintenance of system inertia and frequency regulation can be provided by synchronous condensers and battery storage. Renewables themselves can contribute to balancing and frequency control. Wind farms can deliberately generate below the available level, leaving room to ramp up if necessary. A major study by an IEA task force[66] on power system operation with high shares of wind and solar recently concluded that 'they have the potential to form the backbone of future power systems, when the full range of inverter capabilities are utilised".

Some parts of the European electricity grid already regularly operate with close to 100% renewables. Portugal and Denmark have experienced periods during which the instantaneous share of wind and solar is greater than 100%. The Danish system has successfully operated for several periods, from as early as 2015, without the contribution of any large thermal power plants,[67] during which system support was provided by interconnection, synchronous compensators, and small-scale local power plants. In parallel with the development of this operational expertise, data collection and forecasts continue to improve, providing system operators with better foresight of expected renewable output and thus make timely interventions, where required, to ensure the safe and reliable operation of the grid.

## Policy recommendations:

- Facilitate greater cooperation and learning between national electricity system operators, to increase system-wide preparedness for frequent, very high penetration of wind and solar as early as the late 2020s.
- Promote new markets for flexibility and low-carbon grid supporting technologies, essential to minimise unnecessary gas infrastructure and lower gas dependence.

[66] IEA WIND TCP task 25

[67] As described by Holttinen et al. 2020 (IEEE Transactions on Power Systems).

### Box 4.4.1: Grid operators preparing for highly renewable or fossil-free operation

The GB system operator National Grid (ESO) is preparing to operate the power system for periods of time without any fossil sources by 2025. At 1pm on 5th April 2021, carbon-free sources provided 80% of generation, with wind and solar contributing a combined 60%, allowing the grid to reach a record level of low carbon intensity.

In March 2022, the Ireland and Northern Ireland electricity grid became the first in the world to be technically prepared to accommodate 75% of variable generation at any point in time.[68] The grid operator (EirGrid) is continuing the work with plans for the grid to be able to accommodate 95% of electricity generation at any point in time to come from wind and solar by 2030.

German TSO 50Hertz is aiming, by 2032, to cover the total electricity consumption within their grid area (eastern Germany and Hamburg) over the course of a year with 100% renewable energy.

## 4.5 Increasing flexibility is crucial

### Enabling demand flexibility and deploying key power technologies facilitates the cost-efficient integration of wind and solar, while avoiding unnecessary gas investments.

The clean power pathways see wind and solar become the dominant source of electricity as supply expands to meet additional demands from electrification. The future power system is therefore one which is able to successfully integrate high shares of variable generation and manage rising power demand peaks. Increasing system flexibility is key to meeting this challenge, and enabling fossil capacities to be phased out without compromising system reliability and resilience.

[68] Eirgrid: “Electricity Grid to Run on 75% Variable Renewable Generation Following Successful Trial”.

**A range of flexibility sources is key to integrating wind and solar, and providing for their distinct flexibility needs.**

Currently, fossil fuel-based turbines and hydropower provide the majority of system-wide flexibility services. However, as the large-scale deployment of wind and solar drives a significant increase in system flexibility needs, these assets will be unable to provide the necessary flexibility, particularly as fossil capacities are progressively phased out. The pathways see other technologies assume their role, ensuring enhanced supply-side flexibility, while developments in power demand facilitate the system's increasing flexibility. In this manner, the future clean power system is able to constantly change its operation according to real-time demand and/or potentially large and rapid fluctuations in generation, ensuring that the grid is prepared to provide continuous and reliable service.

Wind and solar require different flexibility solutions according to the temporal variability of their typical generation patterns.[69] Solar power predominantly requires flexibility services which can balance intra-day variations, while wind generation, owing to its stochastic nature, creates a need for flexibility over longer time frames, typically within and between weeks. Variations in demand between seasons – driven by temperature patterns – will increase as heating is electrified, creating the need for technologies which can balance renewable output accordingly over even longer periods.

By 2035, a varied portfolio of technologies ensures that the system's flexibility needs are covered across all temporal scales. Figure 4.5.1 displays the cost-optimal flexibility portfolio for the two clean power pathways in 2035, compared to 2020 and the Stated Policy scenario. While the development of flexibility options differs slightly according to pathway storylines, three technologies clearly emerge as the main providers of flexibility in a clean power system. These are electrolysis, interconnection and clean dispatchable generation sources. Battery storage and demand side management also play a significant role, particularly at the daily level.

All modelled pathways see flexibility needs increase but the growth is uneven across countries and timescales, depending on the prevalence of wind or solar, and the characteristics of new demand sources. It follows that national flexibility portfolios vary according to the temporal needs and available national resources. Figure 4.5.2 provides an overview of the technology providing the largest flexibility contribution in 2020 and 2035 in the modelled pathways across three temporal scales.

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[69] For a precise definition of the three temporal scales of flexibility needs and their relevant calculations, refer to this linked report.

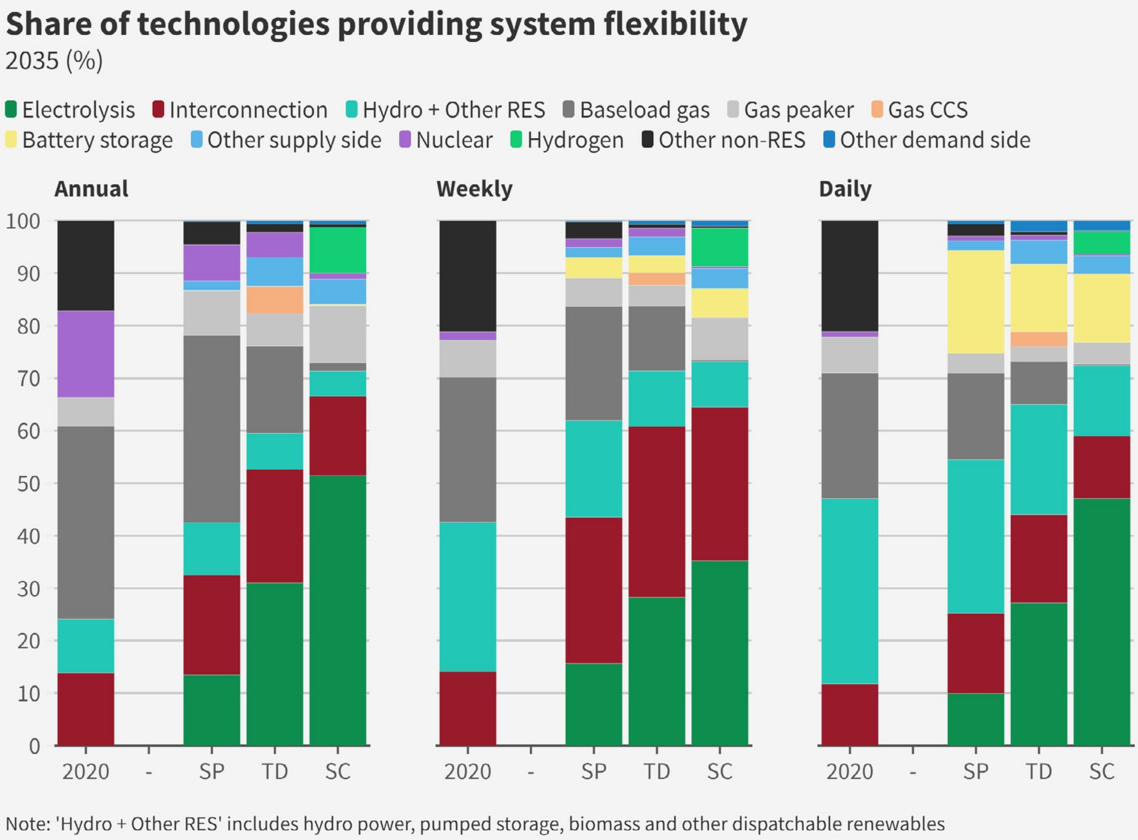



**Figure 4.5.1:** Technologies providing system flexibility at the three different temporal scales, by percentage contribution in 2020 and 2035 in the three modelled scenarios. Not reflected here is the absolute increase in the power system's flexibility needs between 2020 and 2035 which occurs in all three modelled pathways owing to the deployment of wind and solar, as well as the additional electricity demand from new demand sources.

## Leveraging load shifting capacities delivers cost-efficient integration of wind and solar and mitigates peak demand growth.

Load shifting is the process of moving electricity demand from one time period to another, typically from peak to off-peak hours (referred to as peak shaving). This can be accomplished by optimised charge and discharge from battery storage (utility-scale batteries and V2G-enabled EV batteries), and demand-side flexibility, consisting of active and smart household and industrial consumers responding to price signals.[70]

[70] The capacities of storage technologies and demand-side flexibility are almost exclusively determined by the storyline assumptions, but their impact on hourly profiles and utilisation is determined by power system modelling. See the accompanying Technical report for details.

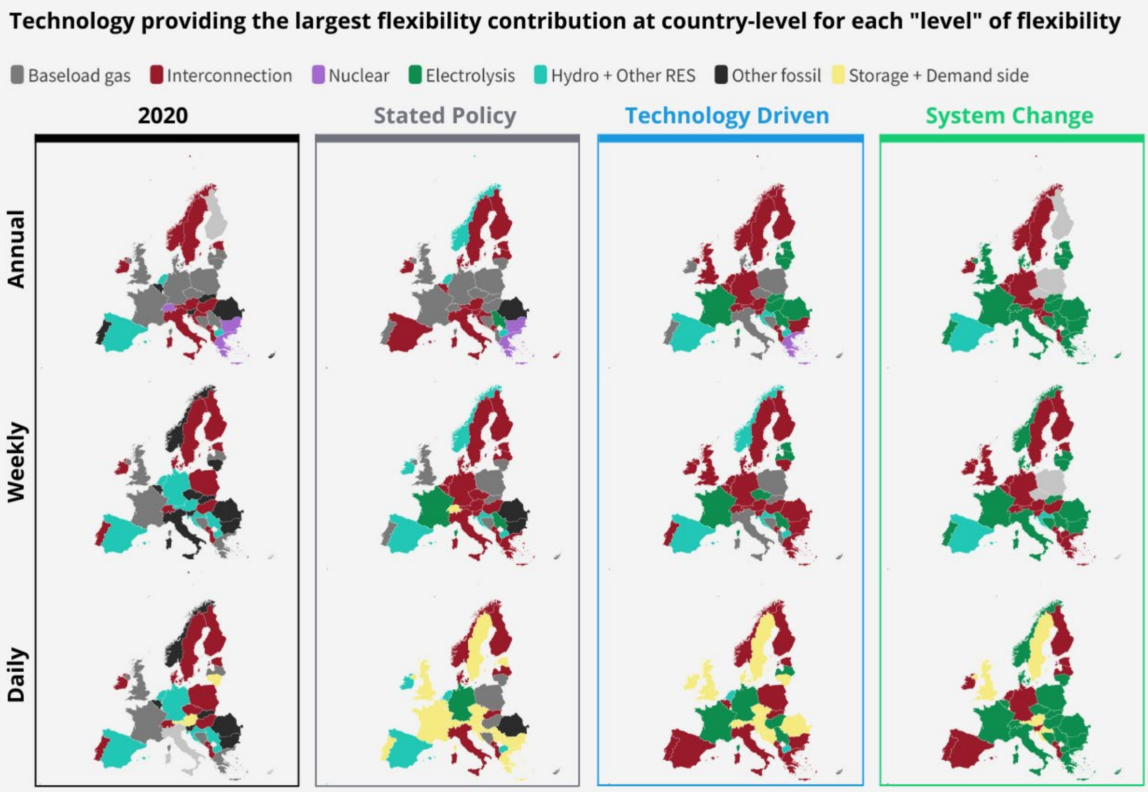



**Figure 4.5.2:** Technology providing the largest flexibility contribution in each country. This is provided for the three temporal scales of flexibility (annual, weekly and daily), comparing 2020 to 2035 Stated Policy, Technology Driven and System Change.

By its nature, the role of battery storage and demand-side flexibility is largely concentrated at the daily level, shifting demand by a number of hours to better coincide with variable renewable output. Peak shaving is key for supporting grid resilience (see Section 4.6 for more details on this) and enabling the most cost-efficient development of the future power system.

Faster electrification in the two clean power pathways causes faster growth in both total electricity demand and peak power demand than in the Stated Policy scenario (Figure 4.5.3). However, peak demand growth is mitigated by additional demand-side flexibility in clean power pathways. Between 2020 and 2035, electricity demand grows by 2.9% and 3.4% per year in Technology Driven and System Change respectively. Growth in peak demand is slower, at 3% and 3.1% respectively. In contrast, in the Stated Policy scenario electricity demand growth (1.3%) is outpaced by peak demand growth (1.9%). The mitigating impact of demand-side flexibility on demand peaks in the clean power pathways is illustrated in Figure. 4.5.3.

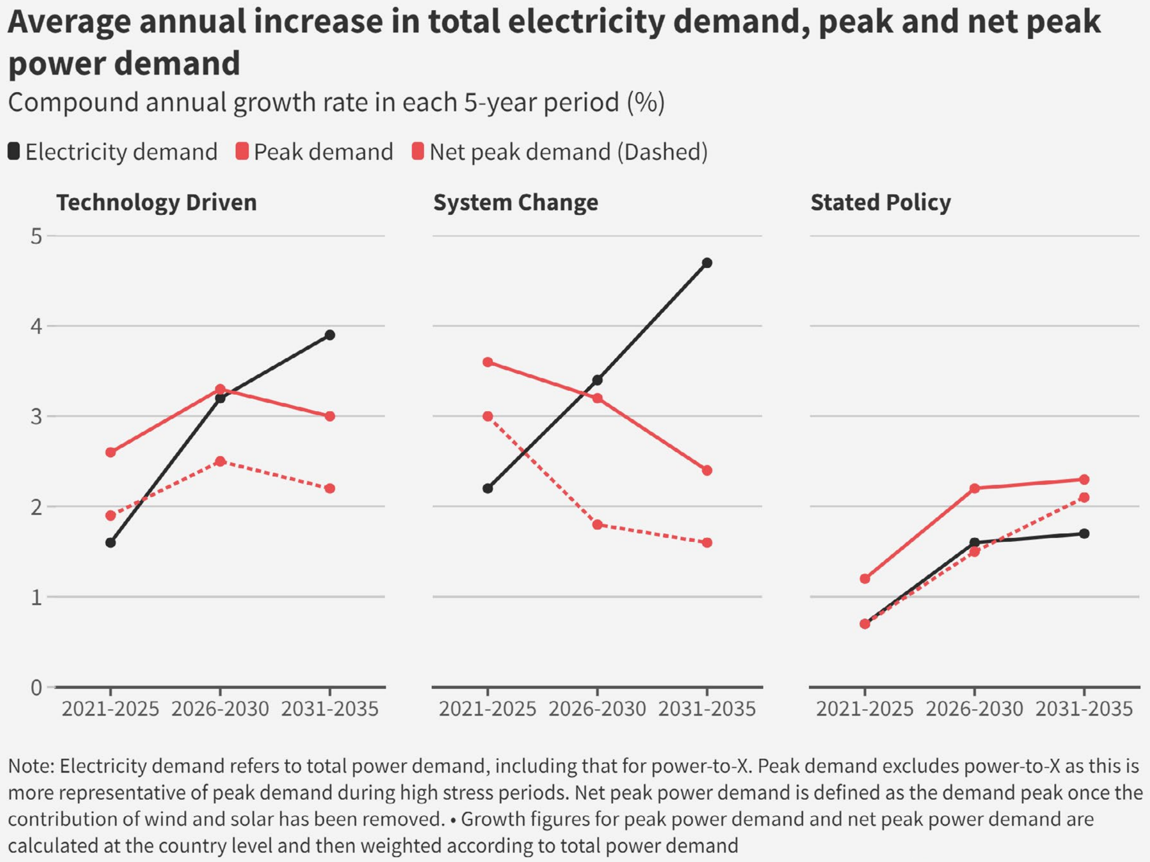



**Figure 4.5.3:** Average annual increase in total electricity demand, peak power demand (here excluding P2X, to better represent the peak load that is driven by demand as opposed to "over" supply from wind and solar generation) and net peak power demand. Driven by assumptions of higher electrification rates and demand for P2X, the clean power pathways see electricity demand increase rapidly between 2020 and 2035, at an average rate of approximately 3% per annum. This is lower in the Stated Policy scenario where power demand increases at an average rate of 1.9% per annum. The growth rate in peak demand, although also lower in this scenario, continues to increase towards 2035; in contrast, there is a notable downturn in the growth rate of peak demand in the clean power pathways, demonstrating the mitigating impact of flexibility on peak demand growth. This same trend can be observed for net peak power demand: the rapid deployment of wind and solar causes the growth rate of net peak demand to slow over the time horizon, while the Stated Policy scenario sees minimal difference in the growth rate of peak and net peak demand by 2035.

As power systems are typically sized according to the expected peak power demand, enabling demand-side flexibility to manage the electricity load facilitates the cost-efficient design of the future power system, reduces electricity prices and minimises the need for peaking capacities.

**Three technologies are key to integrating variable renewables and ensuring system balance: Electrolysis, Interconnection and Clean dispatchable capacities.**

The growth rate of countries' power demand profiles is managed through enhanced demand-side flexibility and this, combined with battery storage, also enables better alignment between demand and variable renewable output. However, other technologies are required to ensure supply-demand balance in a power system dominated by wind and solar.

The cost-optimal portfolio of flexibility tools for the clean power pathways reveals that, across the three temporal scales of flexibility, three technologies provide the most significant contribution, namely electrolysis, interconnection and clean dispatchable capacities.

Exchange over interconnectors enables system balance when mismatch between supply and demand is geographic. The clean power pathways see expansion of the European grid that far exceeds the planned cross-border transmission projects. By 2035 total interconnection increases by a factor of 2.1 in the Technology Driven scenario and 2.4 in the System Change pathway relative to 2020, compared to just 1.5 in Stated Policy

When renewable output exceeds demand, electrolysers correct imbalances on the grid by using the remaining supply to produce green hydrogen. While the majority of green hydrogen is consumed by the end-use sectors, this in turn also constitutes a source of flexibility, generating power at times of low renewable output. Electrolysers ensure that curtailment is kept at a minimum despite the rapid scale-up of wind and solar, along with the associated costs. In the Technology Driven and System Change pathways, curtailment does not exceed 2.5% and 5% of total variable renewable generation, respectively.

When demand exceeds generation from wind and solar, and sufficient power exchanges are not available, an increasingly clean dispatchable fleet supplies the remaining demand. In the Technology Driven pathway, this consists of generation from hydropower and other renewables, nuclear and gas CCS. In System Change, nuclear plays a smaller role and Igas CCS does not feature. Instead, hydrogen turbines play a larger role, and are deployed earlier due to the more ambitious fossil phase-out timeframes.

While fossil gas capacities also play a role in balancing supply and demand at different timescales, their relative contribution decreases significantly between 2020 and 2035 in the clean power pathways. Indeed, the contribution of baseload gas to flexibility is almost entirely replaced by hydrogen turbines in the System Change pathway.

It is clear that dispatchable capacities provide crucial supply-side flexibility to the European power system, and while the cost-optimal combination has been presented here, the modelled sensitivity scenarios demonstrate that these can take a variety of forms and combinations. Choices here are discussed further in Section 4.8.

**Investing in flexibility reduces system dependence on thermal capacities and minimises gas infrastructure.**

The impact of either additional or reduced flexibility options on the clean power pathways was explored through the modification of the Technology Driven scenario. Three scenarios provide insight into the resulting trade-offs: delayed interconnection, lower demand flexibility and Technology Driven-B (see Table 4.5.1). In these pathways, clean power by 2035 continues to emerge as the cost-optimal outcome for a 1.5C compatible pathway. Furthermore, differences in power system flexibility does not appear to have a material impact on wind and solar deployment. Instead, the scenarios see trade-offs between flexibility options to facilitate the integration of wind and solar.

In Technology Driven-B, where almost an additional 200 GWh of utility-scale battery storage are introduced by 2035, the power system sees a reduced need for dispatchable generation. The 2035 technology mix features a smaller gas fleet (abated and unabated), 25 GW or 10% lower than that in the Technology Driven pathway.[71] However, it is not a direct trade-off between battery storage and thermal capacities given the different temporal scales across which the two technologies are able to provide balance to the system. The additional battery storage also slightly tips the balance of renewable deployment in the favour of solar, likely due to its effectiveness at shifting solar output into evening periods when demand is higher; however, this effect is minor, with an extra 55 GW (7%) of solar deployed by 2035.

Lower Demand Flexibility sees similar trade-offs between flexibility and thermal capacities, but in reverse. A smaller portion of demand is assumed to be flexible and the capacity of other demand-side flexibility tools such as DSR and V2G-enabled EVs is reduced. This minimises the mitigating impact of demand-side flexibility and battery storage on growth in peak demand; as a result, the power system's flexibility needs are larger and additional investments are required to manage supply-demand imbalances.

[71] As the deployment of grid-scale battery storage at this scale is likely to occur – see Box 3.4.1 on modelling of utility-scale battery storage for more details - it may be the case that the two clean power pathways overestimate the need for thermal capacity, particularly unabated gas peakers.

| | Delayed interconnection | Lower demand flexibility | Technology Driven-B |
|---|---|---|---|
| **Battery storage** | +2 (+1%) | -98 (-40%) | +199 (+81%) |
| **DSR** | - | -22 (-44%) | - |
| **Baseload gas** | +4 (+3%) | - | -3 (-2%) |
| **Gas peaker** | +7 (+7%) | +45 (+42%) | -15 (-14%) |
| **Gas CCS** | +15 (+44%) | +7 (+19%) | -8 (-22%) |
| **Interconnection** | -42 (-21%) | +2 (+1%) | -4 (-2%) |
| **Solar** | - | -13 (-2%) | +53 (+7%) |
| **Wind** | -16 (-2%) | - | -6 (-1%) |

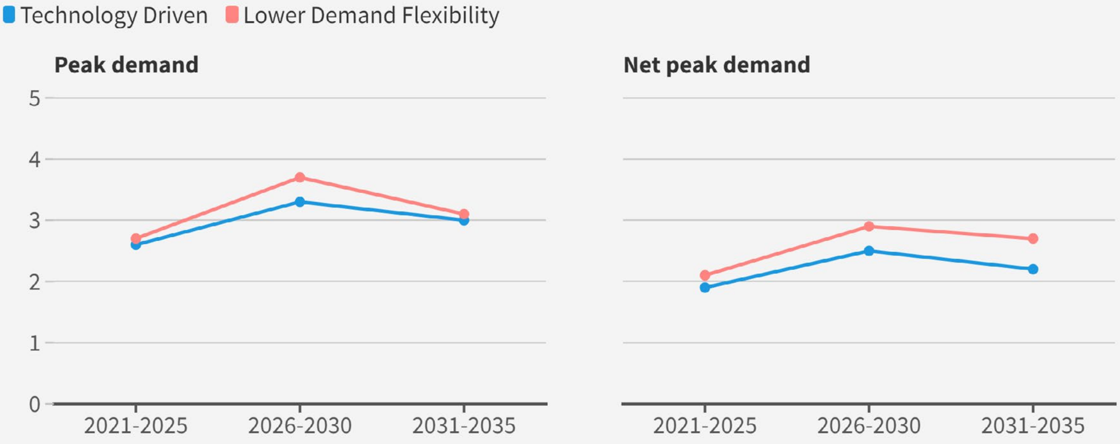
**Table 4.5.1:** Difference in capacity (GW, and GWh in the case of battery storage) in 2035 between the named sensitivity scenario and the Technology Driven pathway. The percentage difference is also provided in brackets in order to give a sense of the relative scale of change.

This drives investment in a further 7 GW of gas CCS and 45 GW of unabated gas peaking capacity. While this represents almost a 50% growth in the unabated gas peaking fleet, generation from these assets only increases by 15%. Maintaining these extra, low-utilisation assets would likely incur additional policy costs, not accounted for here.

A similar increase in thermal capacities is observed in the Delayed Interconnection scenario. This sensitivity scenario explores the impact of minimal increase in cross-border transmission projects beyond that currently planned, either as a result of delayed action or limited regional cooperation. Consequently, the European grid expands by a factor of 1.3 by 2035 over the 2025 Reference grid, much slower than in the clean power pathways and comparable to the factor of 1.2 in the Stated Policy scenario.

## Impact of lower demand flexibility on the growth rate of peak and net peak power demand

(% per annum)




Note: growth figures for peak power demand and net peak power demand are calculated at the country level and then weighted according to total power demand • Net peak power demand is defined as the demand peak once the contribution of wind and solar has been removed.

**Figure 4.5.4:** Impact of lower demand flexibility on the growth rate of peak power demand and net peak power demand. When the system's load shifting capacity is reduced, the two grow at a faster annual rate which drives the installation of additional gas peaking capacity in order to meet the unmitigated growth of hourly demand.

While clean power by 2035 is still possible in the case of slower interconnection expansion, additional thermal capacities are required, primarily in the form of gas CCS. This comes with risks, as CCS technology is unproven at scale, and would increase the system's vulnerability to gas price volatility and prolong Europe's gas dependence.

It can be concluded that, while flexibility tends to receive less attention at policy level, it is a necessary complement to power system planning. Maximising flexibility reduces system dependence on thermal capacities for providing balance and meeting growing demand peaks. It avoids unnecessary infrastructure build and allows for a decline in fossil assets while ensuring system reliability.

### Policy Recommendations:

- Maintain and, where required, modernise the existing hydropower infrastructure as it constitutes a key contributor to flexibility in clean power pathways.
- Incorporate incentives for smart devices and DSR in policies which drive electrification, particularly those targeting the transport and heating sectors.
- Promote the use of V2G capabilities and incentivise smart charging, as these can provide significant load shifting services.
- Promote regional cooperation and prioritise timely planning and development of new interconnection projects. To integrate the wind and solar capacities necessary for a cost-optimal 1.5C compatible pathway, cross-border transmission capacity should be approximately 40-60% larger by 2035 than represented by planned projects.

## 4.6 A clean system is reliable and resilient

### A highly renewable power system is reliable and resilient even to extreme weather events.

As renewables come to dominate the power system and dispatchable capacities decline, it is essential that the system remains secure, even in the case of extreme weather events. Granular modelling of the clean power pathways reveals that Europe can operate a 95% clean power system by 2035 without compromising reliability, and that the weather-dependent, intermittent nature of wind and solar does not pose a threat to the resilience of the grid, even under stressful climatic conditions.

The pathways presented are modelled such that supply matches demand at the hourly level, in a way that complies with European reliability standards.[72] The use of three climatic years ensures that a range of weather patterns, and their impact on the temporal-dependent elements of both supply and demand, are taken into account.

[72] ec.europa.eu/energy/sites/default/files/methodology_for_the_european_resource_adequacy_assessment.pdf

This includes a weather year notable for periods of both record low temperatures and severe heat waves (2010), intended to push the modelled 2035 clean power systems to react to instances of simulated high system stress.[73]

This section presents two instances of system stress, intended to demonstrate the resilience and reliability of the power system during extreme weather events. It is also intended to provide confidence that dispatchable – particularly fossil – capacities may be permanently reduced as wind and solar increases, without compromising power system security.

Resilience is defined here as the system's ability to withstand high-intensity, low probability (HILP) events, while reliability is considered as the system's ability to deal with low-intensity, high probability (LIHP) events.[74] In each case, the climatic conditions themselves are considered the event and their impact on the power system investigated. For information on how the HILP and LIHP events were identified, see Box 4.6.1.

**2035 clean power systems are resilient to a simultaneous cold spell and dunkelflaute.**

The 2010 climatic year stands out as a test for grid resilience as it incorporates two concurrent unfavourable HILP meteorological conditions which cause residual demand (hourly demand remaining after wind and solar contribution is removed) to peak, causing system stress. A harsh cold spell drives up power demand while dunkelflaute, characterised by calm winds and overcast conditions, results in a prolonged reduction of wind and solar output. Such events require immediate intervention from system operators to maintain the supply-demand balance through demand-side management and ramping up dispatchable capacities.

Figure 4.6.1 demonstrates the response of the 2035 power system in the three modelled pathways during the two-week HILP. During this time, wind and solar output is up to 30% lower than the monthly average for January in a normal weather year, while optimised demand sees an increase of up to 20% the monthly average in the Technology Driven scenario.

[73] The use of just three climatic years may be considered a limitation of the model as including additional historical weather patterns may uncover more severe HILP events. Furthermore, it may be the case that future weather events will be more extreme than those on record.

[74] Ahmadi, S., Khorasani, A.H.F., Vakili, A., Saboohi, Y. and Tsatsaronis, G., 2022. Developing an innovating optimization framework for enhancing the long-term energy system resilience against climate change disruptive events. Energy Strategy Reviews, 40, p.100820.

During this period of peak residual load, there remains a notable portion of wind and solar in the generation mix. This is because it is exceeding rare for meteorological events to affect the entirety of the Europe simultaneously.[75] Furthermore, even during extreme weather events, there are few regions in Europe which experience both anomalously low wind speeds and solar radiation during the same period, suggesting some positive covariability of wind and solar generation and benefits to their parallel scale-up. The successional regional impact of unfavourable weather conditions moving over Europe indicates the importance of interconnections in alleviating regional or national residual demand peaks through electricity imports from neighbouring countries whose wind and solar output is then unaffected by the weather conditions.[76]

The impact of demand-side management is particularly prominent during the HILP event. The cold spell causes an increase up to 20% in hourly demand compared to the average in January 2035; this impact would be more pronounced without the mitigating role of downside flexibility. These load shifting technologies smooth demand to better match supply and thus alleviating imbalances on the grid. During the HILP event, demand-side flexibility reduces hourly demand by up to 10% in the Technology Driven pathway and up to 15% in System Change. This ensures that the additional generation required from thermal assets is minimised.

The role of discharge from energy storage, including both pumped hydro and battery storage, can be seen across the three scenarios. Although supply from these sources is comparatively small, their flexibility enables contributions at critical times. This, combined with demand-side flexibility, reduces the system's dependency on dispatchable capacity and minimises the ramping up of fossil generation during times of high residual load.

[75] Analysis of multi-decadal data has shown that while some large meteorological events are common across Europe, the resulting peak power events do not necessarily impact the whole region simultaneously [H. C. Bloomfield, C. C. Suitters, D. R. Drew, "Meteorological Drivers of European Power System Stress", Journal of Renewable Energy, vol. 2020, Article ID 5481010, 12 pages, 2020. doi.org/10.1155/2020/5481010].

Readers may also wish to refer to the following analysis: Grams, C.M., Beerli, R., Pfenninger, S., Staffell, I. and Wernli, H., 2017. Balancing Europe's wind-power output through spatial deployment informed by weather regimes. Nature climate change, 7(8), pp.557–562

[76] Net imports/exports are not included in this section which focuses on grid resilience at system level as the European power system was modelled as a self-contained system; therefore, the balance of imports and exports would result in zero at system level.

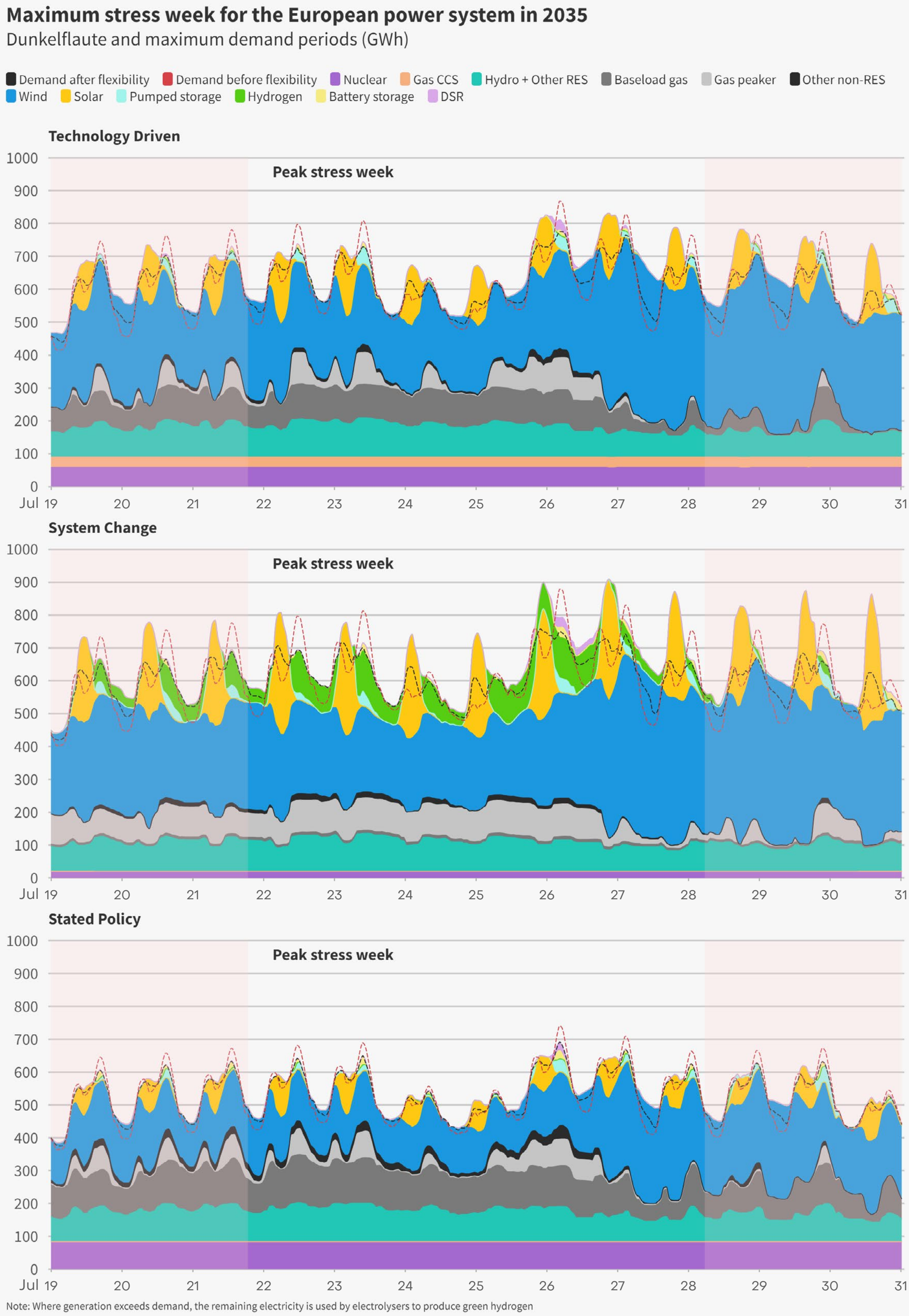



**Figure 4.6.1:** Hourly generation over a two-week period in 2035 in the modelled pathways. The middle 7-day period represents the power system's reaction during a maximum stress week for the European grid, constituting a HILP event caused by a simultaneous cold spell and dunkelflaute.

Across the three scenarios, the remaining demand shortfall is provided predominantly by fossil gas generation assets; at their maximum hourly contribution during the two-week HILP event, unabated baseload and peak gas plants provide 28% and 14% of electricity generation in the Technology Driven and System Change scenarios, respectively. With the earlier deployment of electrolysers and hydrogen turbines in the latter pathway, a substantial portion of required peaking is provided by hydrogen assets, allowing fossil gas capacities to be phased down. The peak hourly contribution of fossil gas assets during the 2035 HILP event reaches a maximum of 110 GW in System Change, compared to 204 GW and 226 GW in Technology Driven and Stated Policy.

**2035 clean power systems are reliable, managing large solar fluctuations during the day and meeting high evening demand peaks even during hottest periods.**

At the European system level, the maximum monthly solar output is usually in July. Given the large solar fleet deployed by 2035 in the clean power pathways and the typical generation profile of solar, large intra-day fluctuations in power output can be expected, particularly during the summer months. The LIHP selected combines this phenomena with a period of high electricity demand caused by heat waves in 2010 (Figure 4.6.2).

Excess solar generation in daytime hours is used by electrolysers for green hydrogen production, minimising curtailment and ensuring system balance. The difference between demand and generation is most prominent in the System Change scenario which sees the largest deployment of both solar PV and electrolysers, owing to the pathway's higher 2035 hydrogen demand. By contrast, the smaller wind and solar fleet in the Stated Policy pathway is unable to cover a large share of the (lower) power demand, even during daytime hours; consequently, this scenario sees semi-continuous unabated baseload gas generation.

Power from unabated gas is minimised in the clean power pathways during the selected two-week summer period. Its role is predominantly concentrated during the evening peak owing to the natural limitation of solar generation to daytime hours. This mismatch is exacerbated by the typically lower wind generation during the summer months; wind power in July is about 50% lower than that during November, the month with the highest wind generation during a normal weather year.

In this context, the impact of demand-side flexibility is again notable. It allows up to a maximum of 12% or 22% of hourly demand to be shifted towards hours of solar generation, in Technology Driven and System Change respectively. Energy storage also plays a role, discharging during the evening peak hours and thus minimising the residual load to be covered through ramping up dispatchable assets.

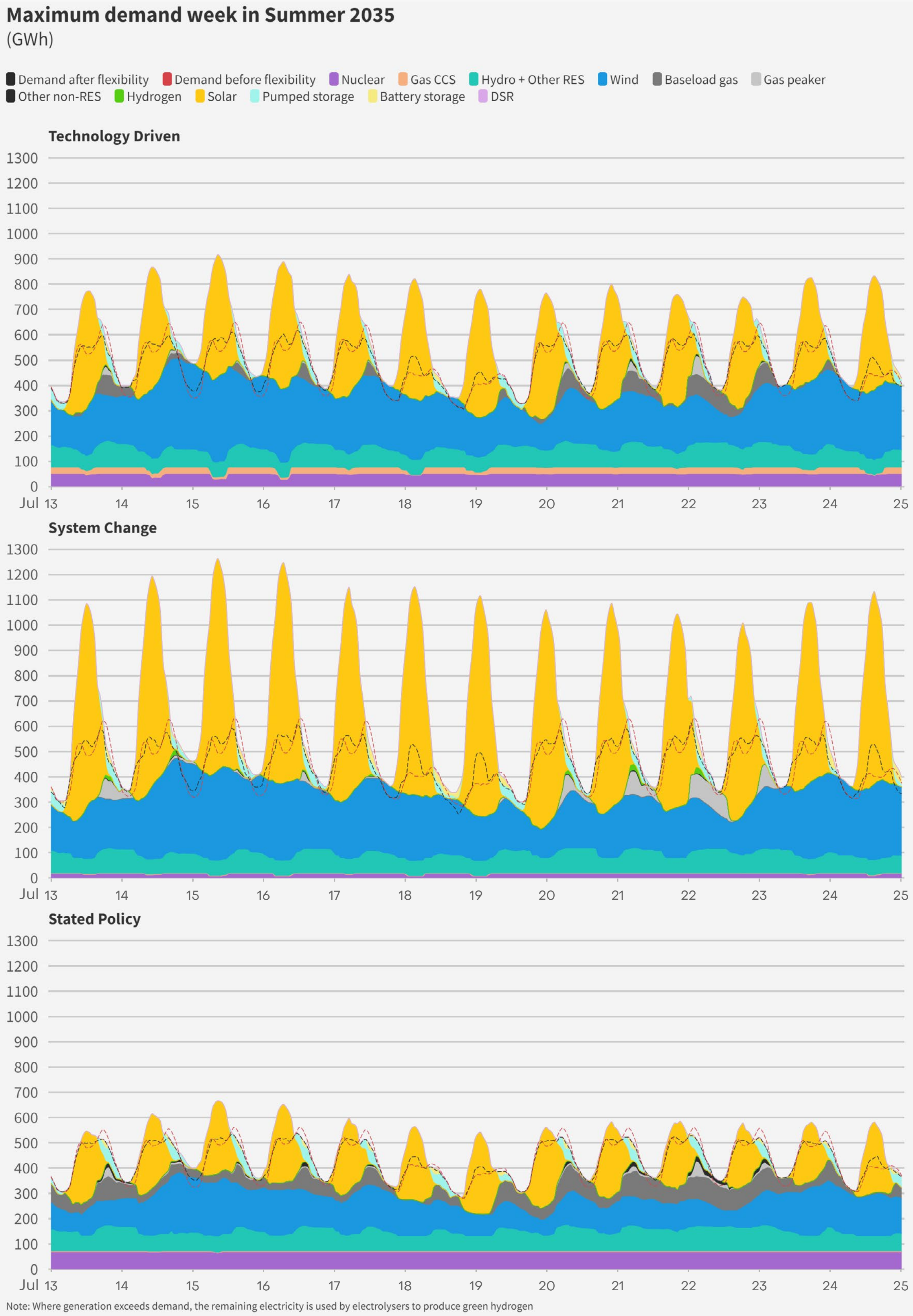



**Figure 4.6.2:** Hourly generation over a two-week period in 2035 in the modelled pathways. The middle 7-day period represents the power system's response to a LIHP event during summer months, where solar output is at its peak and electricity demand is high due to a heat wave.

Unabated fossil gas reaches a maximum hourly contribution of 153 GW and 93 GW during the LIHP event, corresponding to less than 70% and 80% of its installed capacity in the Technology Driven and System Change scenarios, respectively. Furthermore, given the much lower remaining demand, the System Change scenario sees minimal use of hydrogen peaking to meet the summer peaks, in contrast with the Winter stress period where additional dispatchable capacity is required.

**Clean power systems work in a variety of national contexts.**

Following on from power system resilience at the European level, this section provides insight into country-level responses to system stress, showcasing that clean power pathways are robust at all levels. Figures 4.6.3a-d display the national generation mix of four countries during their maximum stress 24-hour period[77] during the winter months of 2035.

Four countries are presented to demonstrate that power systems with distinct characteristics, from different generation portfolios to different demand profiles, are able to ensure a system balance and resilience. The selection covers all regions of Europe, taking into account different energy resources and levels of interconnectivity. It features countries with various starting points, all of which reach more than 90% clean power in their national generation mix by 2035 in Technology Driven and System Change, but with different levels of contribution from wind and solar.

While there is variation in how the countries ensure resilience, a shared feature notable across all is the impact of peak shaving and load shifting provided by demand-side flexibility and energy storage, particularly in the evening peak hours.

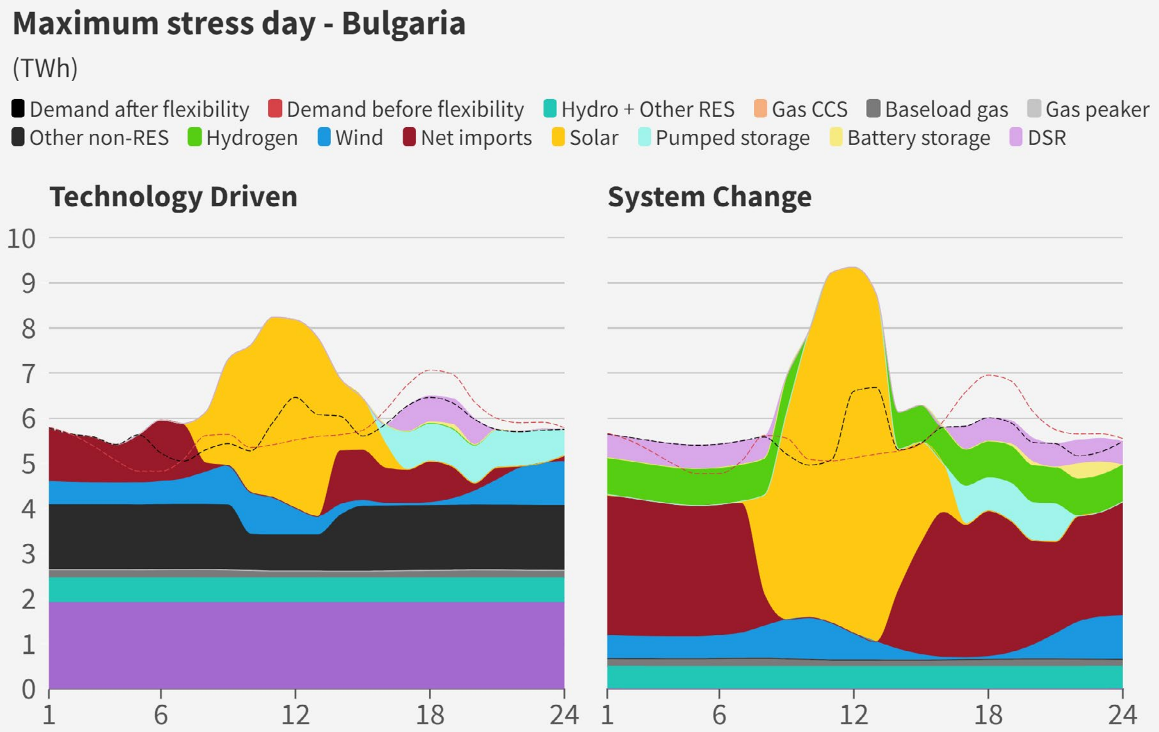
[77] The maximum stress period is defined as the 24-hour period during which peak net electricity demand (or highest residual load) occurs. This stress period would be the result of the combination of high power demand and lower than average wind and solar generation owing to the weather-dependency of residual load.

## Box 4.6.1: Identification of HILP and LIHP events

To demonstrate the resilience and reliability of a decarbonised power system where the bulk of generation comes from variable renewable sources, two different examples of power system stress are investigated. These are a high-intensity, low probability (HILP) disruptive weather event and a low-intensity, high probability (LIHP) weather event, both of which may cause may cause a surge in power demand (e.g. heating demand spikes during extreme cold spells) and sharp fluctuations in wind and solar output. These select periods were identified based on the below descriptions, following a similar approach to the 2022 TYNDP Scenarios Report.

The HILP event is that which concurrently features the highest electricity demand and highest residual load, that is, the remaining demand which must be met by the power system once the wind and solar contribution have been taken into account. This is defined as the rolling seven-day period with the highest direct electricity demand (excluding P2X) and the highest residual load.

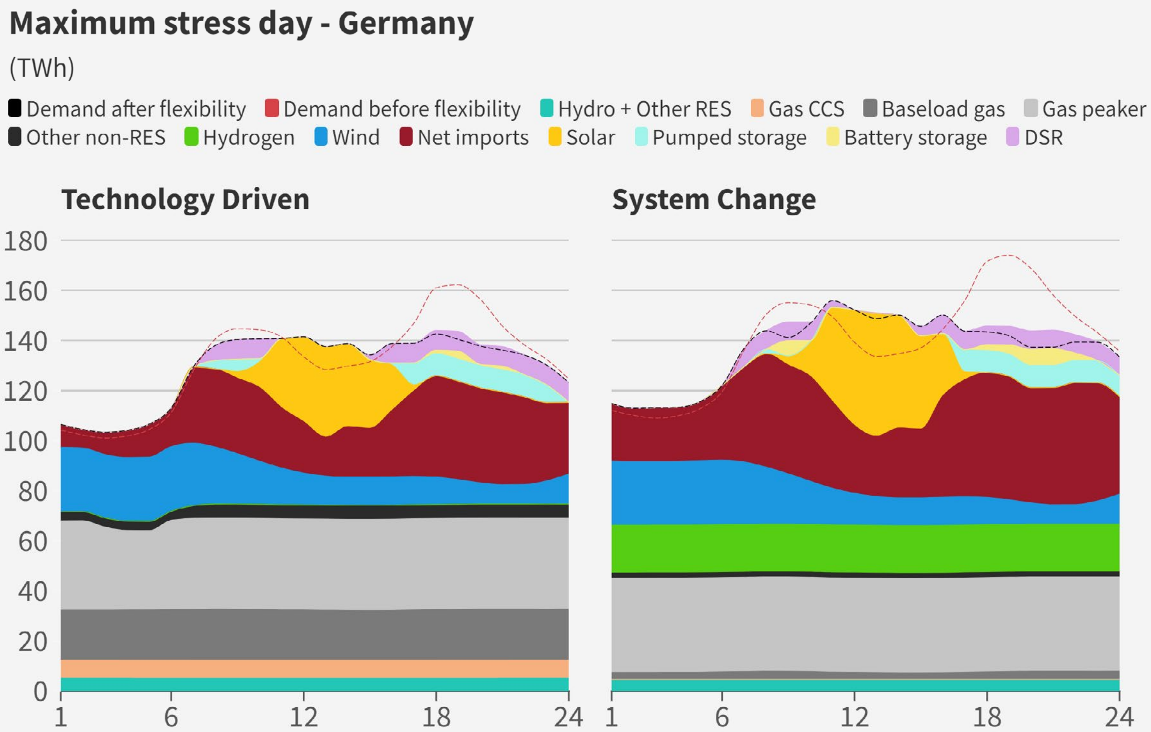
The LIHP event selected is that with large intra-day supply fluctuations in solar output, typical of summer months, set during the week with the highest electricity demand period in Summer. This latter period of system stress was defined by demand as opposed to residual load to provide contrast to the period with the highest residual load as it may be the case that wind and solar generation still constitute the largest share of generation during hours of peak electricity demand. This is defined as the seven-day rolling period during the summer months with the highest direct electricity demand.




**4.6.3a** Hourly generation at the country level in 2035 during the 24-hour maximum stress period – Bulgaria.

Currently dependent on coal and nuclear, Bulgaria's generation mix transitions to more than 97% clean by 2035, largely through deployment of wind and solar and, in the Technology Driven scenario, maintaining its existing nuclear fleet.

From a poorly interconnected country, Bulgaria's interconnection capacity quadruples over the 15-year period in both clean power pathways, allowing net imports to provide an important source of power during the period of peak residual load. This is complemented by the ramping up of thermal capacities, largely in the form of nuclear and coal in Technology Driven; until 2035, after which it is phased out entirely in the least-cost pathway, Bulgaria retains approximately 30% of its existing coal fleet in reserve. In the System Change pathway, the role of coal and nuclear generation, both of which have been completely phased out in line with the storyline, is replaced by a smaller thermal output from hydrogen turbines and a much larger import volume.




**4.6.3b** Hourly generation at the country level in 2035 during the 24-hour maximum stress period – Germany.

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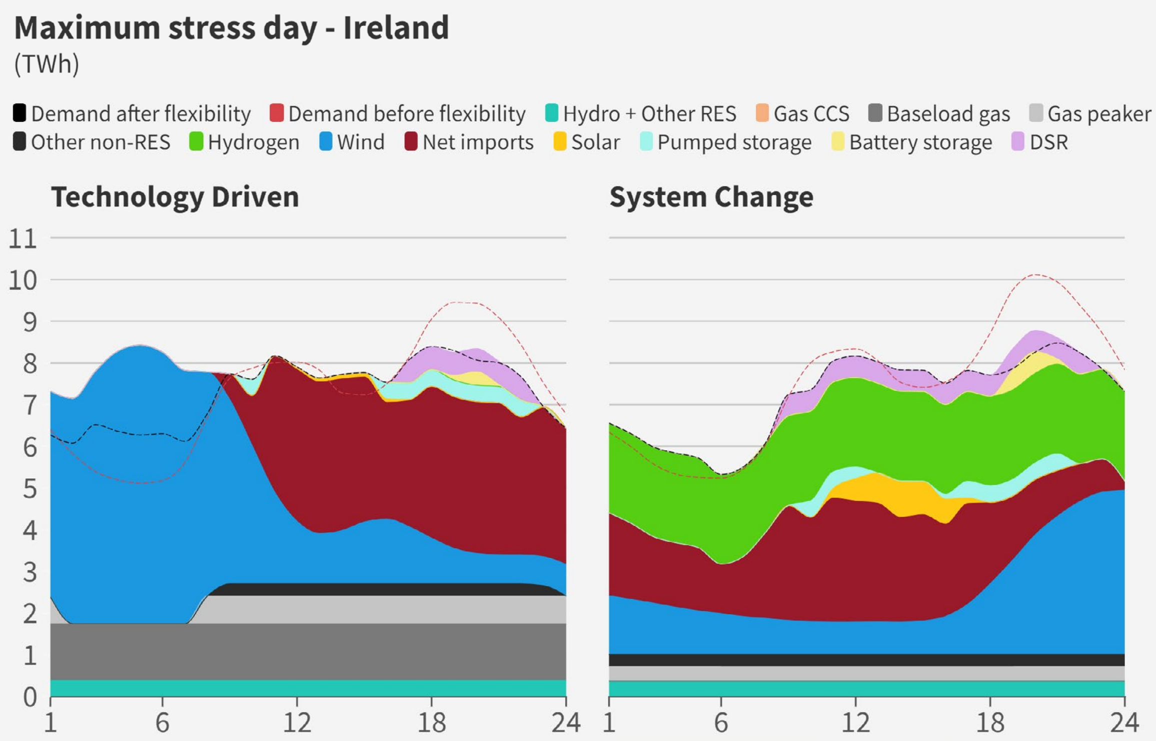
Germany's large power system expands in the clean power pathways by over two-thirds its current size. In this process, it achieves 91% clean power primarily through large-scale deployment of wind and solar.

The peak stress period for Germany in 2035 is a clear instance of dunkelflaute during a cold spell, forcing the power system to react to the supply-demand imbalance through ramping up of its gas power reserves and increasing import volumes. The latter is relatively easy to accomplish as Germany is already a well-connected country which also sees its transmission capacity almost double in the two decarbonisation pathways. The role of fossil gas is somewhat mitigated in the System Change pathway through the introduction of hydrogen turbines and higher import volumes.




**4.6.3c** Hourly generation at the country level in 2035 during the 24-hour maximum stress period – Ireland.

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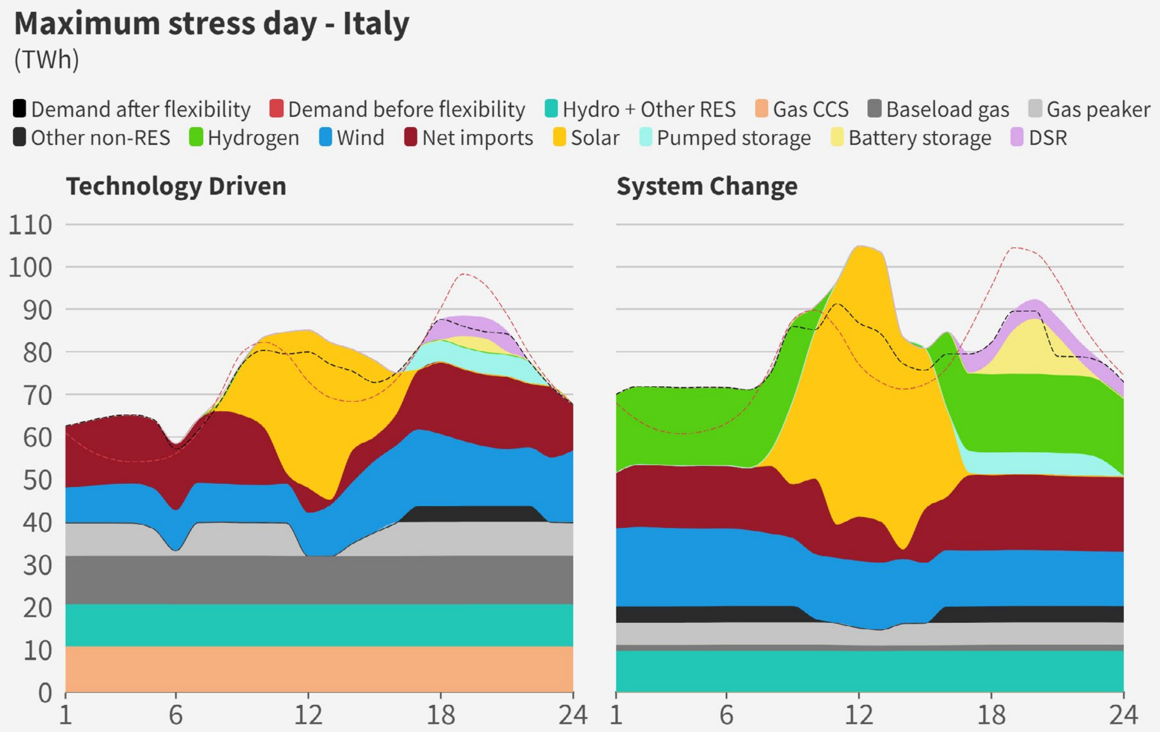
Ireland presents a particularly interesting case as a country with relatively poor interconnections and high dependence on wind in 2035 (90–95% of generation in clean power pathways). Additionally, the 15-year period sees a structural decline in the country's dispatchable capacities by about 50%.

Ireland's maximum stress day occurs as a result of a sudden drop in wind generation. Despite this, the system proves resilient, with the remaining fossil gas assets ramped up during hours of the peak residual load. However, the largest contribution to system stability during this period is net imports. This dependency on imports is alleviated in the System Change pathway through generation from hydrogen turbines, which also reduces the contribution from fossil gas.




**4.6.3d** Hourly generation at the country level in 2035 during the 24-hour maximum stress period – Italy.

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Italy's currently high reliance on natural gas decreases as it reaches 92–96% clean power by 2035; indeed, its unabated fossil gas capacity decreases by 50–85% in Technology Driven and System Change, respectively. The country sees a significant solar deployment, as well as commissioning of new onshore and offshore wind farms.

As a result, even during the period in which Italy experiences the peak residual load, the contribution of wind and solar is still considerable. Generation from gas CCS in Technology Driven or hydrogen turbines in System Change reduce dependency on baseload or peaking fossil gas plants to meet high demand levels, as do net imports.

## 4.7 Limited room for new fossil fuel capacity

### Fossil generation must be phased down and no new baseload (unabated) gas plants commissioned after 2025.

Phase out coal by 2030 and reduce unabated gas to <5% of generation to make Europe's power system fit for the Paris Agreement. In order to remain within a 1.5C carbon budget, this study agrees with multiple previous analyses that coal must be phased out by 2030, with the possible exception of a small fleet operating effectively as a reserve. In addition, unabated gas generation must contribute no more than approximately 5% of Europe's power supply by 2035.

**The role of existing baseload gas capacity shifts from power provider to capacity provider.**

By 2030, the baseload[78] gas fleet in both clean power pathways is 20% smaller but provides ~40% less generation, indicating a shift from bulk power to provision of capacity. After a temporary increase in 2025, utilisation of the baseload gas fleet falls to approximately 30% of load hours by 2030, down from ~60% in 2020.

**No baseload (unabated) gas plants need to be commissioned after 2025 for a clean power sector by 2035.**

This shifting role of gas from a bulk generator to a capacity provider has clear implications for investment decisions being made today about gas infrastructure. This refers to the build of new gas power plants and to that of gas transport infrastructure. In both clean power pathways, investment quickly pivots away from unabated baseload capacity to peaking capacity, at least until low or zero-carbon gas capacities become available in the 2030s.

[78] The category 'unabated baseload gas' used in this report comprises large Combined Cycle Gas Turbines (CCGTs) and Combined Heat and Power (CHP) units. Broadly speaking, the category captures all gas generation assets that are not specifically designed for operation in low-utilisation (peaking) mode. While several distinct generation technologies can fulfil the peaking role, to reduce complexity this modelling only considers Open Cycle Gas Turbines (OCGTs).

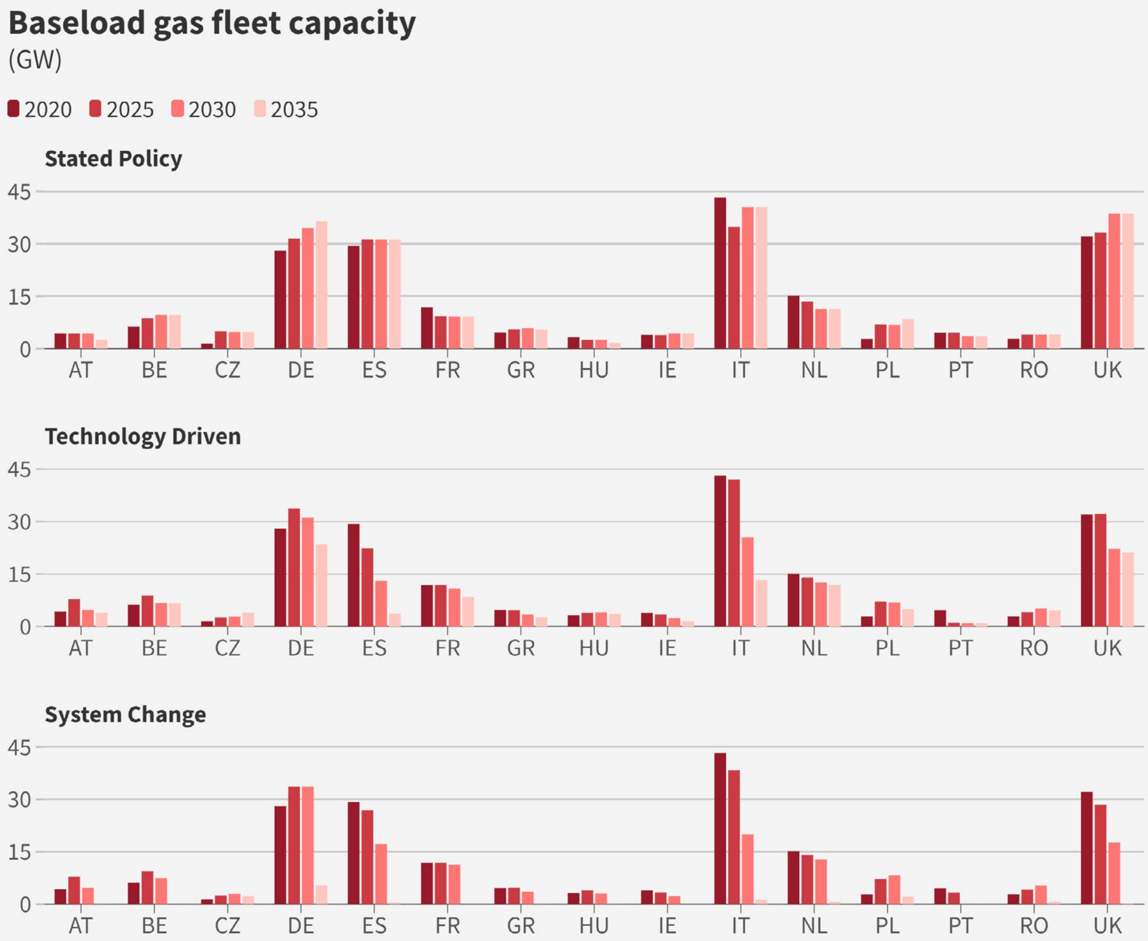



**Figure 4.7.1:** Unabated baseload gas (CCGT+CHP) fleet over time, by country and pathway. The countries with the 15 largest fleets are shown. These countries account for more than 95% of installed capacity in 2025 in the Stated Policy pathway.

In the least-cost clean power pathways, no new large unabated gas capacity is commissioned further to what is expected by system operators by 2025.[79] This shows that if adequate wind and solar (and supporting infrastructure) can be delivered, the commissioning of baseload gas can end with the existing pipeline.

[79] The ENTSO-E/ENTSOG TYNDP National Trends scenario (2020) is taken to represent the best estimate of system configuration in 2025. It shows a growth in baseload gas which is interpreted here as the 'expected' deployment. Estimated additions agree well with the pipeline according to Global Energy Monitor's Europe Gas Plant tracker (accessed June 2021). These expected developments may change as a result of the current energy crisis and REPowerEU plans to shift away from gas.

The Stated Policy pathway shows a clear over-investment in baseload gas until 2035. The existing fleet is either maintained or continues to increase in most countries, requiring investment in new capacities. This represents an obvious stranded asset risk and raises serious questions for utilities and developers currently planning more than 60GW baseload gas to be commissioned between 2026 and 2035.

**Investments in unabated gas should quickly pivot away from baseload assets into more flexible sources.**

In Stated Policy, baseload gas capacity accounts for 7% of power system investment between 2020 and 2035, totalling €90 billion. This is approximately double the investment in the same technologies in clean power pathways, in which baseload gas only accounts for 2–3% of power system investment before 2035.

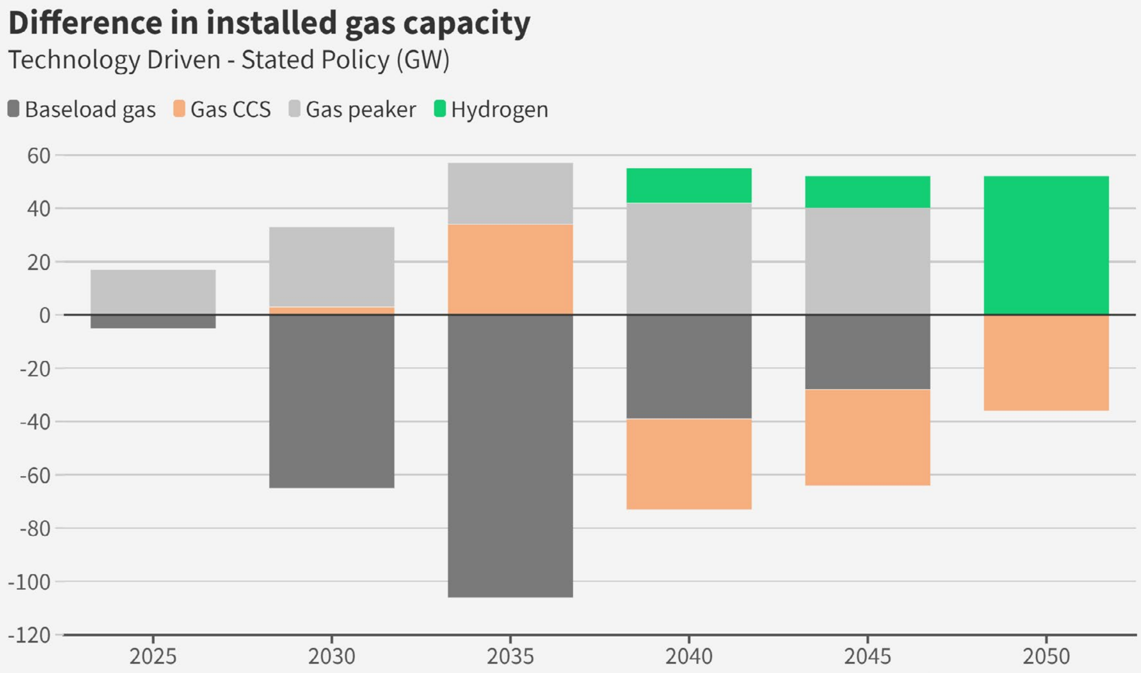
The expansion of gas peakers in the clean power pathways ensures system balancing, and their utilisation is sufficiently low to remain within the carbon budget. This presents a relatively low cost way to maintain the required dispatchable fleet before clean firm capacities and long duration storage can be scaled up. Gas peakers account for only ~2% of investment in the power system between 2020–2030 in the clean power pathways.

However, sensitivity analysis reveals that investment in gas peakers beyond 2025 is not the only way to ensure system security. Bringing forward investment in alternative clean dispatchable capacities can remove the need for any investment in unabated gas after 2025 (peaking and baseload). Trade-offs between dispatchable capacity options are discussed in the next section (4.8).

The modelling does not include conversion of existing assets, such as the addition of carbon capture equipment or fuel switching to burn hydrogen or biomethane.

In reality, these options could reduce the investment needs in clean dispatchable assets by repurposing the existing gas fleet. Also, a requirement that new assets are 'ready' to burn renewable gases could permit the continued development of baseload gas beyond 2025. A definition of readiness would need to include strict criteria, backed up by strong regulation and governance.

In summary, this analysis shows that investments in unabated gas should quickly pivot away from baseload assets into peaking assets that are better suited for providing flexibility and operating with low utilisation. If adequate wind and solar (and supporting infrastructure) can be delivered, the commissioning of baseload gas plants can end from 2025. From 2030, new clean dispatchable technologies enter the system, in this case gas CCS or hydrogen-burning turbines, to maintain a smaller but cleaner dispatchable fleet.



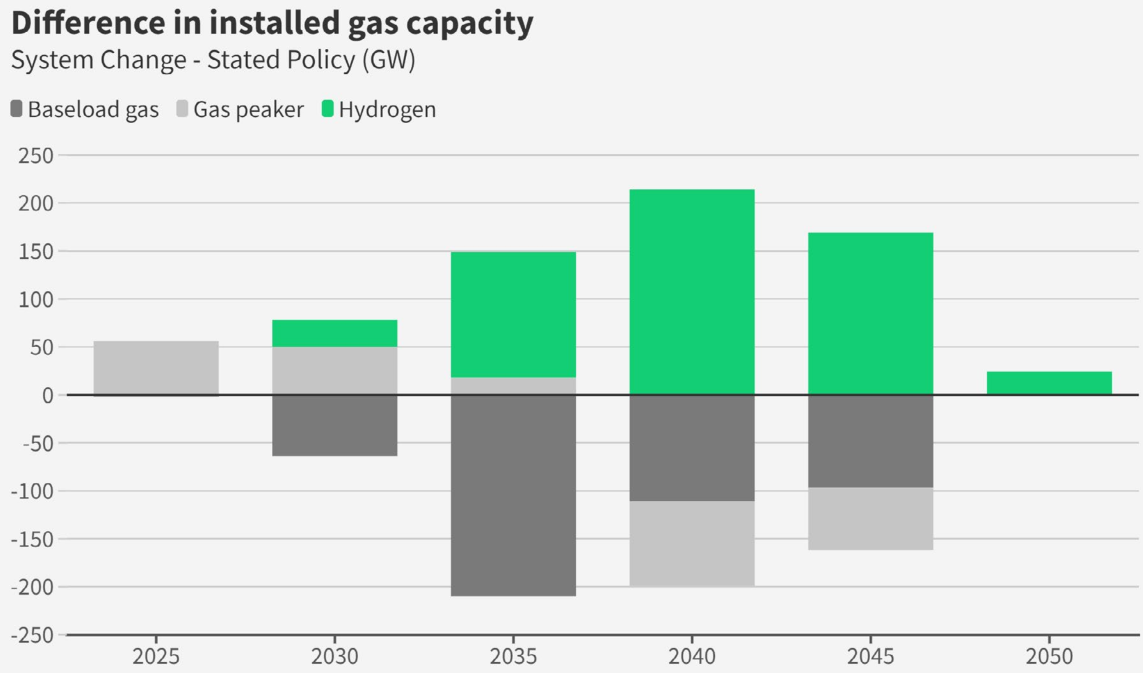




**Figure 4.7.2:** Difference in gas capacities over time. Both Technology Driven and System Change pathways use less baseload capacity every year than Stated Policy, which are partially offset by a larger fleet of flexible gas peakers.

### Policy recommendations:

- Deliver sufficient wind and solar plus interconnection so that the commissioning of unabated baseload gas assets can end with the existing pipeline (i.e., by 2025).
- Create market conditions that support decreasing utilisation of the unabated gas fleet through 2035, maintaining the availability of existing capacity for its full technical lifetime.
- Prioritise the readiness of zero or low-carbon dispatchable capacity options as quickly as possible in order to avoid an overcapacity of conventional gas assets, at unnecessary cost.

## 4.8 A smaller and cleaner dispatchable fleet

### Dispatchable capacities continue to play a role in a clean power system but the fleet is smaller and cleaner by 2035, despite growth in electricity demand.

The modelled pathways demonstrate that Europe's power system becomes less reliant on dispatchable generation for system stability as wind and solar grow to dominate supply. This is a notable outcome given that the clean power pathways see both total electricity demand and peak power demand increase rapidly over the 15-year period.

**Reductions in fossil capacity do not need to be compensated by a growth in clean dispatchable capacities.**

In the modelled pathways, the size of the clean dispatchable fleet remains largely unchanged between 2020 and 2035. Variations in composition of this fleet are mainly the result of storyline assumptions, including assumed nuclear lifetimes and, in the case of Stated Policy, the commissioning of new nuclear. Gas CCS and hydrogen turbines compensate for the structural decline of nuclear in the Technology Driven and System Change pathway, respectively.

The overall decline in the power system's dispatchable capacity is the result of the structural decline of the fossil fleet; it decreases by one-third in Technology Driven and two-thirds in System Change by 2035.

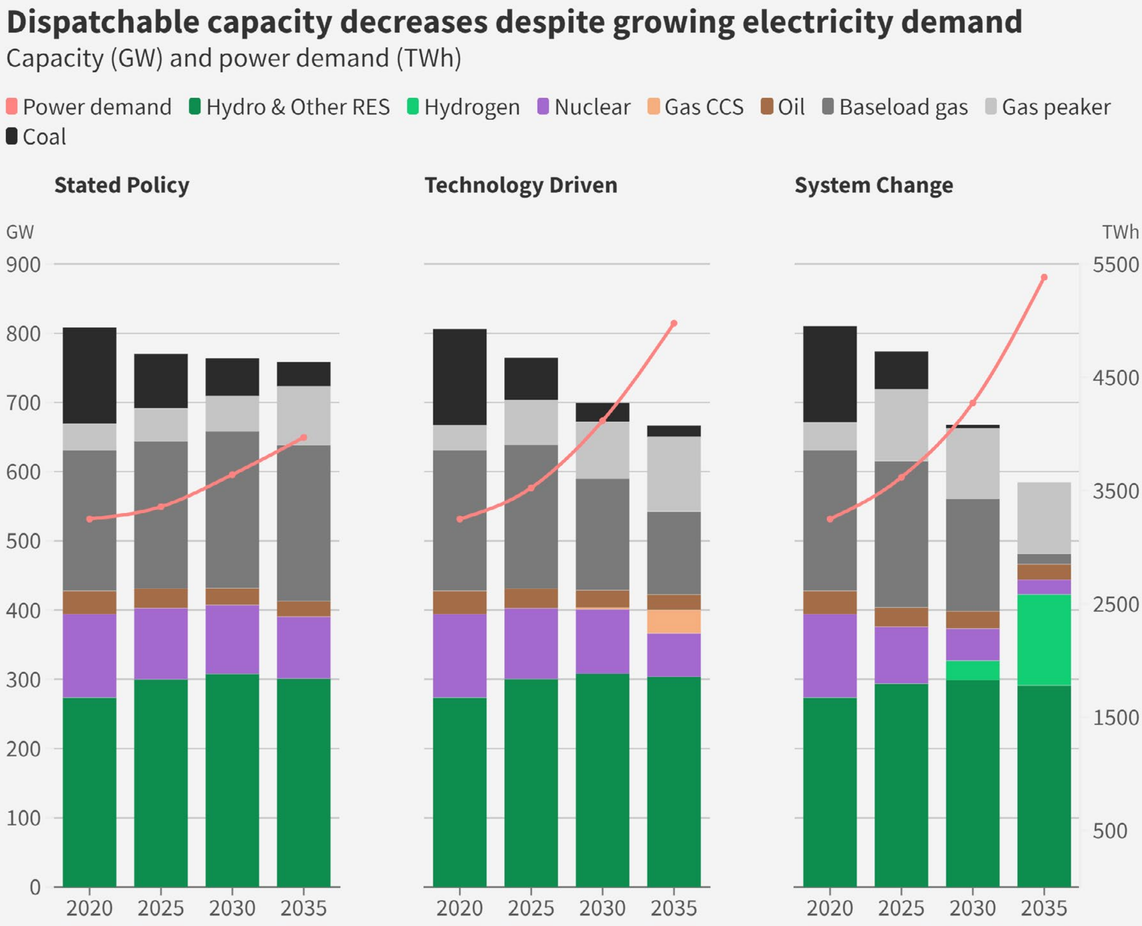



**Figure 4.8.1:** Downward trend in capacity of dispatchable generation technologies in the three modelled pathways between 2020–2035, compared to the upwards trend in power demand (including demand for P2X). While power demand increases more rapidly in the clean power pathways, these scenarios actually see the fastest decline in dispatchable capacity. Growth in power demand does not need to be supported by growth in dispatchable technologies.

This is driven primarily by coal phase-out commitments, which by 2035 see existing coal capacities fall by 75% in the Stated Policy pathway, 90% in Technology Driven, and 100% in System Change. In Technology Driven, approximately 16 GW of coal is retained in 2035 to ensure power system resilience during system stress periods (see Fig. 4.6.3a), but the annual contribution to power supply is negligible (<1%).

**The composition of the dispatchable fleet may take a variety of forms and still achieve clean power by 2035. The technology choices present different risk profiles, but estimated cost differences are minimal.**

The clean power pathways clearly demonstrate that dispatchable capacities continue to deliver high system value. The least-cost pathways feature different configurations of gas peakers, hydrogen turbines and gas with CCS, and do not invest in new nuclear. However, sensitivity analysis reveals that other configurations are possible at minimal extra cost.

Three sensitivity scenarios specifically explore decisions regarding dispatchable capacity technologies, which are affected by political priorities, social acceptance, and technology readiness, as much as economics. These are:

- **No gas CCS**, which assumes that use of gas CCS technology is not possible at scale in the power sector.[80]
- **Nuclear Plus**, in which all planned new nuclear plants and possible lifetime extensions are assumed to go ahead. A small amount of nuclear small modular reactors are also included after 2035 (8 GW commissioned between 2035 and 2050), as this technology is nearing technological readiness[81] and a number of European countries are already showing interest.
- **Limited New Gas**, in which political direction precludes investment in **any** new unabated gas power plants after 2025, including both baseload and peakers.[82]

Not only does clean power by 2035 continue to emerge as the cost-optimal outcome in these sensitivity scenarios, but it does so at negligible extra system cost (less than +/-0.5% difference) in all cases compared to the Technology Driven pathway. The relative difference in the size of the dispatchable fleet in 2035 is minimal, varying between 1–2%, further supporting the result that a resilient and bigger clean power system can be achieved without the need for an enlarged dispatchable fleet. It is also clear different fleet configurations are equally able to support the decarbonisation of the power sector.

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[80] The technology remains largely unproven, and the supporting investment landscape and regulatory preparedness lacking. Furthermore, given the long timeframes for such large-scale infrastructure projects (approximately 7–10 years for CCS), this implies a risk that CCS projects for the power sector would not materialise at the scale required and in a timely fashion to contribute to the clean power transition in Europe.

[81] www.iea.org/reports/nuclear-power

[82] The deployment of new gas peaker capacities between 2021 and 2025 is informed by Draft TYNDP 2022 data, in a similar way to the cap on baseload capacity in the Technology Driven pathway.

## Differences in composition of the dispatchable fleet in 2035 compared to Technology Driven

Differences in capacity (GW) and generation (TWh) in 2035

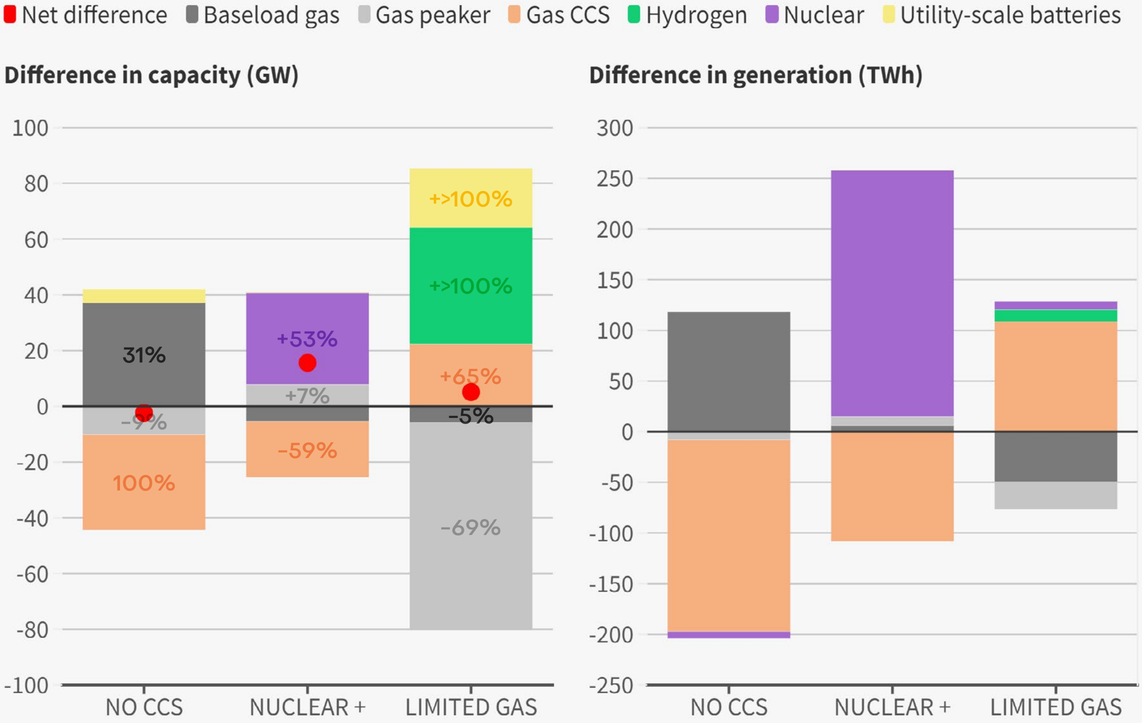


**Figure 4.8.2:** Difference in composition of the dispatchable fleet in 2035 in three sensitivity scenarios compared to the Technology Driven pathway. Percentage figures indicate the relative difference in capacity of a particular technology between Technology Driven and the sensitivity.

In the No Gas CCS scenario, the role of the 34 GW fleet is directly replaced by new unabated baseload gas plants. While the Technology Driven pathway sees no new baseload gas after 2025, approximately 40 GW is added to the system between 2026 and 2035 if CCS is not available. Four countries account for over three quarters of this extra development: Germany, Italy, Poland, and Czechia. These same countries dominate the early investment in gas CCS seen in the Technology Driven scenario.

While the nuclear fleet still declines in the Nuclear Plus scenario, reducing 20% to 92 GW in 2035, it is larger compared to Technology Driven (62 GW) and System Change (21 GW). Higher nuclear capacity in this pathway alleviates the need for additional baseload generation, primarily reducing the deployment of gas CCS, by almost 60% to just 14 GW in 2035.

This implies that the commissioning of new nuclear capacities together with lifetime extensions can reduce reliance on CCS technology, which has yet to be proven at scale. It also follows that the realisation of nuclear plans would minimise the build of new unabated gas plants which would be required should the deployment of gas CCS be disrupted. The case for new nuclear must also of course consider safety risks and the issue of waste disposal.

The Limited new gas scenario mainly affects gas peaking capacity – which emerges in clean power pathways as a cost-optimal outcome. The peaking fleet is 70% smaller in 2035 compared to the Technology Driven pathway. The ~80 GW shortfall in dispatchable capacity is primarily compensated by earlier investment in clean dispatchable technologies, with an extra 40 GW of hydrogen turbines and 20 GW gas CCS deployed by 2035. In addition, 20 GW of utility-scale batteries are deployed, replacing a portion of the flexibility services offered by gas peakers in the Technology Driven scenario. The conclusion here is that bringing forward investment (and investor confidence) in clean dispatchable capacities can remove the need for any unabated gas investments after 2025.

Together, the sensitivity analysis around dispatchable capacity options demonstrates that the trade-offs between technology options are not primarily about economic cost, rather a balancing of different risk profiles. Delivering the required levels of wind and solar can minimise the importance of this issue by minimising the size of the dispatchable fleet required.

**The wind and solar deployment levels are unaffected by choices between dispatchable capacity options, which have bigger implications for Europe's dependency on fossil gas.**

A notable outcome of the scenarios that explore different configurations in the dispatchable fleet is that none significantly impact wind and solar deployment by 2035, confirming this as the central challenge for power sector decarbonisation.

The composition of the dispatchable fleet has a more notable impact on the pathways' consumption of natural gas for power generation, particularly that of the No Gas CCS and Nuclear Plus scenarios. Despite the focus of the Limited New Gas scenario, minimal differences are seen in Europe's natural gas demand for power as additional gas CCS plants compensate for the required thermal generation.

Total pathway consumption of fossil gas in the power sector is reduced by 12% in No Gas CCS and 9% in Nuclear Plus. This effect arises mainly from changes after 2030. While this outcome may be expected in the case of the Nuclear Plus scenario, it is perhaps less intuitive in the case of No Gas CCS, which sees additional baseload gas power plants commissioned to compensate for the missing gas CCS.

Although the unabated gas fleet is larger than in the Technology Driven pathway, its use is restricted by the carbon budget. This, and earlier investment in hydrogen turbines reduce gas consumption in the No Gas CCS scenario. A risk associated with this alternative pathway is ensuring such controlled utilisation of a larger unabated gas fleet once the infrastructure has been built.

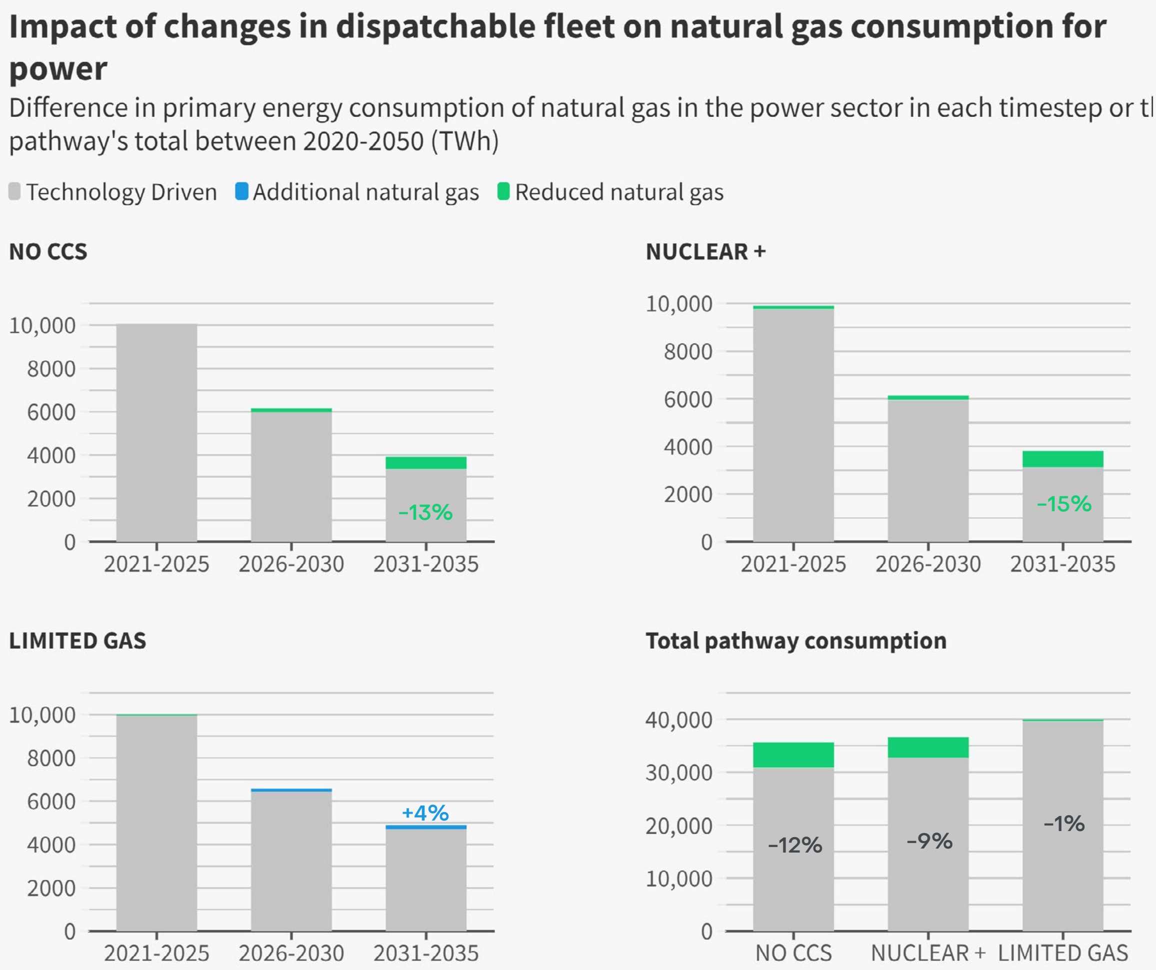


**Figure 4.8.3:** Difference in the primary energy consumption of natural gas for power generation between Technology Driven and three sensitivity scenarios. This is shown for each year between 2020–2035 for each sensitivity. This is also shown as the difference in the natural gas consumption for power over the entire pathway, that is, between 2020–2050, for each sensitivity scenario.

## Policy Recommendations:

- Choices regarding dispatchable power infrastructure should allow for a wide range of costs, benefits, and risks, not restricted to power system economics. Infrastructure decisions should seek to minimise risk by considering national resources, public opinion, and competing policy objectives such as reducing gas dependence.
- Provide clear political direction at national level on the identified portfolio of new clean dispatchable capacities required to support the electricity transition. This will allow fossil assets to be phased out without compromising the reliability and resilience of the power system.
- Where required, enact regulatory changes to accommodate investment in new technologies. For instance, the commercial deployment of gas CCS may be hindered by the current relevant legal frameworks of many European countries.[83]

[83] 'CCS Readiness Index' developed by the Global CCS Institute

5 Benchmarking

# Comparison to other scenarios

In this section, key metrics for the power sector and wider energy sector transition in the modelled pathways are compared against selected official pathways that serve to guide planning of Europe's energy system. Specifically, the 'Distributed Energy' (DE) and 'Global Ambition' (GA) scenarios from ENTSO-E's 2022 'Ten Year Network Development Plan' (TYNDP). The MIX' (EU-COM MIX) scenario from the EU Commission's 'Fit for 55 Impact Assessment', is taken to represent the Fit-for-55 policy ambition. The clean power pathways are also compared against the EU Commission's 'REPowerEU' plan where data is available. Comparisons are made at the EU27 level in 2030 and 2050 only, as the common scope and data availability between scenarios.

These external scenarios provide useful benchmarks against which to assess the credibility of modelling results presented here. Conversely, the ambition of these external scenarios can be judged against the requirements of a clean power system as set out by this report.

ENTSO-E is the EU's leading energy system planning authority, and as such the DE and GA scenarios provide a highly-credible reference point for energy system development towards net zero. The MIX scenario describes energy system evolution consistent with the EU's target to reduce emissions 55% by 2030 compared to 1990.

# 5.1 Electricity generation

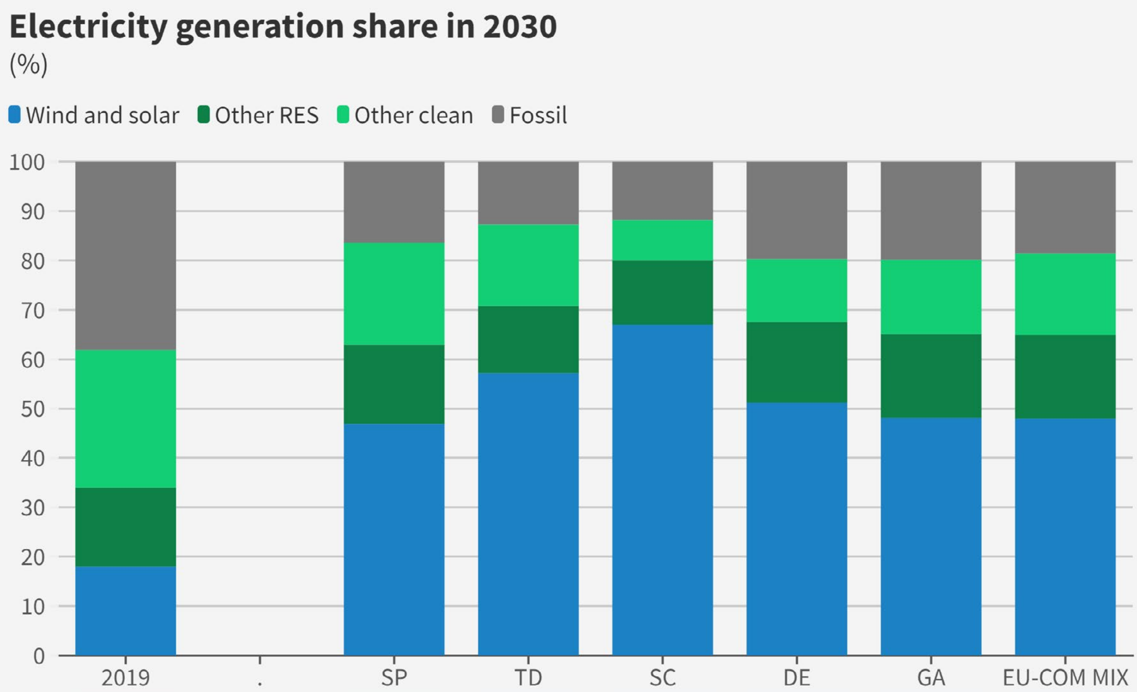


**Figure 5.1.1:** Electricity generation share by technology type in the EU27 in 2030 in the modelled pathways and TYNDP and EU-COM MIX scenarios compared with 2019.

Both modelled pathways to a clean power sector in Europe by 2035 show a high clean share of generation by 2030 – between 87–88%. Wind and solar provide the bulk of this, achieving a share of 57–67% of total power generation by 2030. Both TYNDP scenarios and the MIX scenario fall short of these level, achieving a clean share of 81% and 83% respectively and wind and solar penetration between 48 and 51%. As a result of their higher share of wind and solar, the clean power pathways also have a higher share of (total) renewable generation (71–80%) than the TYNDP and MIX scenarios (65–68%).

## Electrification

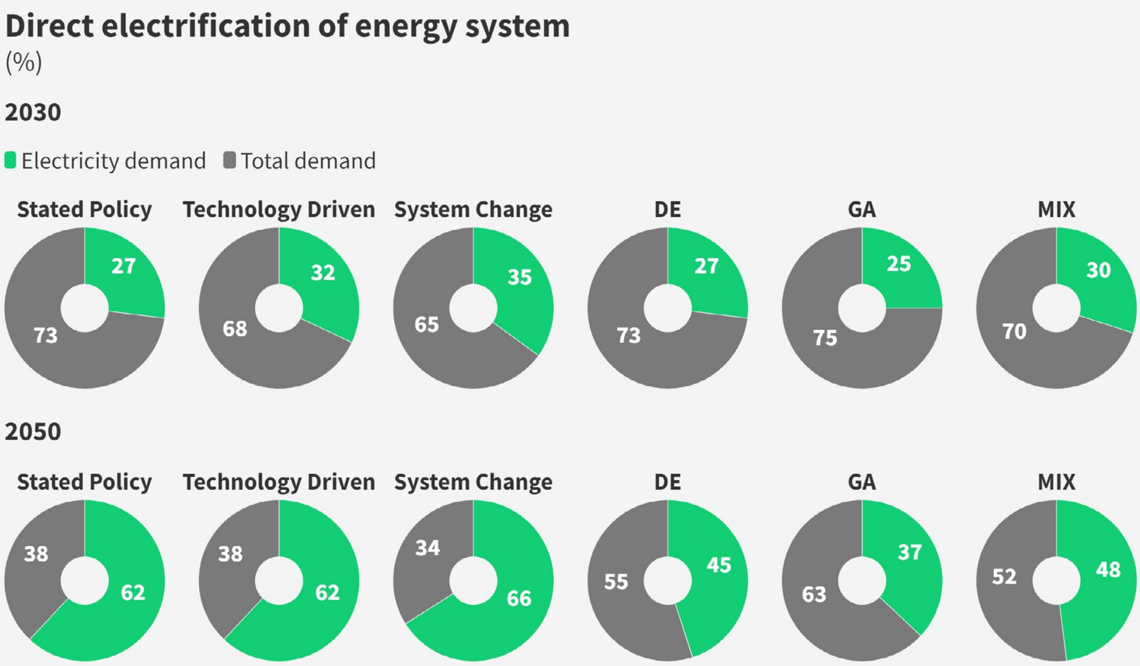


**Figure 5.1.2:** Electricity demand as a share of total energy demand in the EU27 in 2030 and 2050 in the modelled pathways and TYNDP and EU-COM MIX scenarios.

DIrect electrification of final energy demand in 2030 ranges from 32–35% in the modelled scenarios, higher than the TYNDP scenarios (25–27%) and the EU-COM MIX scenario (30%). This difference is mainly accounted for by higher electrification of transport in the modelled pathways – 2–3 times higher than TYNDP and EU-COM scenarios – and to a lesser extent by higher electrification of industry. By 2050 the clean power pathways achieved significantly greater electrification in all sectors but again show the largest difference with the TYNDP and EU-COM scenarios in the transport sector. The result is a far higher level of final energy demand electrification in the modelled pathways of 62–66% compared with 37–46% in the TYNDP scenarios and 48% in the EU-COM MIX scenario.

## Wind and solar generation share

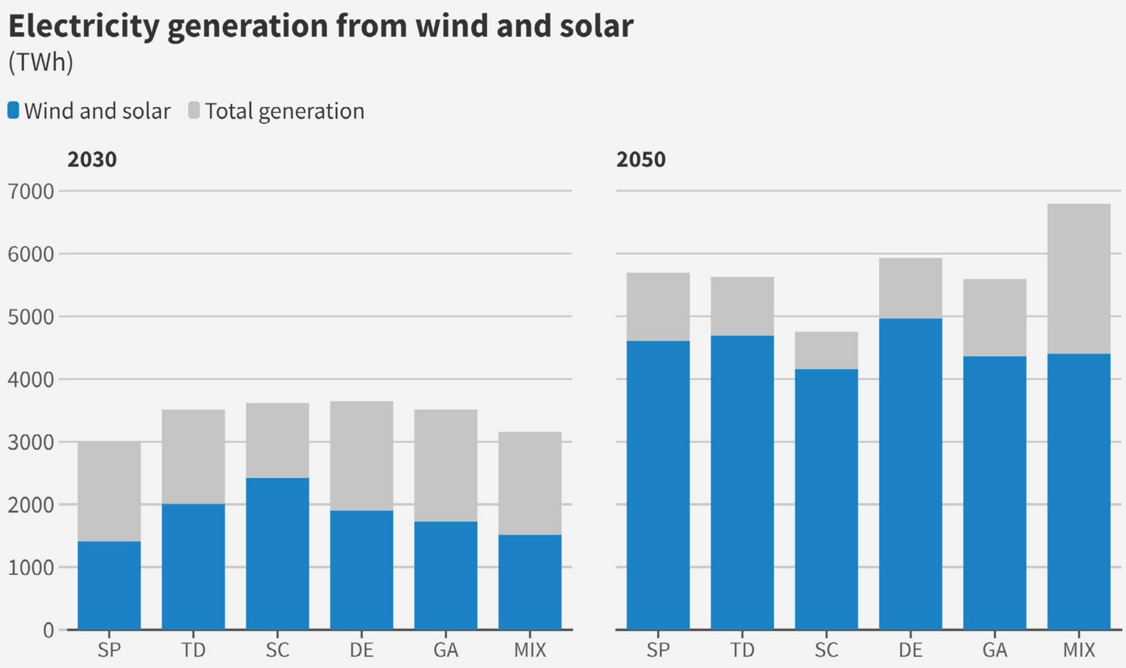


**Figure 5.1.3:** Electricity generation from wind and solar and total electricity generation in the EU27 in 2030 and 2050 in the modelled pathways and TYNDP and EU-COM MIX scenarios.

The higher share of wind and solar achieved by the modelled pathways by 2030 is a result of higher production from these sources, rather than lower overall production. However, by 2050, total wind and solar production in modelled pathways is comparable to TYNDP and EU-COM scenarios, while the total power supply is the same or lower. This is likely due to additional energy savings or efficiency gains assumed in the pathways in this report.

## Carbon intensity of power supply

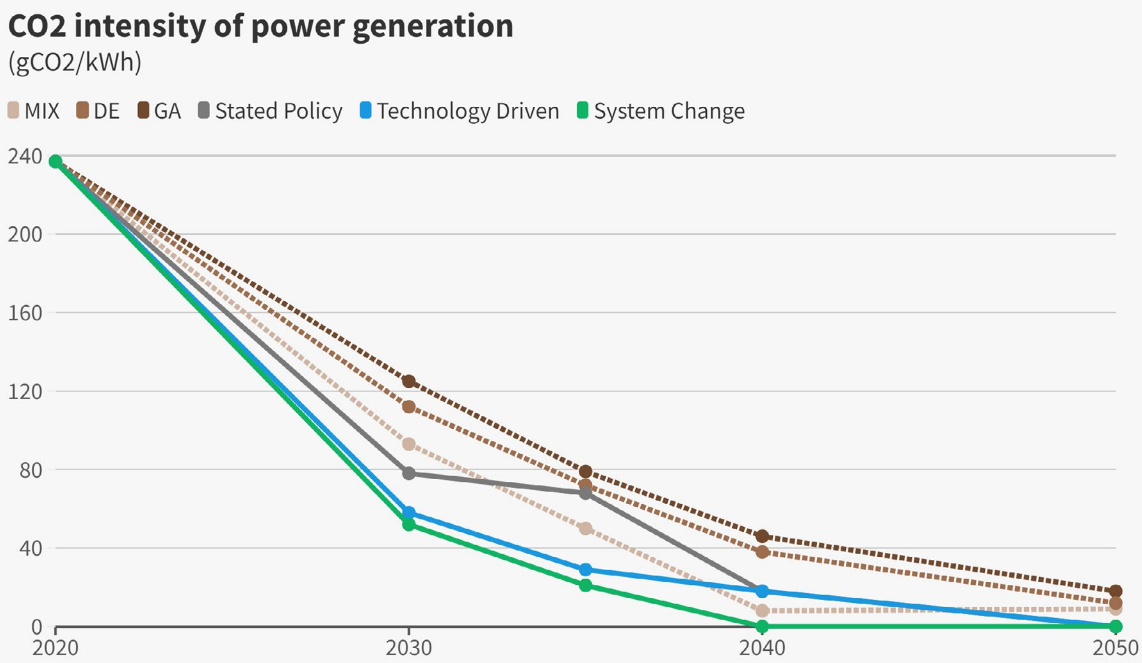


**Figure 5.1.4:** Carbon intensity of electricity generation (including P2X) in the EU27 in 2030 and 2050 in the modelled pathways and TYNDP and EU-COM MIX scenarios.

By 2030, the clean power pathways in this report achieve a significantly lower grid carbon intensity of 49–58g$CO_2$/kWh, compared to 115–125$CO_2$/kWh in TYNDP scenarios and an estimated 93$CO_2$/kWh in the MIX scenario. The combination of higher levels of electrification and lower-carbon electricity allow the modelled scenarios to unlock decarbonisation more effectively than the TYNDP and EU-COM scenarios.

# 5.2 Wind and solar capacity

Accelerating wind and solar deployment is a central challenge for enabling 2035 clean power, and it begins with defining adequate ambition. By 2030, the combined installed capacity of wind and solar is significantly greater in the Technology Driven and System Change pathways (1,075–1,420 GW) than the TYNDP (820–900 GW) and EU-COM (810 GW), but better aligns with the announced REPowerEU target (1,235 GW). However, by 2050, a higher level of energy efficiency and energy savings Technology Driven and System Change scenarios mean that differences in fleet size are less pronounced.

## Wind capacity

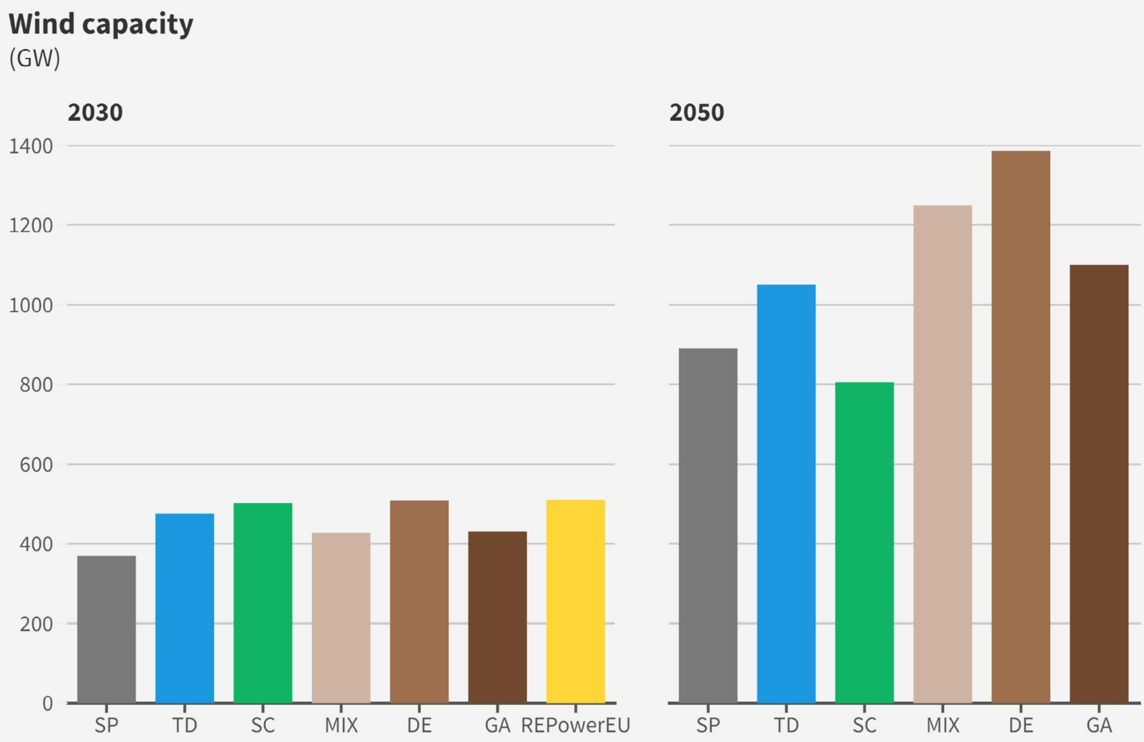


**Figure 5.2.1:** Total installed wind capacity in 2030 and 2050 in the modelled pathways and TYNDP and EU-COM MIX scenarios. REPowerEU 2030 target also included.

Wind capacity in the clean power pathways in 2030 is 475–500 GW. This is towards the upper end of the range in TYNDP scenarios (430–510 GW), substantially above the MIX scenario (440 GW), but in line with the new REPowerEU target (510 GW). However, in 2050 installed wind capacity is lower in the clean power pathways (805–1050 GW) than both the TYNDP (1,100–1,385 GW) and the MIX (1,255 GW).

## Solar capacity

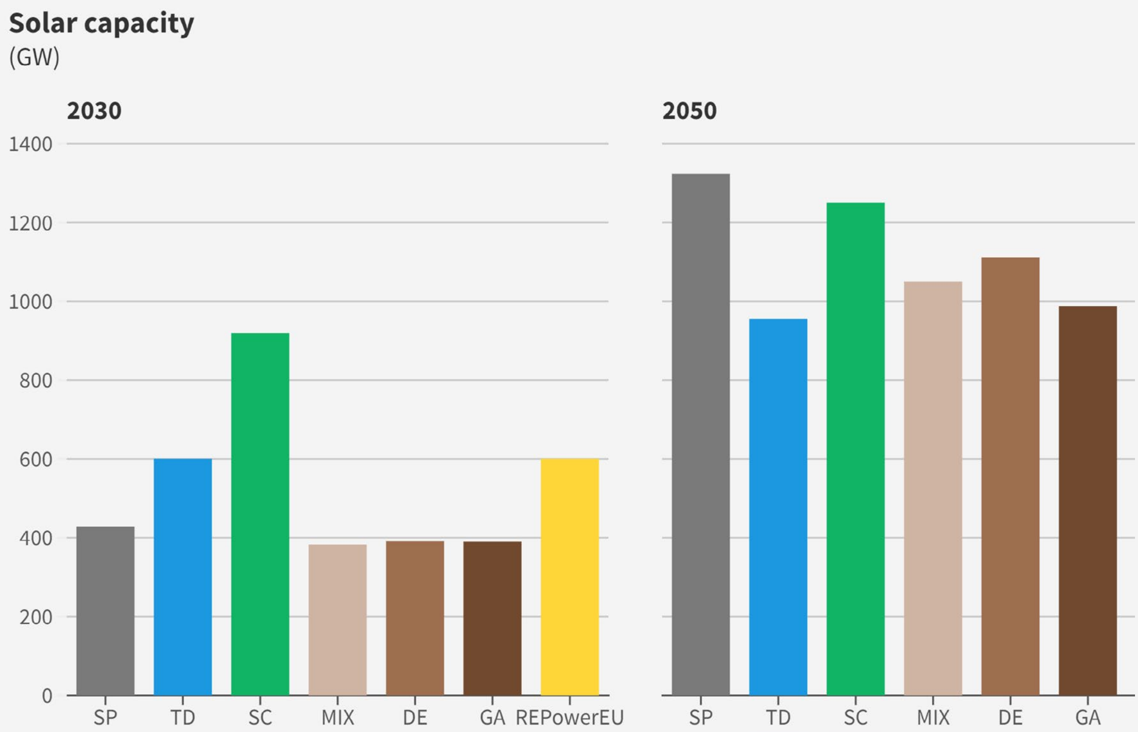


**Figure 5.2.2:** Total installed solar capacity in 2030 and 2050 in the modelled pathways and TYNDP and EU-COM MIX scenarios. REPowerEU 2030 target also included.

A much larger difference in solar capacity is observed between the clean power pathways in this report and external pathways. TYNDP scenarios use only 390 GW, and the MIX scenario even less with 370 GW. In contrast, the solar fleet in the Technology Driven scenario is almost twice as high at 600 GW, and the System Change scenario is 2.5 times higher than with 920 GW by 2030. Once again the modelled pathways better align with the ambitions of REPowerEU which targets 600 GW of solar capacity by 2030. However, by 2050 the modelled pathways and TYNDP and MIX scenarios are more comparable, all reaching approximately TW scale in solar capacity.

Industry-association Solar Power Europe provides two 2030 capacity deployment scenarios of differing ambition: a 'Medium scenario' anticipating the most likely development of solar power given the current state of play of the market, and an 'Accelerated High scenario' in which solar power policy optimised on a path towards 100% renewable electricity in 2050 is accelerated to deliver higher short-term ambition and quickly reduce reliance on gas imports. The TYNDP and EU-COM scenarios both miss SPE's Medium scenario. In contrast, the System Change pathway sees solar deployment broadly in line with the Accelerated High scenario.

# Overview of modelling limitations

The energy system is complex and integration is increasing across multiple energy carriers – a trend which must continue as Europe transitions away from fossil fuels toward a more efficient and renewables-dominated system. This analysis is based primarily on power system modelling, in effect isolating one aspect of an interdependent energy system. Steps have been taken to minimise the shortcoming of this simplification, but important limitations remain. The most significant of these include:

- **The modelling was carried out before the war in Ukraine**, and the escalated energy crisis that followed. Commodity (e.g., fossil fuels) and technology costs are therefore based on pre-war forecasts. While the modelling results for the three main pathways have not been updated, all attempts have been made to adapt the findings to increase their relevance in present context. Furthermore, sensitivity modelling was used to explore variations in key assumptions that better reflect the wartime energy landscape (e.g., higher fossil fuel prices, a political aversion to new fossil gas infrastructure, and pro nuclear power). Comparison is also made, where possible, to the REPowerEU plan – the EU27 energy response to the invasion of Ukraine.

- **Some potentially important sources of flexibility are omitted due to model limitations.** These mainly concern technologies or systems that are adjacent to the power system. Specifically, the interplay between power and district heating systems is only partially captured by modelling load-shifting in DH-connected large heat pumps. In reality, heat networks offer more flexibility through heat storage both within the network itself or in dedicated thermal storage (insulated hot water tanks). This could result in lower power demand peaks for heating, and hence lower power system peaking capacites. The sources of demand flexibility that are included may also be underestimated, as their uptake is dependent on adequate price incentives, and the mobilisation of an active consumer base equipped with the right technology and knowledge.

- **Some aspects of system cost are not included**, notably national (internal) transmission and distribution systems, which will require substantial investment. See Box 3.5.2 for a discussion of the likely impact of this limitation on the study results.

- **Some aspects of power system operation are simplified.** No specific provisions are made for system inertia. It is implicitly assumed that grid supporting technologies will be widely deployed, as is already underway in several European countries that already anticipate a high penetration of non-synchronous sources. Also, thermal generation assets are assumed to be able to quickly vary their output. In reality, engineering constraints limit the speed of this ramping. The result is that the flexibility thermal assets (especially baseload assets) is likely overestimated. However, tests carried out with more realistic ramping rates reveal a minimal impact on pathway results.

- **Pathways are computed using three years of historic weather data** to test the system at each point in time along the trajectories. While one of these years was chosen to specifically represent an 'extreme' year in terms of weather and temperature conditions (unfavourable for renewables), ideally more years would be used to capture an even wider range of weather conditions. However, three years is commonly assumed to provide an adequate basis for energy system planning.

- **Pathway computation is driven by least-cost optimisation.** This is an effective way to explore power system evolution while minimising costs, which should always be a policy priority. However this is not the sole policy priority, nor do cost considerations solely determine power system development in reality. Other factors have sway, such as competing policy priorities, economic and industrial capacity, and social acceptance of new infrastructure. The sensitivity scenarios aim to address the most important impacts on power system development resulting from these non-cost factors, but they are not exhaustive.

- **Cost optimisation of complex systems, such as the power system, is inherently uncertain.** While each modelled pathway represents the 'least-cost' trajectory, in practice there will exist many alternative near-optimal solutions, which may have materially different outcomes. To mitigate this, the results presented attempt to focus on outcomes that are common to the modelled clean power pathways and which are robust to sensitivity analysis. In the interest of transparency, a separate technical report is provided which provides detailed input assumptions.

## 7 Abbreviations

| | |
|---|---|
| **CCS** | Carbon capture and storage |
| **ENTSO-E** | European Network of Transmission System Operators for Electricity |
| **EU27** | European Union |
| **Europe** | Refers to the following: EU27, the United Kingdom, Norway, Switzerland and the Western Balkan six (Albania, Bosnia and Herzegovina, Kosovo,[84] Montenegro, North Macedonia, Serbia) |
| **EV** | Electric vehicle |
| **GW/ GWh** | Gigawatt/ Gigawatt-hour |
| **H2** | Hydrogen |
| **HILP** | High-intensity, low probability event |
| **IEA** | International Energy Agency |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LIHP** | Low-intensity, high probability event |
| **Mt** | Megatonne |
| **NTC** | Net transfer capacity |
| **P2X** | Power-to-X |
| **TSOs** | Transmission system operators |
| **TWh** | Terawatt-hour |
| **TYNDP** | Ten Year Network Development Plan |
| **V2G** | Vehicle-to-grid service |

[84] All references to Kosovo, whether the territory, institutions or population, in this text shall be understood in full compliance with United Nations' Security Council Resolution 1244 and without prejudice to the status of Kosovo.

## 8 Glossary

| | |
|---|---|
| **Abated gas** | Gas CCGT plant with CCS |
| **Battery storage** | Refers to both utility-scale batteries and vehicle-to-grid enabled batteries in electric vehicles, unless otherwise specified |
| **Clean power** | Zero- and low-emissions sources of electricity; unabated fossil fuels are excluded |
| **Direct electrification** | Switching from a fuel source of energy to electricity |
| **Dispatchable capacity** | Power generation technologies which can produce electricity on demand; this refers to all technologies included in this study except for wind and solar |
| **End-uses** | The transportation, industrial, commercial and residential sectors |
| **Energy sector** | Covers the power sector and all end-use sectors |
| **Europe** | Refers to: EU27, the United Kingdom, Norway, Switzerland and the Western Balkan six (Albania, Bosnia and Herzegovina, Kosovo,[85] Montenegro, North Macedonia, Serbia) |
| **Gas peaker** | Gas OCGT plant |
| **Indirect electrification** | Replacing fossil fuels with green hydrogen (or derived fuels) |
| **Net peak demand** | The highest power demand once the wind and solar contribution has been taken into account |
| **Peak demand** | The highest power demand on an electricity grid during a specific time period |
| **Power-to-X** | The conversion of electricity into hydrogen through electrolysis |

[85] All references to Kosovo, whether the territory, institutions or population, in this text shall be understood in full compliance with United Nations' Security Council Resolution 1244 and without prejudice to the status of Kosovo.

| | |
|---|---|
| **Residual demand** | Remaining demand once the contribution of wind and solar is taken into account |
| **Thermal capacity** | Fuel-powered generation technologies; this includes all fossil-fuel fired plants, nuclear power and hydrogen turbines |
| **Unabated baseload gas** | Gas CCGT and CHP plants |
| **Unabated gas** | Baseload gas and gas peakers; gas CCS is excluded |

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