MISSION SOLAR 2040

Europe's flexibility revolution

SolarPower Europe

www.solarpowereurope.org

MISSION SOLAR 2040

Europe's flexibility revolution

SolarPower Europe

SolarPower Europe – Leading the Energy Transition

SolarPower Europe is a member-led association that aims to ensure that more energy is generated by solar than any other energy source by 2030.

www.solarpowereurope.org

Table of contents

SolarPower Europe

Project lead: Michael Schmela, SolarPower Europe.

Project manager: Raffaele Rossi, SolarPower Europe.

Internal co-authors: Raffaele Rossi, Michael Schmela, & Dries Acke, SolarPower Europe.

External co-authors: This report was conducted with the support of Artelys. Contributing authors: Thomas Brouhard, Thomas Rousselet, & Christopher Andrey, Artelys.

Please cite as: SolarPower Europe (2024): *Mission Solar 2040: Europe's flexibility revolution*.

For media use and queries: Bethany Meban, SolarPower Europe b.meban@solarpoweurope.org

Date of publication: June 2024.

ISBN: 9789464669183.

Contact: info@solarpowereurope.org.

Thanks to our Sponsor Members:

BayWa r.e. · edp · enel · plenitude · First Solar · HUAWEI · Iberdrola · lightsource bp · LONGi Solar · sunnova · Trinasolar · WACKER

Design: Onehemisphere, Sweden. contact@onehemisphere.se

Cover image: ShaunMKelly/Shutterstock.com

BECOME A MEMBER OF SOLARPOWER EUROPE

SolarPower Europe is the leading European solar association. Join our solar community today to unlock a world of shining benefits for your organisation.

Industry Influence

Help us shape the solar policy framework in Europe, by joining forces with industry leaders.

Networking Opportunities

Connect with 300+ members from across the entire solar value chain. Join exclusive networking opportunities at our events.

Expert Knowledge

Get access to the latest solar best practices, comprehensive market intelligence, weekly policy update, quarterly market updates webinars and knowledge exchange within our workstreams.

Visibility and Promotion

Be visible in front of an engaged solar audience of 25K+ monthly unique visitors on our website, 85K+ followers on social media, 27K+ newsletter subscribers, and more.

Amazing Discounts

Get exclusive member discounts for SolarPower Europe and partner events, advertising on partner media outlets, sponsorship opportunities and more.

Join SolarPower Europe today

www.solarpowereurope.org/membership

SolarPower Europe

Executive summary

Solar is growing much faster than anyone would have expected, as market expansion keeps surprising all solar and energy analysts. As the global solar market is on track to exceed 500 GW of new installed capacity in 2024 and is projected to cross the TW level before 2030, the effects of this strong acceleration are also visible in the European Union. Having reached an operating solar fleet of 269 GW in 2023, the EU is projected to control nearly 900 GW of solar capacity by the end of the decade, outpacing national and EU solar targets.

Meanwhile, current trends in the EU power system, coupled with climate and energy policy targets towards 2030 and 2040, indicate that variable renewable energy sources like solar PV and wind will provide the largest bulk of EU electricity supply in the coming decades. The REPowerEU plan, and more recently the EU Commission 2040 impact assessment scenario, outline pathways and targets for a large increase in variable renewable energy generation.

However, a deep integration of variable renewables, in particular solar energy, into the power system does not come without challenges. Already today, some Member States with comparatively high levels of solar PV penetration are starting to face issues related to the smooth integration of variable renewable generation in their power mixes. These issues include both challenges of technical nature (integration of solar projects into the grid, increasing level of curtailment) and financial nature (market structure, investment attractiveness and remuneration of renewable producers).

This study explores the interplay between the rollout of PV capacity and the deployment and operation of flexibility solutions in the EU power system, looking at the 2030 and 2040 time horizons. Modelling simulations of investment and hourly EU power system operations over a full year, it analyses three scenarios with increasing levels of solar PV and flexibility solutions, namely flexible capacities and flexible demand from electrification (see Table 1).

TABLE 1 OVERVIEW OF SCENARIO STRUCTURE

SCENARIO	KEY EXPECTATIONS	SOLAR PV CAPACITY	ELECTRIFICATION LEVELS	FLEXIBLE CAPACITIES
Solar-As-Usual (SAU)	**Baseline scenario:** Lack of flexibility solutions limits RES integration. High solar curtailment and cannibalisation expected.	Baseline	Limited	Limited
Solar + Flexibility (SF)	**Intermediate scenario:** Flexible capacities reduce curtailment and cannibalisation.	Baseline	Limited	Increased
Solar + Flexibility + Electrification (SFE)	**Advanced scenario:** Unlocking flexibility solutions improves system operations. Curtailment and cannibalisation are	Increased	Increased	Increased

Executive summary / continued

The study results highlight the fundamental role of flexibility solutions in a power system characterised by a strong penetration of variable renewable generation. Tapping flexibility potential not only enables the deployment of more solar as the key to meet climate targets and security – it also allows to make better use of abundant, clean and cheap electricity. The analysis shows that:

1. **Unlocking flexibility solutions enables further PV deployment**, resulting in additional solar electricity into the EU power mix. Solar capacity exceeds 1.2 TW in 2030 and 2.4 TW in 2040, providing 32% and 39% of EU power demand respectively.
2. **Unlocking flexibility solutions reinforces the PV business case.** In 2040, solar curtailment rates are reduced by 49% and solar capture prices increase by 54% compared to the baseline.
3. **Unlocking flexibility solutions reduces total energy system costs,** thanks to the massive cost savings from the electrification of the heat, transport and hydrogen sector. Annual net system cost savings amount to 32 billion EUR in 2030 and 160 billion EUR in 2040.
4. **Unlocking flexibility solutions lowers total GHG emissions.** Carbon emission linked to the additional power demand from electrification are largely counterbalanced by cross-sectoral emission savings from the reduction of carbon-intensive alternatives. Annual net GHG emission savings amount to 151 $MtCO_2eq$ in 2030 and 555 $MtCO_2eq$ in 2040.

This Mission Solar 2040 report finds that building a clean energy system based on renewables, flexibility and electrification is the best way to bring the benefits of the energy transition to Europe's businesses and citizens and secure Europe's overall competitiveness and prosperity. Our policy recommendations (p. 7) outline some of the crucial actions to support the scale up investments in renewables and in clean flexibility.

50 MW hybrid plant, El Andévalo, Spain. © Iberdrola

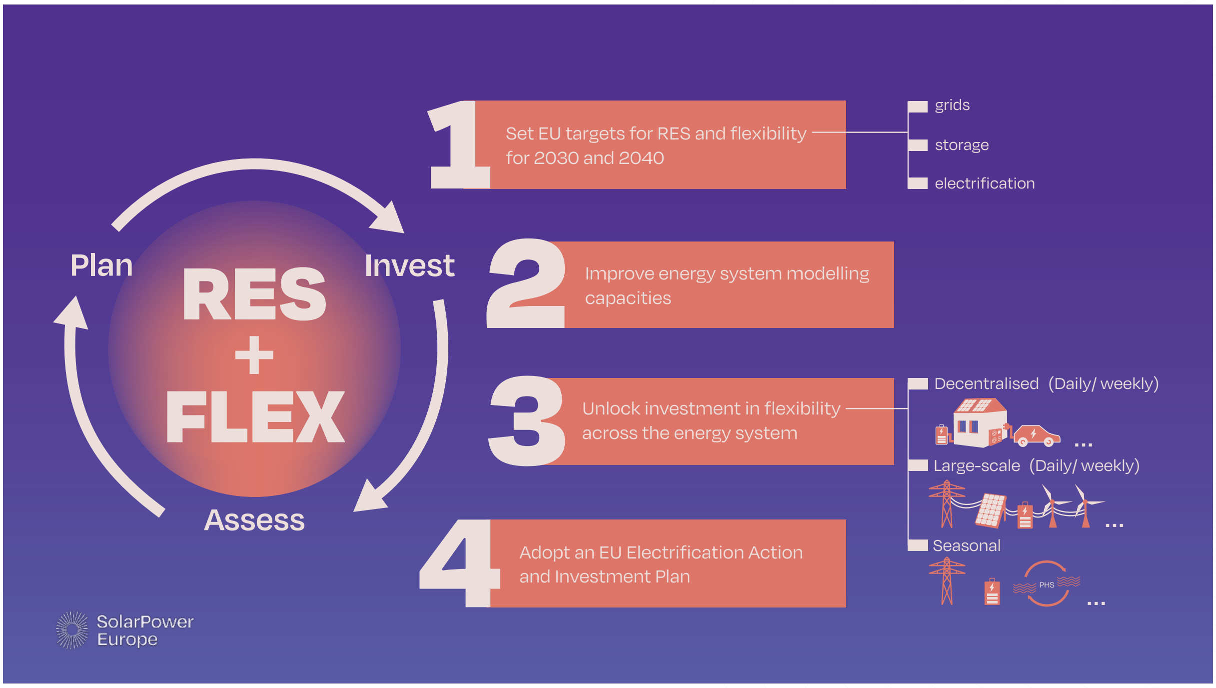
POLICY RECOMMENDATIONS

This Mission Solar 2040 report finds that building a clean energy system based on renewables, flexibility and electrification is the best way to bring the benefits of the energy transition to Europe's businesses and citizens and secure Europe's competitiveness and prosperity, compared to a current policies scenario.

The challenge, however, is to scale up investments in renewables and, especially, in clean flexibility in the coming years. The new political cycle is an opportunity to take this next step in the energy transition agenda, starting with the following policy recommendations:

1. **Set political goals for renewables and clean flexibility for 2030 and 2040**

   The current EU regulatory framework includes 2030 targets for renewables. This must continue after 2030 and be complemented with parallel goals for grids and storage. Establishing such targets is essential to provide a political steer and ensure political oversight on clean flexibility. This is currently lacking, which partially explains the slow progress in this area. An analysis of the latest National Energy and Climate Plans (NECPs) backs



up the argument: while ambition levels for renewables have substantially improved, it is not matched with objectives and investment plans in grids and storage. This disconnect cannot continue if we are to avoid the limits to renewables growth as outlined in the report.

It's important to carefully distinguish between the roles and targets of cross-border transmission grids, local distribution grids, and storage.

- This report assumes that cross-border transmission grids increase by 157 GW (+130%) to reach 278 GW by 2040. This should be translated into a political objective for cross-border infrastructure for 2040 building on the existing 15% indicative target by 2030;
- On distribution level, and within-country transmission level, political objectives are lacking and urgently need to be established. In particular, the mandate of National Regulators should be modernised in line with the new challenges of the National Energy and Climate Plans. This means that national regulators shall provide new, strong incentives for grid modernisation and build-out in light of the unprecedented investment need, with timely recognition of investments and adequate returns. Anticipatory investments should also be further incentivised and de-risked through the right regulatory framework. Given the diversity of local players, it is better to work with Key Performance Indicators for Distribution System Operators (DSOs), for example around grid hosting capacity or average time to grid connection, making sure that targets are achievable and accompanied with adequate incentives. Maximum deadlines should also be introduced for the permit-granting processes for competent authorities. A one-size-fits-all is unlikely to work in this field, but it remains essential to set clear objectives that guarantee political steering and oversight towards DSOs and regulators;
- On storage, this report speaks to the need to massively scale up battery storage capacity and operation across Europe, with a 20-fold growth from 36 GWh in 2023 to 780 GWh in 2030 and a 50-fold growth to 1.8 TWh in 2040. Setting an EU-level target follows logically from the G7 decision to adopt a global energy storage target of 1,500 GW by 2030, up from 230 GW in 2022.[1] Given the close relation between variable renewables and

© EVBox.com

1 G7 Italy (2024): Climate, Energy and Environment Ministers' Meeting Communiqué.

battery storage, it makes sense to express such target as a percentage of renewables output. This is important as it directly links the role of storage and other flexible capacities to current and future renewables integration. Today, regulators tend to assess the need for storage against security of supply parameters, like reliability standards that are linked to Loss of Load Expectations (LOLE). This approach, however, underestimates the role of storage in supporting cost-effective renewable integration from an optimal socio-economic welfare point of view. This could be solved by adopting a Renewable Integration standard. As a benchmark, our report suggests a 15% battery storage power capacity to variable renewables (VRES) ratio in 2030 and 18% in 2040.

The Electricity Market Design requires Member States to assess their non-fossil flexibility needs both at transmission and distribution level, at different timescales, based on data provided by system operators, and develop related objectives for demand response and storage. That is a good starting point for defining the needs, which we suggest should be formalised as targets and included in the NECPs. In the meantime, the new provisions on flexibility should be implemented without delay, starting from the implementation of capacity remuneration mechanisms fostering the participation of demand response and storage and, in the future, support schemes for flexibility. Here, we suggest creating a dedicated expert group, gathering Member States and regulators to monitor implementation & exchange best practices.

2. Improve energy system planning and assessing capacities for system operators, regulators and policymakers

The energy system is changing rapidly and fundamentally, mainly driven by renewables, electrification and digitalisation trends. Failing to plan for these changes equals planning for failure. As renewables grow at all voltage levels and electrification accelerates – offering new and high potential for flexibility – grid planning is more important than ever.

The Electricity Market Design already requires system operators to regularly conduct grid planning exercises, but evidence shows slow implementation and little innovation. Supporting the development of modern network development plans and implementing new practices such as anticipatory investments or flexibility assessments will be critical. We recommend:

- To swiftly adopt a common EU methodology for assessing flexibility needs for daily, weekly, seasonal flexibility. This should include a methodology to assess the contribution from prosumers or local energy hubs (collective self-consumption) to overall flexibility and congestion management;
- To improve the quality and transparency of energy system modelling tools across Europe. The European Commission should invest in new tools and functions to support Member States, system operators and regulators in upgrading their planning and assessing capacities, in the first instance by strengthening the capacities of ACER in this endeavour. The European Commission should, however, also consider establishing a new European Energy Agency (EU EEA). The EU EEA would host top-notch open-source energy modelling capabilities and act as an independent expertise centre for energy transition economics and scenario projections, using close-to-real time data, advising and supporting European and national policy makers, regulators and system operators. The functions are not dissimilar to the role the Energy Information Administration performs in the United States. The main advantage of such expertise centre is that it turns the ad-hoc support from EU to national actors into more structural capacity-building function in energy system modelling across Europe.

3. Unlock investment in clean flexibility across the energy system

Boost decentralised flexibility by developing local energy hubs and fostering prosumers. It will be very important to deliver daily flexibility at local level to manage local grid congestion. The key lies in combining local solar generation with electrified heating and transport loads in buildings. Smart buildings should not only be thought of as flexible assets but also as local energy hubs where the peak demand is met by local generation – while being connected to the energy system and contributing to the real-time stability of the grid. Energy hubs make sense for the grid and are also easy to understand for consumers. We therefore recommend:

- Engaging with the construction industry in accelerating renovation policies and using that trigger point to roll out digitalised and smart technologies in buildings;
- Creating effective price signals that harness distributed flexibility (smart EV charging and heat pumps), including local flexibility market mechanisms and other types of price signals, such as Time of Use grid tariffs, or self-consumption, including collective self-consumption, with dedicated network fees reflecting actual grid use;
- Working on standardisation of grid requirements at EU level, in close cooperation with standardisation bodies and with the industry, making sure these requirements are defined and standardised on EU level, not on national or local level. This should allow manufacturers to become certified only once and then access the full EU Single Energy Market. This holds true particularly when it comes to standards for DSO-level grid connection, for communication with the grid operators, for instance in the framework of a local flexibility or congestion market, and for communication from device to device (energy dataspace).

Boost large-scale flexibility by investing in standalone batteries as well as hybridised solar and battery projects. We tend to think of flexibility as big battery packs or as grid interconnections. But flexibility can also be harvested at a solar site if it is combined with a battery pack or equipped with a power plant controller or a solar tracker. Yet in Europe, despite the existence of markets for flexibility, financing a battery storage remains generally difficult due to economic barriers. In addition, grid connection procedures are not yet adapted for the grid connection of solar and battery storage plants. It is therefore critical to remove barriers and improve price signals for hybridised solar and storage projects, including adapting the permitting and grid connection procedures for hybridisation. We recommend:

- Allowing a battery co-located with a solar plant to provide energy arbitrage and flexibility services through Contract for Difference by developing an approach that traces the solar electricity eligible to public support. In the

medium term, we recommend assessing future Contract for Difference designs to support system responsiveness of assets;

- Ensuring that capacity mechanisms and ancillary services markets allow the participation of standalone or co-located battery storage on a level-playing field with conventional resources;
- Allowing for a simple grid connection procedure, based on cumulative asset capacity (Requirements for Generators network code), instead of an approach where grid requirements are calculated on every single asset.

Boost seasonal flexibility by investing in grid infrastructure, clean seasonal storage, and other flexibility capacities. Storage assets can alleviate grid needs and ensure we make the most of existing grid infrastructure. This should start by quantifying the actual needs, taking into account the complementarity of solar and wind on a seasonal basis and the changes in electricity use. On that basis, clear price signals should be developed and encompass all types of clean seasonal flexibility capacities. Still, this report shows that large investments are needed in cross-border grid infrastructure to move electricity from zones with high renewable potential to consumption centres and industrial clusters. We recommend:

- Developing a strategy for clean seasonal flexibility, encompassing all clean technologies;
- Prioritising electricity infrastructure in the Connecting Europe Facility for Energy, supported by an enabling framework (permitting and financing) for cross-border grid infrastructure, and introducing dedicated funding tools earmarked for smart distribution networks.

4. Adopt an EU Electrification Action and Investment Plan, as part of a new EU Energy Security strategy

Ultimately, one of the most important drivers for reaching a net-zero economy is to maximise the electrification of the EU energy system. Electrification of end-uses comes with two significant and mutually reinforcing benefits. First, it increases demand for electricity, in turn improving the business case for market-driven roll-out of solar and other renewables. Second, if done smartly, it substantially increases system flexibility opportunities through demand response and load shedding and shifting.

Harnessing this dynamic is essential for the success of the energy transition and for EU's security of supply but requires a surge in upfront investment. The report estimates annualised investment needs at 35 billion EUR in 2030 and 62 billion EUR in 2040, compared to the baseline scenario. In turn, these investments would save 63 and 222 billion EUR in overall energy system costs, leading to a net positive of 32 and 160 billion EUR in 2030 and 2040 respectively.

We, therefore, call on the European Commission to adopt an Electrification Investment and Action Plan, including:

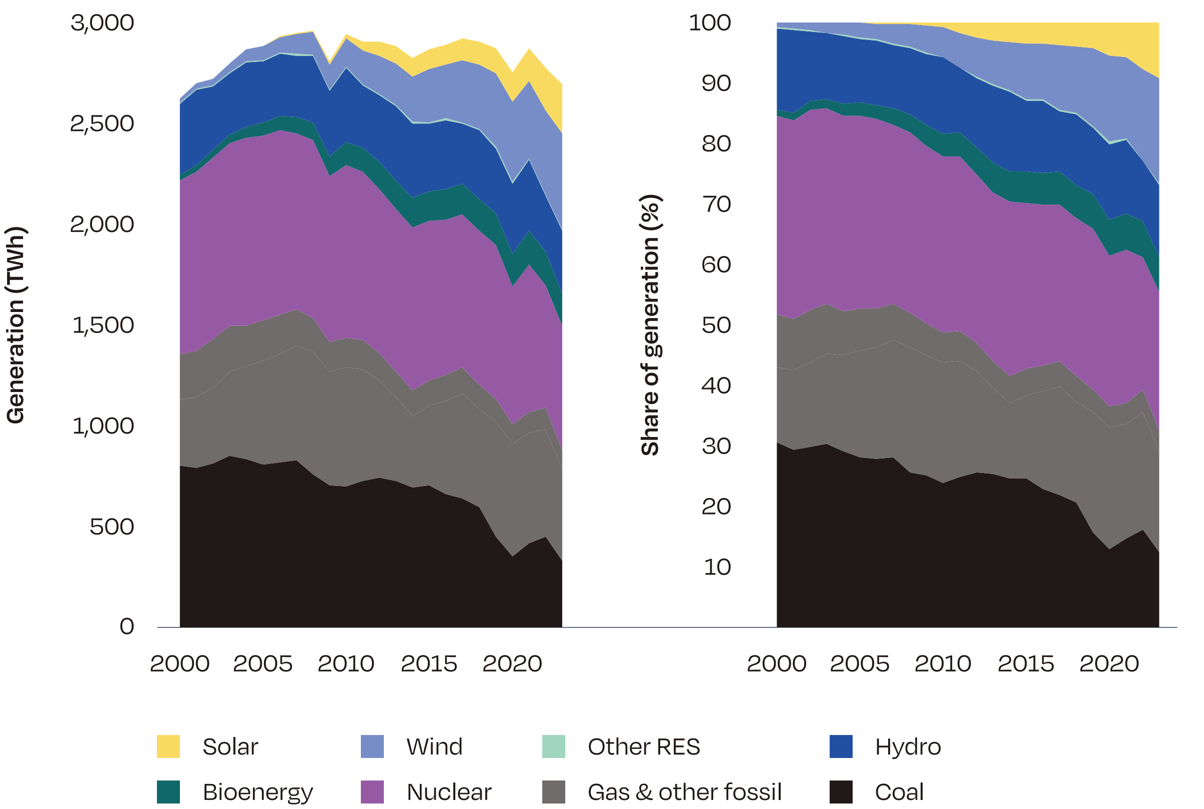
- Setting a direct electrification target of at least 35% of final energy demand by 2030 at EU level and at least 50% by 2040, which should be reflected in the next NECPs;
- Fully aligning existing EU and national funding and financing frameworks with the delivery of the 2030 NECPs. Such alignment is the only way to de-risk and leverage private financing in the direction and at the scale needed. Access to EU funding and financing should, therefore, be made conditional on planning for a successful energy transition, particularly on renewables and flexibility assets.
- Adopting a new EU Electrification Investment Plan. We call on policymakers to make use of the upcoming debate on the next Multi-year Financial Framework (2027-2034) to establish such Fund as Next Generation EU and Resilience and Recovery funds will dry up in the coming years.

Given the fundamental changes in Europe's energy system, shifting to renewables, electrification and digitisation, it is time to redefine and update what energy security means for the EU. We therefore call for adopting such EU Electrification Action and Investment Plan as part of a new, holistic EU Energy Security strategy.

1 INTRODUCTION

Renewable energy sources are gaining momentum in today's EU electricity system. Back in the year 2000, solar and wind energy were hardly visible on the EU electricity landscape, capturing less than 1%of the EU electricity generation. In 2023, solar and wind generation represented 27% of total electricity consumption, providing 721 TWh to the EU power system (Figure 1).[2] This trend has pushed fossil fuels

FIGURE 1 EU ELECTRICITY MIX 2000-2023



2 SolarPower Europe (2024): Global Market Outlook for Solar Power 2024-2028; Ember (2024): European Electricity Review 2024.

down to 33% of the generation mix in 2023, a substantial decline since the 52% contributed in 2000.

The increase in variable renewable energy generation is reflected in the large growth of operating solar PV and wind capacities in the EU, which currently stand at 269 GW_{DC} and 219 GW, respectively.[3] In recent years, the EU solar market has gained strong traction, registering remarkable growth rates in the annual market beyond 40% in the last three years, and reaching 50% to 61 GW in 2023. Interest in solar energy is primarily driven by its versatility and cost competitiveness, in a period where soaring energy prices driven by the Russian invasion in Ukraine took a big toll on EU businesses and households. Solar has been the leading power generation source in the EU when it comes to newly installed capacity, outcompeting all other technologies. In contrast to solar's fast growth pace, the EU wind sector demonstrated slow developments in new installed capacity in recent years, from 15 GW in 2020 to 18.3 GW in 2023, with a 7% compound annual growth rate (CAGR) in the 2020-2023 period, compared to a 45% solar CAGR in the same period.

Despite the efforts of EU Member States to detach themselves from Russian gas imports and to transition away from fossil fuel use, gas maintains a central role in the EU energy system and power system, with a 16% share of EU electricity generation in 2023 and contributing to a relatively high level of average carbon intensity in the EU electricity mix, at 242 gCO_2eq/kWh. Crucially, gas-fired units also still play a central role regarding price formation. In the marginal pricing system, gas often sets the electricity price. In 2023, this happened more than 4,800 out of the 8,760 hours of the year, which is 55% of the time.[4] While gas prices were lower in 2023 compared to the unprecedented highs of 2022, this led to high average electricity prices of 94.9 EUR/MWh across the bloc. In the first 5 months of 2024, average EU electricity prices have further decreased to 68 EUR/MWh.

Current trends in the power system are already challenged by EU ambitions going into 2030 and 2040, calling for profound transformations of the EU energy system as a whole. The REPowerEU Plan from May 2022 places the EU power system in the front row of a rapid acceleration of energy transition objectives

© Iberdrola

3 In the EU, it is assumed that the average DC/AC ratio for solar PV capacity is 1.25. Solar capacity is expressed in DC terms when referred to individually, and in AC terms when together with other power generation technologies.

4 European Commission (2023): The Merit Order and Price-Setting Dynamics in European Electricity Markets.

5 European Commission (2022): REPower EU plan (SWD/2022/230 final).

towards 2030.[5] The plan targets a 500 TWh increase in EU power generation by 2030, up 19% from the 2,700 TWh produced in 2023, supporting the electrification of the heat sector with 41.5 million residential heat pumps and the production of 10 million tonnes of renewable hydrogen. Solar and wind will be the backbone of this transformation, planned to expand to 750 GW_{DC} and 510 GW by the end of the decade, after they reached 269 GW_{DC} and 219 GW in 2023. This would also provide a major contribution to attain the 42.5% EU's binding RES target by 2030.

In February 2024, the EU Commission has also outlined development pathways towards 2040, recommending a 90% net GHG emission reduction target, paving the way to climate neutrality by 2050.[6] Scenarios underpinning the 2040 GHG target impact assessment present strong electrification trends, nearly doubling the EU power consumption to 4,600-5,200 TWh, with total renewable capacities between 1.9-2.3 TW and a 65-75% RES share, and storage and flexibility capacities between 213-275 GW (see Table 2).

While the EU Commission 2030 targets and 2040 ambition already envision a steep increase in solar PV operating capacity, the current and forecasted trends in the EU and global markets project an even faster growth of this technology. According to SolarPower Europe's Global Market Outlook 2024-2028 (GMO 2024), under a Medium Scenario solar capacity across the EU is anticipated to already reach 671 GW_{DC} by 2028, the end of the five-year modelling period. Extending the forecast to 2030 under business-as-usual development conditions, it is projected to reach nearly 900 GW_{DC} of operational capacity (see Fig. 2). This is significantly above the 2030 REPowerEU target, and also much above the aggregated solar target from the 2023 draft revision of NEPCs.

Although SolarPower Europe's market projections may appear very optimistic, they are actually developed under the assumption that the global solar market – which is on track to exceed 500 GW of new capacity in 2024 and is projected to cross the TW level before 2030 – will keep expanding much faster than in Europe, notably driven by the growth in the Asia-Pacific region.

According to the GMO 2024 'most-likely' Medium Scenario, in 2028 the EU will host 13% of the world's solar fleet, down 4 percentage points from the 17% share it operated in 2023. In terms of cumulative CAGR, this would equal to a 20% CAGR in the EU, compared to a 26% CAGR globally, in the period 2024-2028. Our Dec. 2023 assumption for the 2023 market fell 8% short of actual installed capacity.

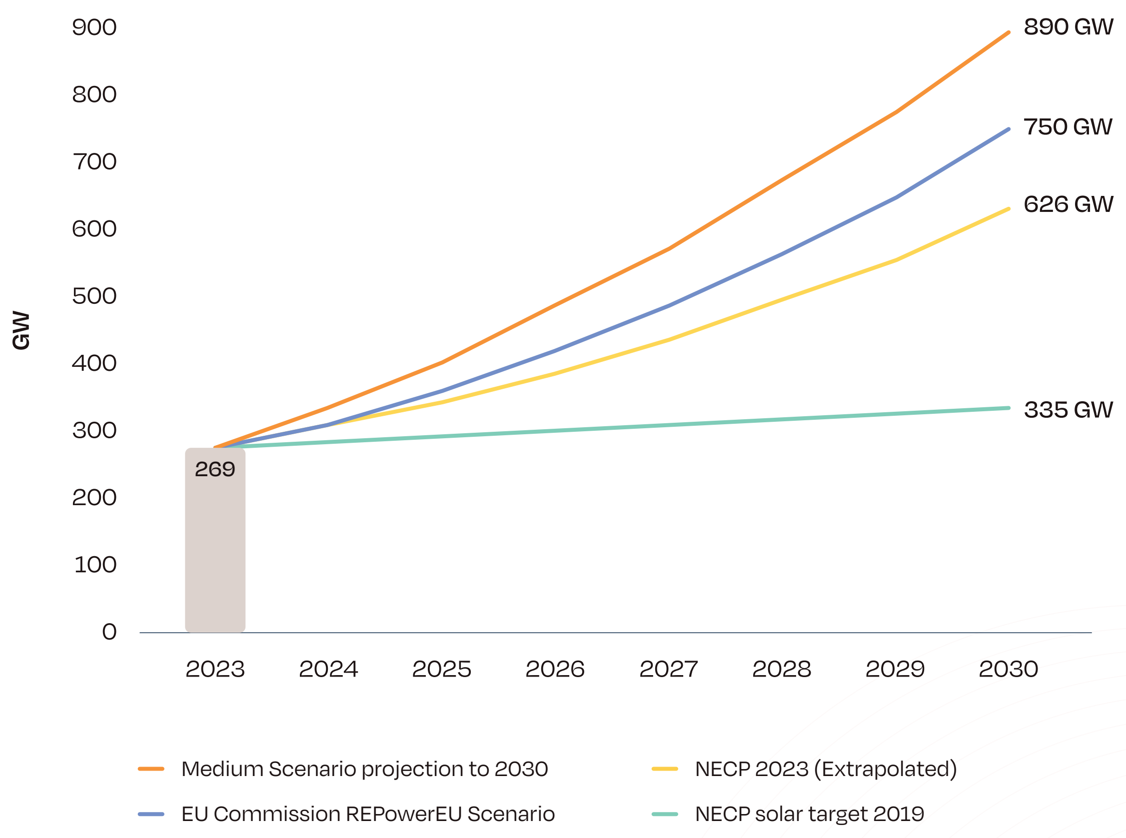
TABLE 2 EU COMMISSION 2040 IMPACT ASSESSMENT SCENARIOS COMPARED TO 2023

	2023	S1 2040	S2 2040	S3 2040
CO_2 emission reductions vs 2005	46%	83%	90%	94%
RES share in gross final energy consumption	23%*	65%	72%	75%
Gross electricity generation (TWh)	2,700	4,563	4,899	5,212
Renewable capacity (GW)	482	1,939	2,142	2,298
Storage and flexibility options (GW)	62	213	254	275

Source: Ember (2024), EU Commission (2024). *: Value for 2022.

6 European Commission (2024): Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (SWD/2024/63 final).

FIGURE 2 EU-27 TOTAL SOLAR PV CAPACITY SCENARIOS 2023-2030



However, a deep integration of solar energy into the power system does not come without challenges. Already today, some Member States with comparatively high levels of solar PV penetration are starting to face issues related to the smooth integration of variable renewable generation in their power mixes. These issues include both challenges of technical nature (integration of solar projects into the grid, increasing level of curtailment) and financial nature (market structure, investment attractiveness and remuneration of renewable producers).

With the expansion of solar energy generation, there is an increasing challenge to avoid that solar energy is wasted through curtailment. In times of low demand and excessive electricity generation, some EU countries, like the Netherlands and Greece, are already shutting down solar PV power plants, which are flexible and easy to manage. At the same time, these market dynamics increase the occurrence of negative power prices across Europe, which has been on the rise in recent years. Negative prices occur in times of high renewable generation, coupled with periods of low electricity demand, and are an indicator of insufficient system flexibility. The regular occurrence of negative prices poses a challenge to solar projects operated in the free market, which, in the absence of flexibility solutions, are faced with low returns on investments.

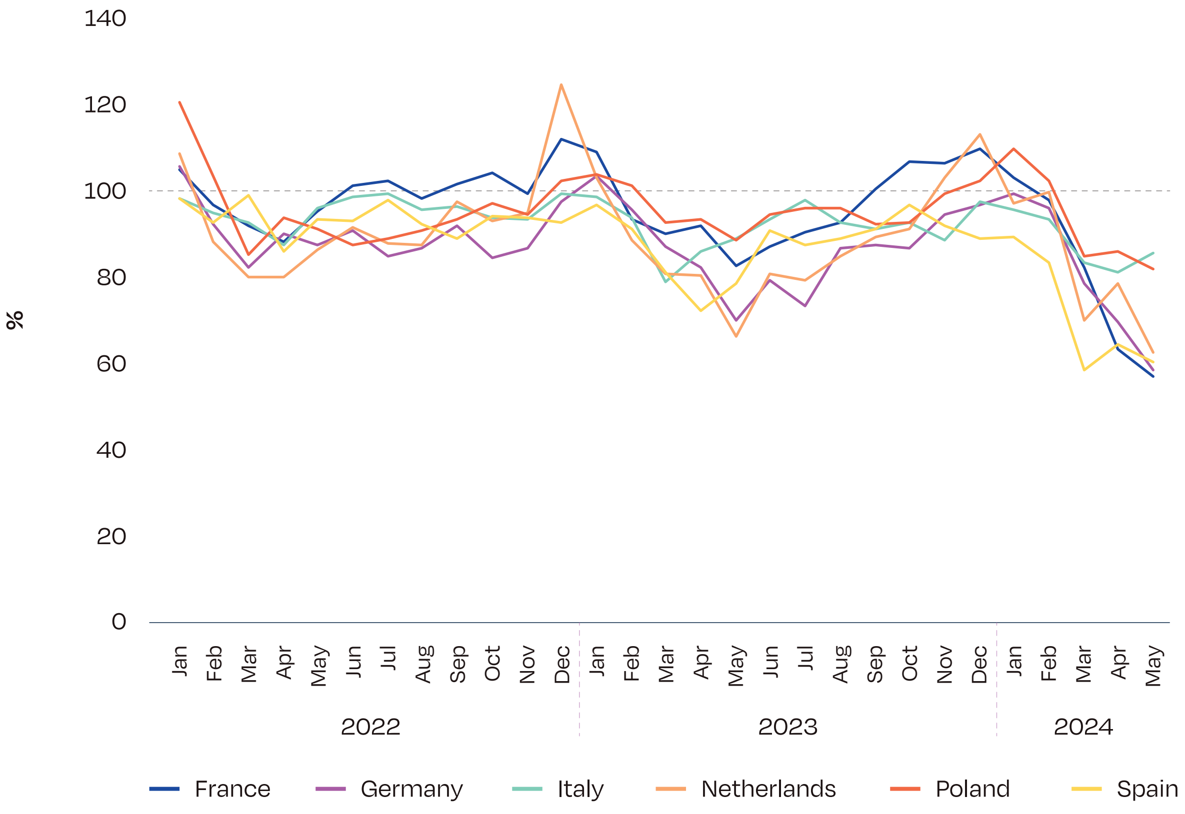
Price cannibalisation is seen as an emerging threat to the economics of solar energy projects. As more solar capacity is added to the system, and all solar assets produce power at the same time, the abundance of solar energy brings down the electricity price, making PV a victim of its own success. As a result, solar capture prices, which are the prices at which solar energy is sold, tend to be lower than the average electricity price, because solar energy is cheap and lowers the market price. This is reflected in low solar capture rate values - the ratio between solar capture prices and the average electricity prices.

In the Netherlands, in May 2023 the solar capture rate stood at 55%. This means that for every 100 EUR that energy producers earned on average from the sale of electricity during that month, solar producers only earned 55 EUR. These dynamics are getting more pronounced in 2024: according to Rystad Energy, this trend has been worsening across several major solar markets across Europe, with capture rates falling below 60% in Germany, Spain, and France in May 2024 (see Fig. 3).

While there are several factors explaining this trend, and some of them are unconnected to solar, it's clear that a lack of system flexibility can lead to challenging dynamics as solar becomes more prominent in the power mix. To address these emerging challenges, appropriate levels of flexibility solutions are therefore required to ensure the balance between supply and demand can be met with low levels of curtailment and to preserve the business case for solar developers.

Against this background, the aim of this study is to explore the interplay between the rollout of solar PV capacity and the deployment and operation of flexibility solutions in the power system, looking at 2030 and 2040 time horizons. This study presents a range of scenarios whereby different levels of system flexibility are unlocked, and whose effects on the power system are analysed. This work also illustrates a set of recommendations on the required evolution of the regulatory and policy frameworks to ensure solar PV, enabled through flexibility solutions, can play its role in the decarbonisation of the European economy.

FIGURE 3 SOLAR PV CAPTURE RATES EUROPE 2022-2024



Source: Rystad Energy (2024).

2

METHODOLOGY AND SCENARIO DESCRIPTION

The objective of the study is to simulate, analyse and compare EU power system scenarios with increasing deployment levels of solar PV and flexibility solutions in 2030 and 2040.

The evaluation of the role that flexibility solutions play in the integration of solar PV is based on the comparison of three scenarios that differ in terms of options to provide flexibility services and in terms of demand levels. The modelling covers the entire European electricity system, and its interlinkages with the mobility, heating, and hydrogen systems, both in 2030 and 2040.

The flexibility solutions that are at the core of this study are:

- Flexible infrastructure technologies
  - Stationary battery energy storage systems (BESS);
  - Cross-border electricity interconnection capacities;
- Flexible demand-side technologies
  - Heat pumps, with constraints on provision of heating levels;
  - Electric vehicles, with constraints on reaching state-of-charge in the morning;
  - Electrolysis for renewable hydrogen production.

Not all flexibility solutions can offer the same types of flexibility services. The needs for flexibility services can be described in terms of timescales:

- On a daily level and below, flexibility needs emerge to integrate solar PV and to balance the grid in real time, compensating for RES and demand forecast errors as well as for outages;
- On a weekly level, flexibility needs are primarily driven by the need to integrate different wind regimes;
- On a seasonal level, flexibility needs are mainly related to the variation of the electricity demand for heating and cooling, as well as to the generation patterns of solar PV (highest production in summer, lowest in winter) and wind (with the opposite pattern in most of Europe).

The role of, and need for, the different types of flexibility solutions is dependent on the type of services they can provide. While some technologies can only cover short-term flexibility services (e.g., stationary batteries, flexible operation of heat pumps, charging of EVs, demand response), others can cover a wider range of flexibility services (interconnectors, flexible use of electrolysers). For instance, EVs have constraints that need to be met every day (e.g., a charged vehicle must be provided to the user in the morning) thereby preventing these assets to provide flexibility services over longer time periods. In contrast, electrolysers can provide flexibility services on a seasonal timescale thanks to underground hydrogen storage: they can run during periods of low prices (corresponding to low residual demand) and pause their operations during periods of high prices while hydrogen storage ensures that green hydrogen can continue to be delivered to end-users.

Under these conditions, an extensive modelling of hourly supply-demand equilibrium dynamics in the European power system was carried out to evaluate the impacts of different levels of deployment of flexibility solutions on the operations and uptake of solar PV.

The Artelys Crystal Super Grid modelling platform was used to perform simulations of the three scenarios of the study in the timeframes 2030 and 2040.[7] Each simulation consists in the joint optimisation of investment and hourly operations of the European power system over a full year (8,760 consecutive time-steps), for a perimeter that covers all EU-27 countries and relevant non-EU countries (CH, NO, UK, Western Balkans). Results include the hourly dispatch and price formation of wholesale electricity markets over a full year, and provide the optimal dimensioning of key infrastructure and generation assets – including additional solar capacities.

The three scenarios of the study are designed to evaluate the interdependence between the deployment of solar PV capacities, capacities for battery storage and cross-border interconnectors, and flexible demand from electrification through EVs, HPs, and electrolysers, as shown in Table 3.

In the following section, the storylines and key assumptions for the SAU, SF and SFE scenarios are presented, for both the 2030 and 2040 time horizons.

TABLE 3 OVERVIEW OF SCENARIO STRUCTURE

SCENARIO	SOLAR PV CAPACITY	ELECTRIFICATION LEVELS	FLEXIBLE CAPACITIES
Solar-As-Usual (SAU)	Baseline	Limited	Limited
Solar + Flexibility (SF)	Baseline	Limited	Increased (pre-defined)
Solar + Flexibility + Electrification (SFE)	Increased (endogenous)	Increased (pre-defined)	Increased (pre-defined)

7 Artelys (2023): Artelys Crystal Super Grid.

Solar-as-usual (SAU)

The SAU Scenario represents the baseline configuration where both electrification levels and flexible capacities are limited, while solar PV capacities follow a business-as-usual trajectory based on SolarPower Europe deployment projections according to current conditions and foreseeable market trends. The SAU Scenario serves as counterfactual.

The Solar-as-usual Scenario is derived from the 2030 and 2040 versions of the Distributed Energy scenario from ENTSOs' Ten-Year Network Development Plan 2022 (TYNDP-DE), notably in terms of electricity demand levels, and electricity generation capacities other than solar.[8]

Flexibility solutions

In terms of flexibility deployment levels in 2030 and 2040, the SAU Scenario adopts the TYNDP-DE scenario figures for stationary batteries, electrolysis capacity and associated hydrogen demand, and heat pump power demand. To reflect the features of a baseline scenario, more conservative assumptions have been used regarding the development of cross border electricity interconnection capacities and the uptake of electric vehicles, which were respectively derived from TYNDP 2022 scenarios National Trends (TYNDP-NT) and Global Ambition (TYNDP-GA).

Solar PV

The SAU Scenario assumes solar growth continues under a business-as-usual trajectory according to current conditions and foreseeable market trends. The EU solar PV fleet reaches 902 GW_{DC} in 2030 and 2,090 GW_{DC} in 2040, which respectively represent 8% and 41% increases compared to the TYNDP-DE figures. The cumulative capacity CAGR is 19% for 2023-2030 and 13% for 2023-2040.

Key expectations

- The SAU Scenario represents a configuration where the dimensioning of flexibility solutions does not keep the pace of solar deployment, leading to a substantial lack of system flexibility. High curtailment rates and cannibalisation effects can be expected to materialise this scenario.

8 ENTSO-E and ENTSOG (2022): TYNDP 2022 Scenario Report & TYNDP 2022 Scenario Building Guidelines.

Solar + Flexibility (SF)

The Solar + Flexibility Scenario represents a configuration where electrification levels remain limited, but battery storage and cross-border electricity interconnection capacities are deployed beyond business as usual and provide a moderate level of system flexibility. The SF Scenario illustrates an intermediate level of unlocking flexibility potential.

The SF Scenario is built based on the SAU Scenario, adding flexibility solutions to observe their impacts on the operations of the power system.

Flexibility solutions

The SF Scenario features a more ambitious development level of flexible capacities: batteries and electricity interconnections. The net transfer capacities on each border were raised to TYNDP-DE levels, with an additional 10% increase, to represent a more advanced level of transmission grid development that allows for additional system operation benefits to emerge from market coupling. The resulting capacities are 16% and 19% higher in 2030 and 2040 respectively.

The SF Scenario also integrates a strong acceleration in BESS deployment: battery capacities are set at twice the capacities assumed in TYNDP-DE. Moreover, the model is allowed to invest in additional BESS capacities in order to cost-optimise both investment decisions and the operation of the battery storage fleet with regard to the baseline solar capacities. This results in a total EU-27 BESS capacity of 260 GW in 2030 and 606 GW in 2040.

Solar PV

The SF Scenario assumes the same deployment of solar PV as in the SAU Scenario, i.e. 902 GW_{DC} in 2030 and 2,090 GW_{DC} in 2040.

Key expectations

- The SF Scenario represent a configuration that is more favourable to the integration of solar generation compared to the baseline. A decrease of both solar PV curtailment and cannibalisation effects are expected, which is also beneficial in terms of GHG emission and generation costs in the power system, thanks to the avoided use of carbon-intensive electricity generation technologies.

Solar + Flexibility + Electrification (SFE)

The Solar + Flexibility + Electrification Scenario represents a configuration where both flexibility capacities and electrification levels are increased, providing a high level of system flexibility. The model is also allowed to invest in additional solar capacities to meet the increased level of demand from electrification. The SFE Scenario displays a high level of unlocked flexibility potential.

The SFE Scenario is built based on the SF Scenario, with the addition of increased electrification levels to analyse the impacts of fully tapping flexibility solutions on solar PV deployment and system operations.

Flexibility solutions

In the SFE Scenario, all flexibility solutions are leveraged. Battery and power interconnection capacities are identical to SF Scenario, while a strong increase in power demand from heat pumps, electric vehicles and electrolysers is also assumed. The demand from domestic heat pumps is aligned with the Radical Action scenario from Eurelectric's Decarbonisation Speedways study; the demand from the electric vehicle fleet is aligned with the TYNDP-DE scenario; while the demand from electrolysers is set to match the REPowerEU target of 10 million tonnes of green hydrogen production per year in 2030, and aligned with Eurelectric's Radical Action scenario in 2040. The model is also allowed to invest in additional electrolysis capacities.

Solar PV

On top of the baseline solar PV fleet, the model can invest in additional capacities that are representative of the following technologies: residential rooftop, C&I rooftop, utility-scale without tracking system, utility-scale with tracking system. An overview of investment options can be found in the Annex.

Key expectations

- The SFE Scenario represents a configuration where a high degree of system flexibility and electrification results in an optimised energy system performance coupled with improved market conditions for solar. Further, it displays a setting where unlocking flexibility solutions enables solar PV to grow beyond business as usual, showcasing the relevance of electrification for solar deployment.

Table 4 summarises the scenario building approach presented above. In both 2030 and 2040, each scenario can thus be described as a combination of "low" and "high" development levels for each flexibility solution considered in the study. The key assumptions associated with each scenario are presented in Table 5.

TABLE 4 OVERVIEW OF SCENARIO BUILDING APPROACH

	2030			2040		
SCENARIO	SAU	SF	SFE	SAU	SF	SFE
Flexible demand (electric vehicles, heat pumps, hydrogen demand)	LOW	LOW	HIGH +P2H$_2$ Model invesments	LOW	LOW	HIGH +P2H$_2$ Model invesments
Flexible capacities (interconnectors, stationary batteries)	LOW	HIGH +BESS Model investments	HIGH +BESS Model investments	LOW	HIGH +BESS Model investments	HIGH +BESS Model investments
EU-27 solar capacities	Baseline: 902 GW	Baseline: 902 GW	Baseline: 902 GW + PV Model investments	Baseline: 2,090 GW	Baseline: 2,090 GW	Baseline: 2,090 GW + PV Model investments

TABLE 5 OVERVIEW OF SCENARIO INPUT ASSUMPTIONS 2030 AND 2040

RESOURCE (EU-27)	ASSUMPTION						SOURCE
	2030			2040			
	SAU	SF	SFE	SAU	SF	SFE	
Solar PV capacity (GW_{DC})	902	902	1,231*	2,090	2,090	2,435*	LOW: SolarPower Europe baseline HIGH: SolarPower Europe baseline + model investments
Battery capacity (GW)	97	260	260	173	606	606	LOW: TYNDP-DE HIGH: Twice TYNDP-DE capacities + model investments in SF
Cross-border interconnection capacity (GW)	202	235	235	234	278	278	LOW: TYNDP-NT HIGH: TYNDP-DE + 10%
Electrolysis capacity (GW H_2)	52	52	107*	151	151	181*	LOW: TYNDP-DE HIGH: TYNDP-DE + model investments
HP demand (TWh)	152	152	297	231	231	908	LOW: TYNDP-DE HIGH: Eurelectric's Radical Action
EV demand (TWh)	74	74	134	270	270	359	LOW: TYNDP-GA HIGH : TYNDP-DE
$P2H_2$ Demand (TWh)	184	184	483	1,287	1287	1,539	LOW: TYNDP-DE HIGH: 2030: 10 Mt REPowerEU target 2040: Eurelectric's Radical Action

Note: TYNDP NT/GA/DE: ENTSO-E's Ten-Year Network Development Plan 2022 National Trends/Global Ambition/ Distributed Energy scenarios.
REPowerEU: alignment with REPowerEU targets
Eurelectric's Radical Action: Radical Action scenario from Eurelectric (2023) Decarbonisation Speedways report
*: modelling result

3 KEY RESULTS

The results of our analysis highlight the fundamental role of flexibility solutions in a power system characterised by a strong penetration of variable renewable generation. Tapping flexibility potential not only enables the deployment of more solar, it also allows to make better use of abundant, clean and cheap electricity. A stronger deployment of flexibility options is a win-win option that brings energy system benefits from an economic and climate standpoint, while strengthening the business case of solar and decreasing energy waste.

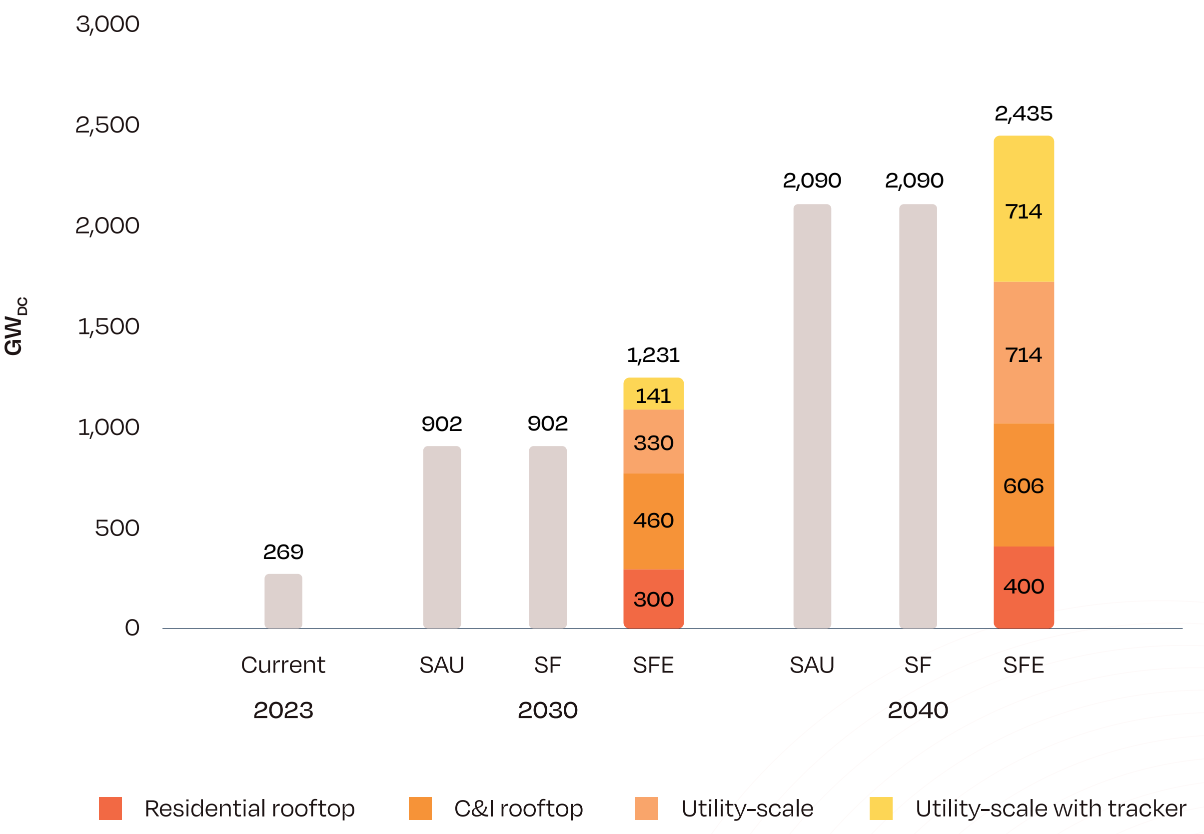
Key message

- Unlocking flexibility solutions enables more deployment of installed PV capacity, resulting in additional solar electricity into the EU electricity mix. Solar capacity exceeds 1.2 TW in 2030 (+36% compared to the baseline) and 2.4 TW in 2040 (+17%), with solar electricity reaching 32% and 39% of the EU's gross electricity generation.

3.1. Unlocking flexibility solutions enables further PV deployment

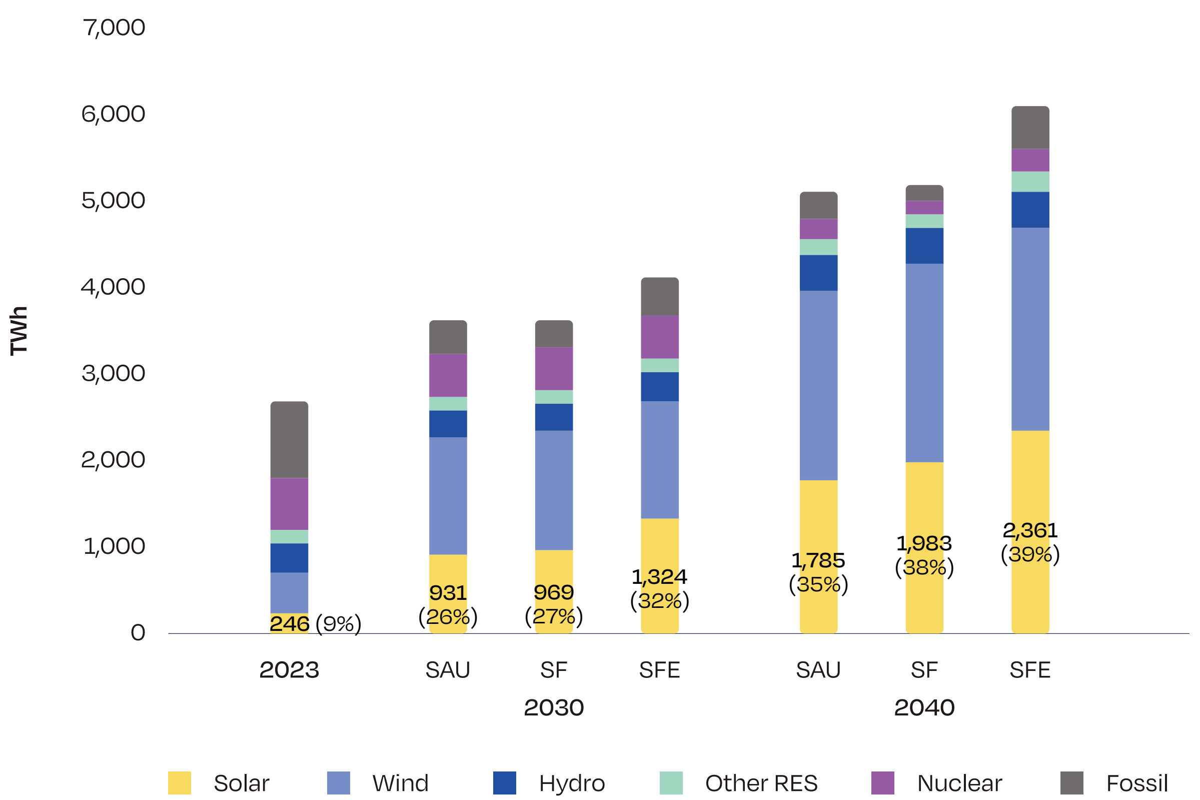
Thanks to the deployment of flexibility solutions, the SFE scenario models additional solar PV capacity installed in the EU in 2030 and 2040, driven by increased electricity demand from clean electrification and supported by additional flexibility capacity. As a result, total solar PV operating capacity is 36% and 17% higher than the baseline levels in 2030 and 2040, reaching 1,231 GW_{DC} in 2030 and 2,435 GW_{DC} in 2040 (see Figure 4). This equals to a 24% CAGR for 2023-2030 and 14% CAGR for 2023-2040, compared to 19% and 13% in the baseline scenario. The segmentation breakdown of installed solar capacity under the SFE scenario displays a balanced approach, whereby rooftop solar provides a 62% share in 2030 and 41% in 2040, while utility-scale solar's share increases from 38% to 59%, driven by cost-competitive tracker systems also in less sunny countries in the decade 2030-2040.

FIGURE4 SOLAR PV CAPACITY SCENARIOS 2030 AND 2040



The increase of operating capacity and better use of solar electricity has a positive impact on solar's penetration in the electricity mix, which stood at 9% in 2023 (see Fig. 5). Under the SF Scenario, in 2030 solar reaches 969 TWh with a 27% share, which is a 1 percentage point marginal increase compared to the baseline 26% share. In 2040, the solar share is 3 percentage points higher than the baseline, reaching 38% and generating 1,983 TWh. Under the SFE Scenario, the increased electrification level leads to larger volumes of solar generation, which reaches 1,324 TWh in 2030 and 2,361 TWh in 2040, respectively 42% and 32% higher than in the baseline scenario. Solar's shares in the power mix reach 32% in 2030 and 39% in 2040.

FIGURE 5 EU ELECTRICITY MIX SCENARIOS 2030-2040



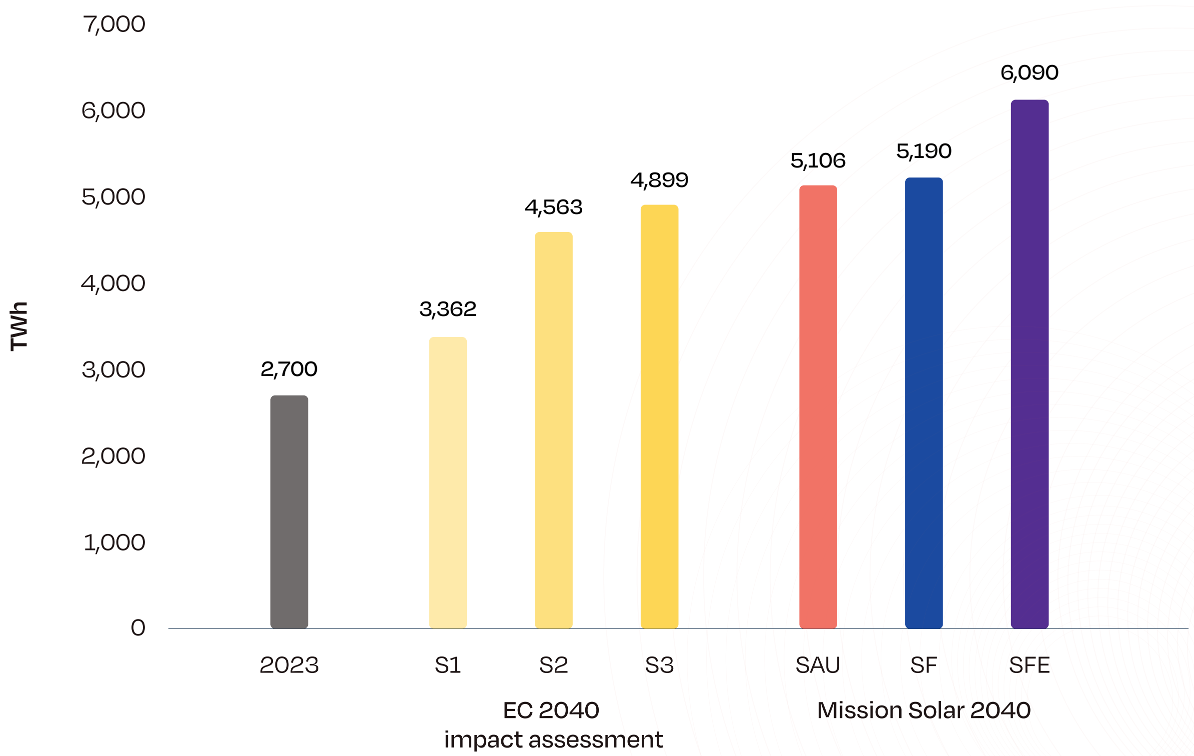
Box 1 – Comparison with the scenarios underpinning the 2040 GHG target impact assessment

In its impact assessment for the 2040 climate target, the European Commission developed three scenarios underpinning different levels of ambition towards the achievement of the 2050 EU climate neutrality target. An overview of the EU Commission scenarios is available on p. 15.

In the EU Commission analysis, gross electricity generation raises considerably from 2,700 TWh in 2023, reaching 3,362-4,899 TWh in 2040 across the three scenarios S1, S2 and S3 (see Fig. 6). This is equivalent to 25-81% growth compared to today's level.

In comparison, the gross power generation assumed in our study stands between 5,106 and 6,090 TWh across the three scenarios investigated. While electricity generation in the SAU and the SF Scenario is comparable to the EU Commission's most ambitious S3 Scenario, the SFE Scenario has a significantly higher level, due to an increased electricity demand from heat pumps, electric vehicles and electrolytic hydrogen generation. In the SFE Scenario, electricity demand is 24% higher than the EU Commission's S3 Scenario, and implies a 126% increase from today's level.

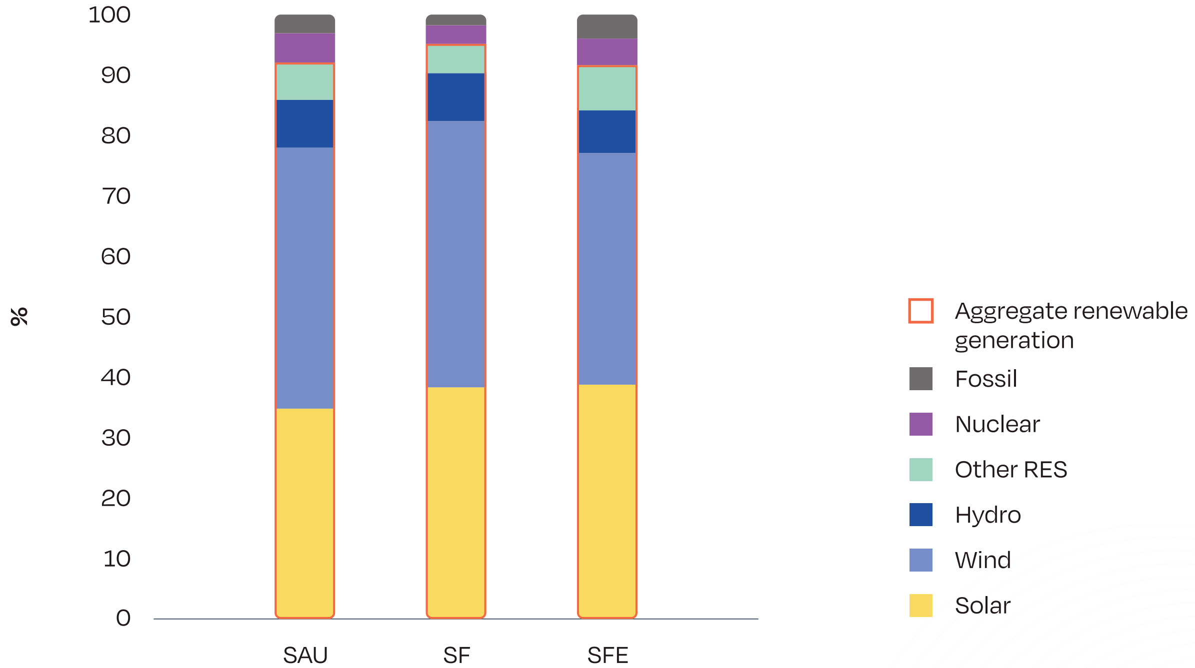
FIGURE 6 SCENARIO COMPARISON OF GROSS ELECTRICITY GENERATION 2040



Box 1 – Continued

In the EU Commission impact assessment scenarios, renewable energy in majority, complemented by nuclear energy, provide over 90% of electricity generation in 2040. The three scenarios analysed in this study are above this level as well. As shown in Fig. 7, the RES share in the electricity mix stands between 92%-95% across the three scenarios, reaching 96-98% with the inclusion of nuclear.

FIGURE 7 RES SHARE IN ELECTRICITY MIX 2040



3.2. Unlocking flexibility solutions reinforces the PV business case

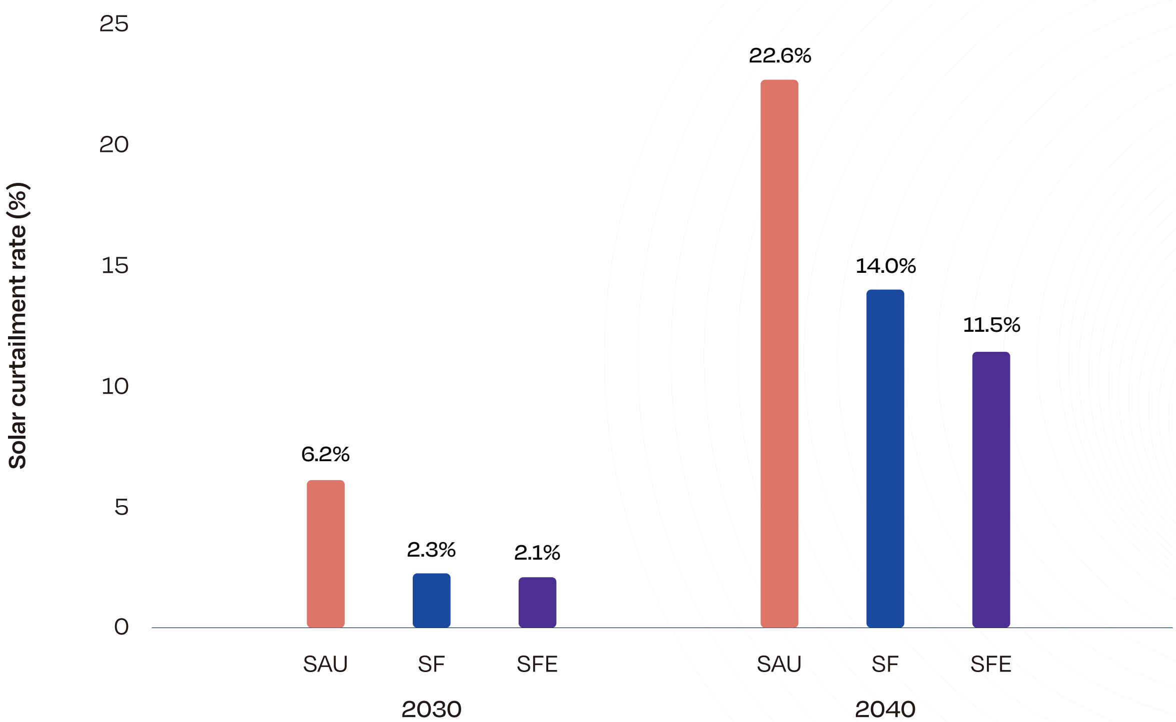
Additional flexibility infrastructure in the form of batteries and power interconnections help increase the share of solar generation that is integrated into the electricity system. This translates into a reduction of solar PV curtailment, which tends to increase considerably if new solar installed capacities are not coupled with an appropriate deployment of flexibility capacities.

Solar curtailment levels in the EU across the three scenarios in 2030 and 2040 are shown in Figure 8. In 2030, solar curtailment stands at 6.2% in the SAU Scenario. In the SF and SFE Scenario, flexibility solutions enable a better usage of solar electricity, whose curtailment is respectively 62% and 66% lower than the baseline, at 2.3% and 2.1%. In 2040, solar curtailment inevitably increases significantly, as low-cost solar becomes the primary source of electricity in the EU. However, this growth can be considerably curbed through flexibility solutions. While in the SAU Scenario solar curtailment reaches 22.6%, the SF and the SFE Scenario display curtailment levels that are respectively 38% and 49% lower than the baseline, at 14% and 11.5%.

Key message

- The deployment of additional flexibility capacities coupled with smart electrification improves the business case for solar. In 2040, solar curtailment rates are reduced by 49% and solar capture prices increase by 54% compared to the baseline. In absolute terms, the SFE Scenario displays much better performance for the solar business case, with solar capture prices much higher than in the other scenarios.

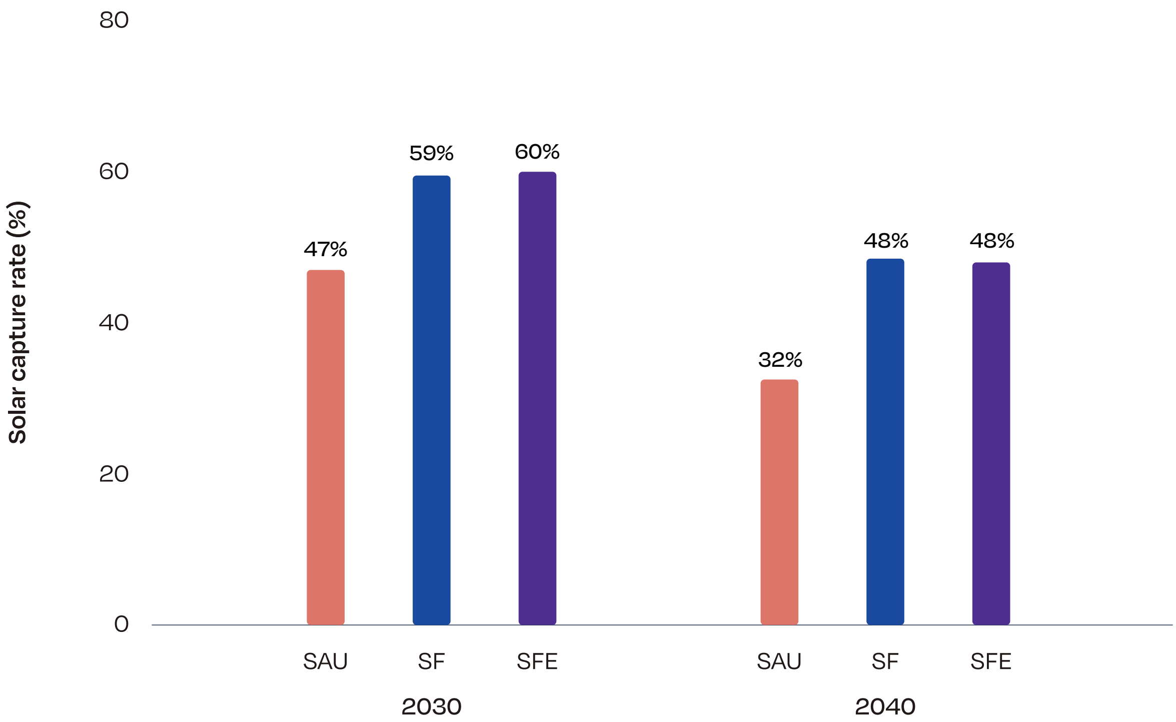
FIGURE 8 AVERAGE SOLAR CURTAILMENT RATES 2030 AND 2040



While significant solar installation volumes are added to support the additional power demand in the SFE Scenario, it still shows a decrease of solar curtailment compared to the SAU and SF Scenarios. This improvement in the usage of solar energy is due to the smart electrification of highly flexible uses, which can absorb peaks in solar production during the day.

Additional flexibility solutions are also able to address the issue of price cannibalisation. In the baseline SAU Scenario, where solar generation does not match with an adequate level of system flexibility, PV electricity is often sold in times of abundance of supply, when electricity has very low prices. As a result, average solar capture rates remain comparatively low, at 47% in 2030 and 32% in 2040 (see Fig. 9).

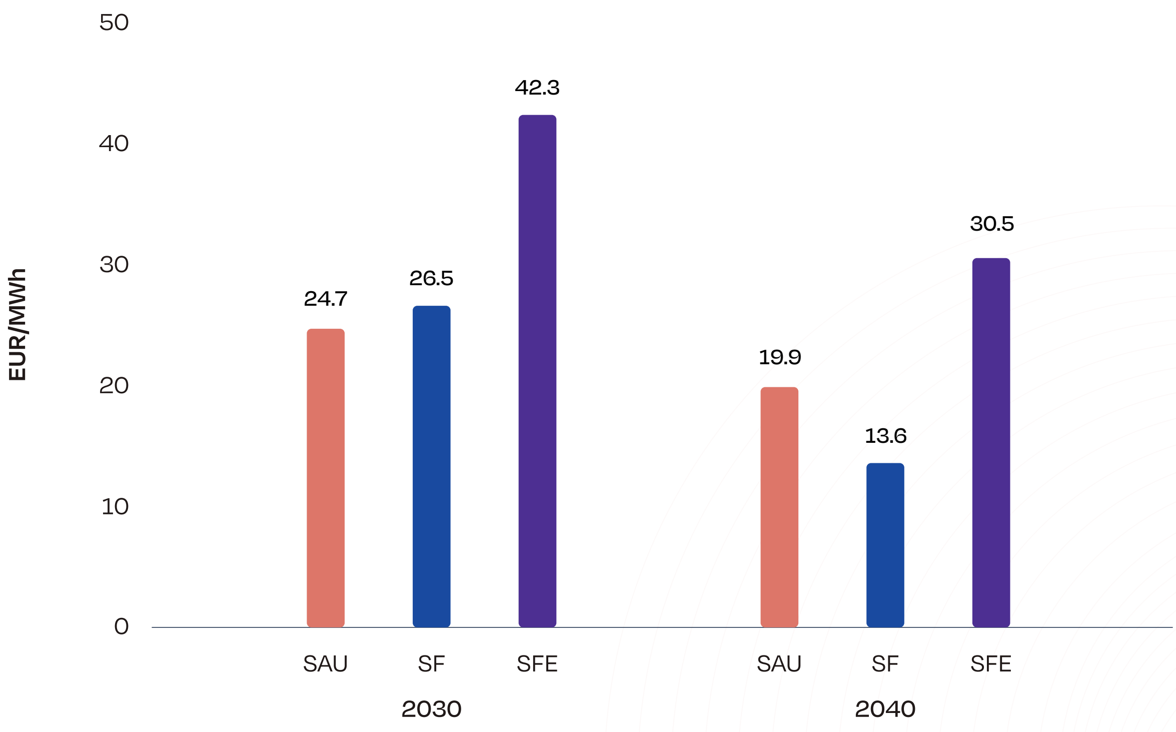
FIGURE 9 AVERAGE SOLAR CAPTURE RATES 2030 AND 2040



Unlocking flexibility solutions has a positive effect on solar capture rates, since solar electricity supply can be shifted to times and places where it is needed, while demand-side flexibility gives better value to times of abundant production. In the SF and SFE Scenario, average solar capture rates are 27-28% higher than the 2030 baseline, and 48-49% higher than the 2040 baseline.

Looking at solar capture prices in absolute terms, the SFE Scenario displays much better performance from the standpoint of the solar business case compared to the other scenarios (Figure 10). The average solar capture price in the SFE Scenario reaches 42.3 EUR/MWh in 2030, which is respectively 71% and 60% higher than the SAU and SF Scenario, and stands at 30.5 EUR/MWh in 2040, which is 54% and 125% higher than the SAU and SF Scenario.

FIGURE 10 AVERAGE SOLAR CAPTURE PRICES 2030 AND 2040



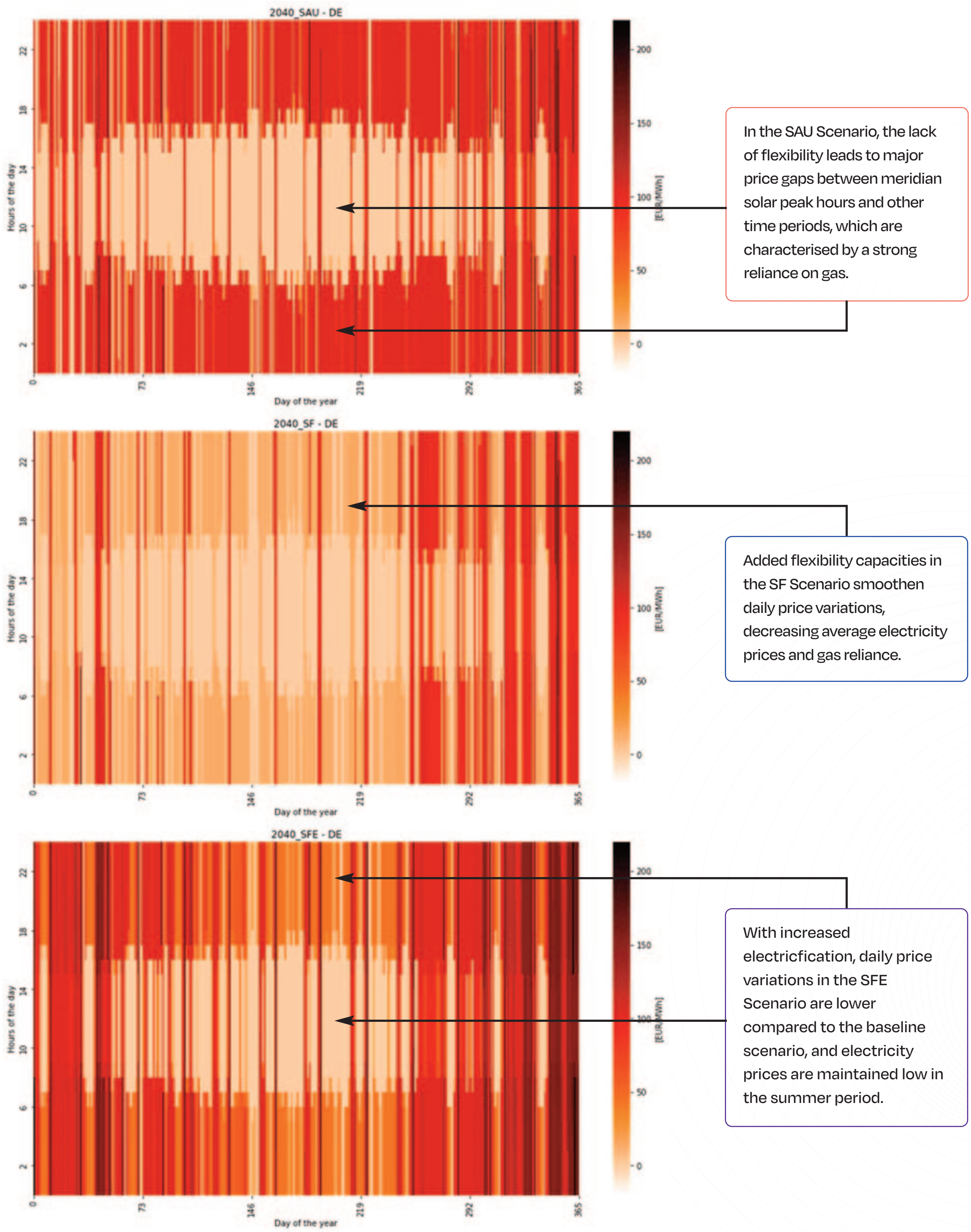
An overview of the electricity price dynamics taking place in 2040 is shown in Figure 11, which depicts the annual distribution of electricity prices in Germany under the three scenarios examined. The country is used as an illustrative example due to its sizeable installed solar capacities and the pivotal role of cross-border interconnectors and battery capacities in hourly dispatch dynamics.

In the baseline SAU Scenario (a), solar deployment coupled with limited flexibility options has visible effects on daily prices, which see strong variations between low daytime prices and high nighttime prices. This is caused by the availability of abundant solar electricity in the solar peak hours, while gas tends to set the price at night.

In the SF Scenario (b), the increase in flexibility capacities smoothens the daily electricity price variations, especially in the spring and summer months. As a result, the average electricity price decreases substantially – and so does the average solar capture price, to a degree that solar business models may become unprofitable.

In the flexibility-driven SFE Scenario (c), the combination of increased flexibility capacities and increased demand-side flexibility from electrification also enables a smoothening of daily price variations compared to the baseline scenario. Electricity prices are maintained low especially in the summer period, while maintaining a profitable business case for solar.

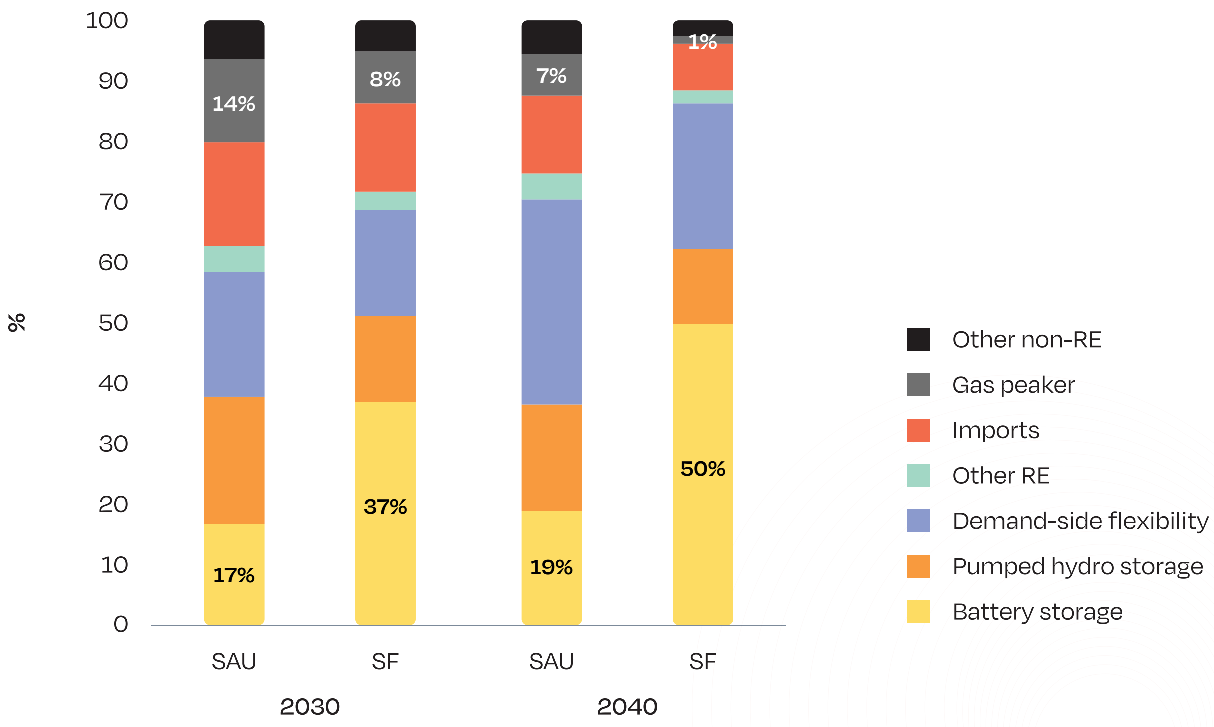
FIGURE 11 GERMANY ANNUAL DISTRIBUTION OF ELECTRICITY PRICES 2040



Box 2 – Addressing daily flexibility needs

As batteries and other flexibility solutions efficiently complement the variability in renewable generation, such as solar ramp-ups and ramp-downs, they also decrease the reliance on dispatchable gas-fired assets for the provision of flexibility. Figure 12 shows the contribution of different technologies to meet system daily flexibility needs in the baseline SAU Scenario and the SF Scenario, which are well suited for comparison as they are based on the same total electricity demand. The percentages shown in the graph indicate how often each technology compensates for a variation of the residual load. In other words, this indicator quantifies the contribution of each technology in meeting daily system flexibility needs. In the SF Scenario, batteries become a major flexibility provider, meeting 37% and 50% of the daily flexibility needs in 2030 and 2040 respectively, compared to 17% and 19% in the baseline scenario. By contrast, the reliance on traditional dispatchable assets is significantly reduced. The production from gas-fired power plants decreases from 14% to 8% in 2030 and from 7% to 1% in 2040.

FIGURE 12 CONTRIBUTION TO DAILY FLEXIBILITY NEEDS 2030 AND 2040, SAU SCENARIO VS SF SCENARIO



3.3. Unlocking flexibility solutions reduces total energy system costs

Flexibility capacities and smart electrification have a positive effect on the total cost of the energy system. While the addition of flexibility capacities and electrification imply additional investments, such increase is largely overcompensated by the massive cost savings in the operation of the electrified sectors.

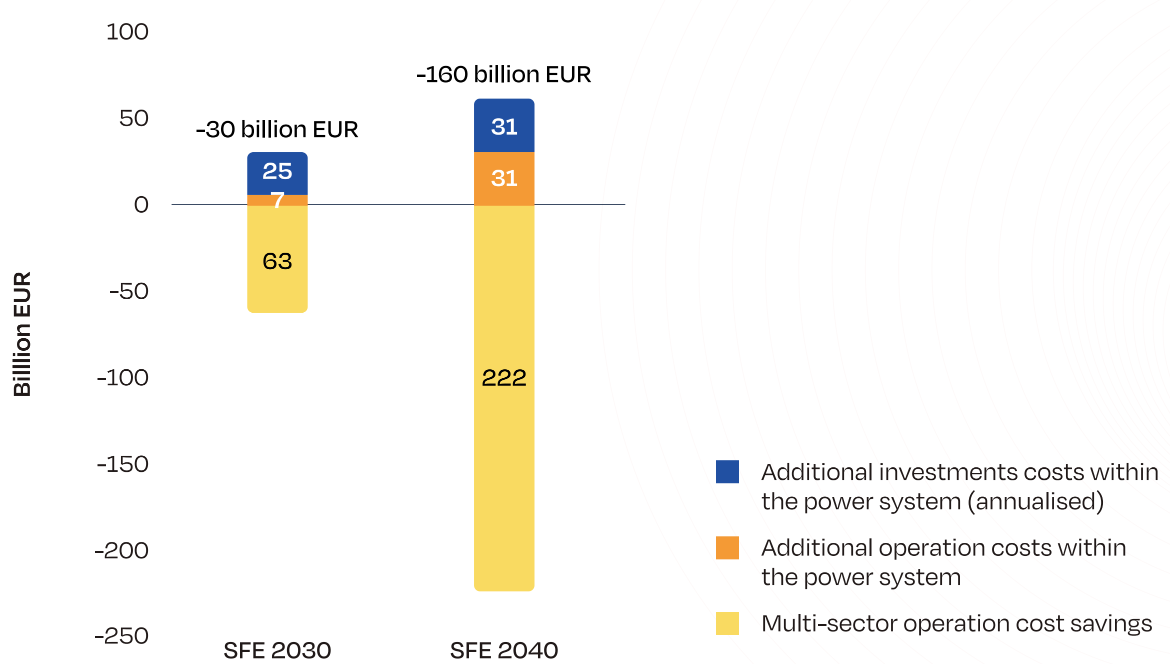
In the SFE Scenario, a 19% increase in total power demand compared to the 2040 baseline is needed to deliver additional energy services that would be relying on conventional energy sources. These services are instead provided through clean electrification via heat pumps for the heat sector, via electric vehicles for the transport sector, and via electrolysers for the hydrogen sector. Electrification entails additional investment costs in the power system, as well as additional operational costs. These are attributable to additional PV, batteries, interconnectors, and electrolyser capacities and their operations. Combined, these costs amount annually to 32 billion EUR in 2030 and 62 billion EUR in 2040 (see Fig. 13). These costs could be mitigated by investment and equipment cost variation related to other energy sectors, where electrification can bring substantial savings.

Key message

- Additional flexibility capacity and smart electrification decrease the energy system's total costs. The SFE Scenario displays much lower operational and annualised investment costs compared to the baseline, thanks to massive cost savings from the electrification of the heat, transport and hydrogen sector. Annual net system cost savings amount to 32 billion EUR in 2030 and 160 billion EUR in 2040.

At the same time, the cross-sectoral electrification brings considerable savings by reducing fossil fuel usage in those sectors. A decrease in the use of gas boilers in the heat sector, ICE cars in the transport sector, and steam-methane reforming in the hydrogen sector leads to 63 billion EUR operational cost savings in 2030 and 222 billion EUR in 2040. As result, net energy system cost savings amount to 32 billion EUR in 2030 and 160 billion EUR in 2040.

FIGURE 13 ANNUAL ENERGY SYSTEM COSTS 2030 AND 2040 IN THE SFE SCENARIO VS. BASELINE



3.4. Unlocking flexibility solutions reduces total energy system costs

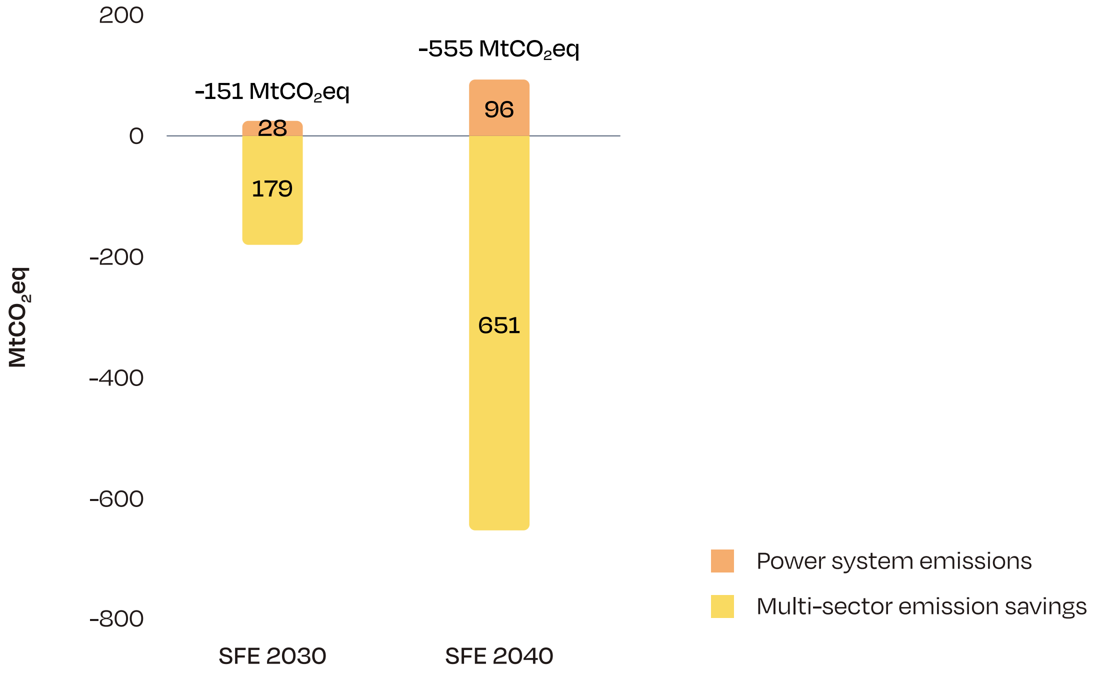
Similarly to total energy system costs, flexibility capacities and smart electrification enable a strong reduction of carbon emissions in the energy sector. A switch to electrified solutions in the heating, transport and industry sectors entails an increase in total power consumption and its carbon emissions. However, this increase is marginal compared to the large GHG emissions reduction in the electrified sectors.

As shown in Fig. 14, the increased total power consumption in the SFE Scenario leads to additional 28 and 96 $MtCO_2eq$ in 2030 and 2040, compared to the SAU Scenario. However, cross-sectoral electrification largely reduces the system's reliance on carbon-intensive alternatives in the heat, transport, and hydrogen sector. The switch to clean electrification results in enormous multi-sector GHG emission savings, which reach 179 and 651 $MtCO_2eq$ in 2030 and 2040, compared to the SAU Scenario. As a result, net GHG emission savings amount to 151 $MtCO_2eq$ in 2030 and 555 $MtCO_2eq$ in 2040. These volumes correspond to 25% and 91% of the EU's energy system emissions in 2023.

Key message

- Additional flexibility solutions and smart electrification enable massive carbon emission savings compared to the baseline. In the SFE Scenario, GHG emissions linked to the additional power demand from electrification are largely counterbalanced by cross-sectoral emission savings from the reduction of carbon-intensive alternatives for heat, transport and industry uses. Annual net GHG emission savings amount to 151 $MtCO_2eq$ in 2030 and 555 $MtCO_2eq$ in 2040.

FIGURE 14 ANNUAL GHG EMISSIONS 2030 AND 2040 IN THE SFE SCENARIO VS. BASELINE

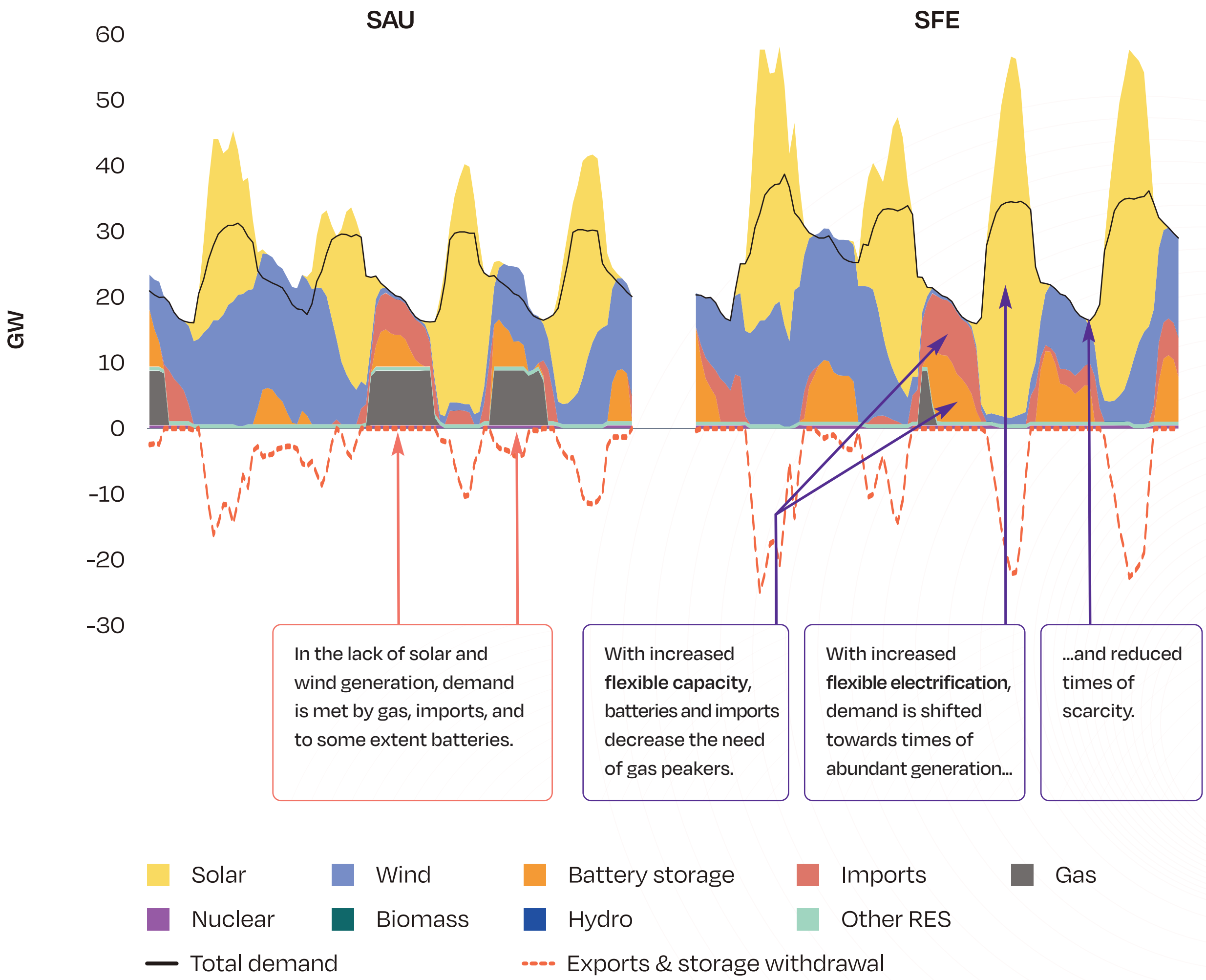


Box 3 – Power system generation and consumption profiles

The benefits of flexibility solutions and smart electrification for an efficient integration of variable renewables in the power system can be observed by comparing generation and consumption profile patterns across scenarios. As solar and wind contribute larger shares of the electricity mix, daily power generation profiles reflect their typical production patterns in a more noticeable manner, with solar peaking in daytime hours and wind growing larger at nighttime.

Figures 15 (and 16) display illustrative production and consumption profiles for a specific spring week in the Netherlands in 2030 and 2040, chosen for the high penetration of wind and solar generation as well as the significant role of flexibility services from batteries and cross-border interconnectors. The production and consumption profiles in the baseline SAU Scenario and the flexibility-driven SFE Scenario are compared. In the SAU Scenario 2030 (left), while solar and wind provide 63% of total electricity, large parts of electricity are still provided by gas when not enough variable renewables are available (Fig. 15). Electricity from gas-fired generators is complemented by imports, and to some extent batteries, which partially absorb excess solar generation and shift it to evening hours. In the SFE Scenario 2030 (right), by comparison, increased battery and interconnector capacities significantly decrease the reliance on gas-fired assets to meet power demand, which is also better adapted to generation.

FIGURE 15 2030 POWER GENERATION AND CONSUMPTION PROFILES IN A REPRESENTATIVE SPRING WEEK IN THE NETHERLANDS, SAU SCENARIO VS SFE SCENARIO

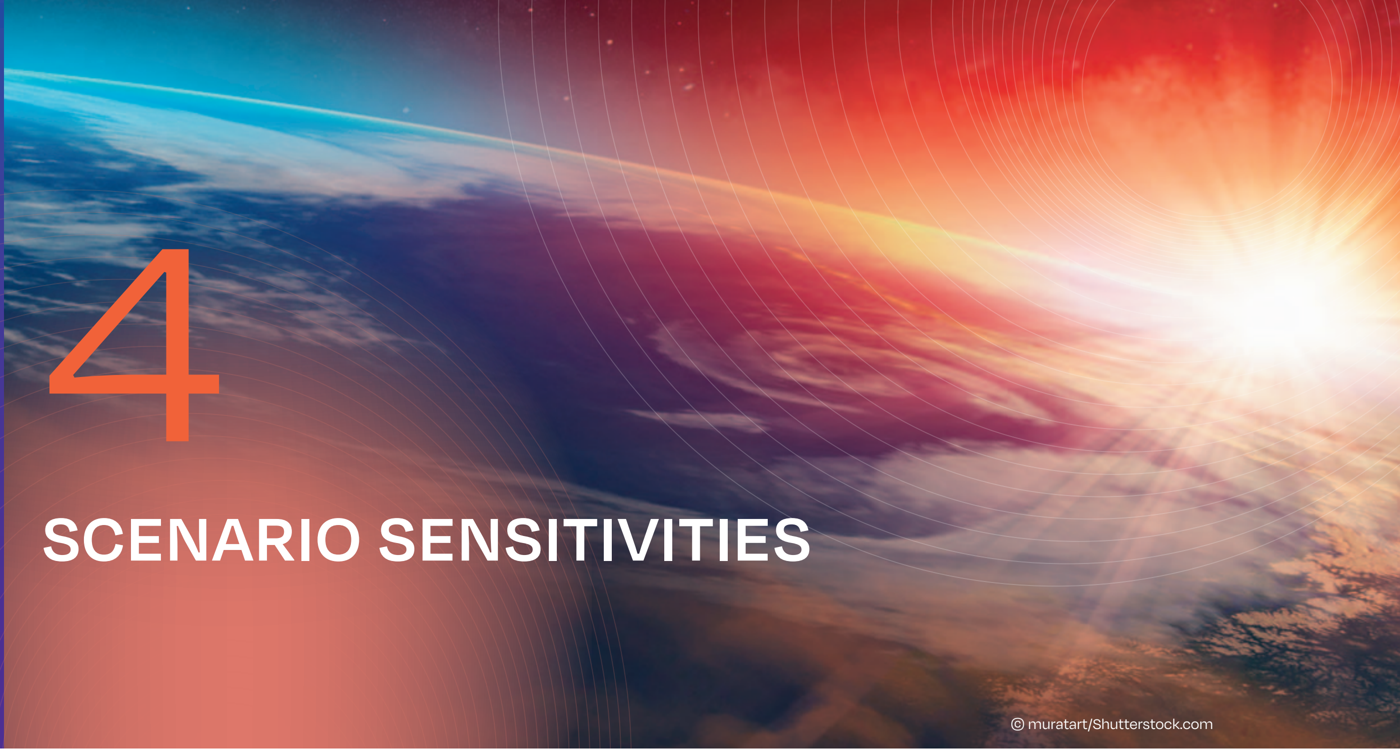


Note: gas generation includes both fossil and renewable-based gas. Assumptions for gas supply mixes in 2030 and 2040 are based on the TYNDP-DE scenario and are shown in the Annex.

Box 3 – Continued

In 2040, increased power demand is met to an even larger degree by variable renewable generation, which reaches 77-78% in the two scenarios (Fig. 16). In the SAU Scenario (left), gas is still used to a considerable extent to meet demand when solar and wind are insufficient. In the SFE Scenario (right), the larger role played by solar PV and batteries are visible in the more pronounced production peaks and storage withdrawals. Larger solar generation is due to more installed capacity, and significantly lower solar curtailment rates. Thanks to the increased BESS installed capacity, the battery fleet is able to meet power demand to a larger degree, fulfilling the need for additional electricity that is driven by cross-sectoral electrification. Increased demand-side flexibility from smart electrification also allow for better adaptation to variable generation profiles.

FIGURE 16 2040 POWER GENERATION AND CONSUMPTION PROFILES IN A REPRESENTATIVE SPRING WEEK IN THE NETHERLANDS, SAU SCENARIO VS SFE SCENARIO



4

SCENARIO SENSITIVITIES

This section illustrates complementary insights through sensitivity analyses building upon the SFE Scenario. Additional modelling runs conducted using Artelys Crystal Super Grid were used to illustrate the impact of alternative assumptions in the most ambitious flexibility-driven scenario. The sensitivities analyse a possible delay in battery deployment in the 2030 time horizon, and a gas retirement scenario with accelerated decommissioning of gas-fired assets in the 2040 time horizon.

4.1. Sensitivity 1: Delayed battery deployment in 2030

Parameter changes

This sensitivity analyses the impacts of a delay in battery deployment in the time horizon 2030. The run is based on the SFE Scenario, with battery capacities set to the baseline SAU Scenario level. Battery capacity is 62% lower than in the SFE Scenario, down from 260 GW to 97 GW.

In a scenario whereby the deployment of battery capacities is delayed, solar integration is slowed down, resulting in a notable increase of GHG emissions and power system operation costs.

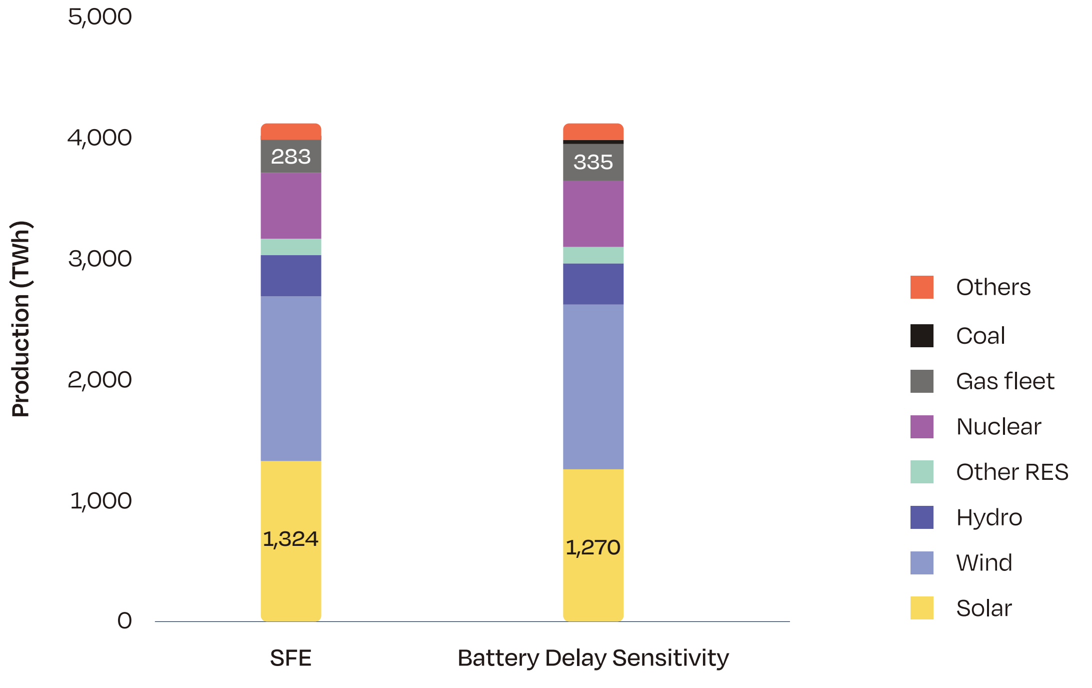
Solar generation	Power generation costs	GHG emissions	Investment costs
-53.7 TWh per year (-4%)	+3.6 Billion EUR per year (+11%)	+22 $MtCO_2eq$ per year (+17%)	-0.5 Billion EUR per year

Main results

Delayed battery deployment leads to a marginal decrease in solar capacity compared to the SFE Scenario. Solar installations are 2% lower and total 1,202 GW_{DC} by 2030. The decreased availability of batteries has a negative impact on solar curtailment, which increases from 2.1% to 3.4%. The decrease in installed capacity and the increase in curtailment bring down solar's share in the electricity mix, which is reduced by 1.3 percentage points from 32.1% to 30.8%, and in absolute terms decreases by 4% to 1,270 TWh (see Fig. 17). By contrast, gas-fired generation increases 18% to 335 TWh, covering 8.1% of the electricity demand, up 1.3 percentage points.

The increase in gas-fired power generation entails a 22 $MtCO_2eq$ growth in annual GHG emissions (+17%), and 3.6 billion EUR higher annual power generation costs (+11%), while annualised investment costs marginally decrease by 0.5 billion EUR due to the lower battery and solar capacities.

FIGURE 17 2030 POWER GENERATION MIX, SFE SCENARIO VS BATTERY DELAY SENSITIVITY



4.1. Sensitivity 2: Accelerated gas retirement in 2040

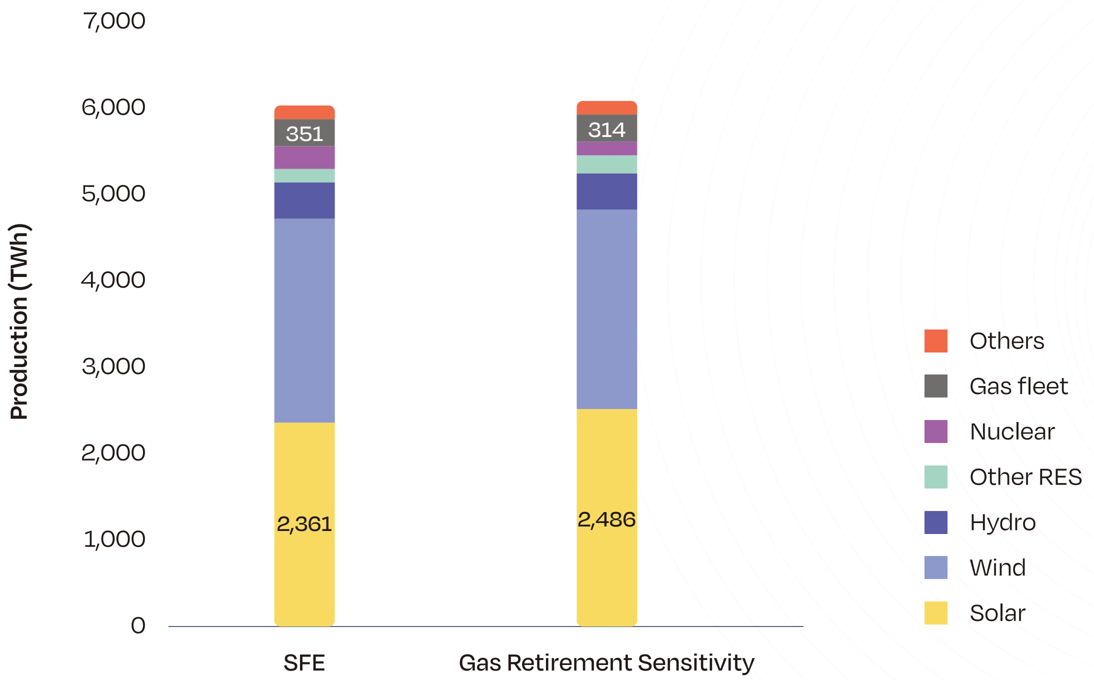
Parameter changes

This sensitivity analyses the impact of accelerated gas phase-out in the time horizon 2040. The run is based on the SFE Scenario, with a change in gas-fired generation capacity. While in the SFE Scenario gas capacity is an exogenous input, in this sensitivity both open cycle gas turbine (OCGT) capacity and combined cycled gas turbine (CCGT) capacity are optimised along with solar PV and battery capacities, in order to explore the potential for additional retirements of gas-fired units. Investment parameters are presented in the Annex.

In a scenario whereby gas phase-out is accelerated, solar and battery capacities are further deployed. The increase in solar generation brings down GHG emissions in the power sector, while increased investment costs are compensated by lower power generation costs.

Solar generation	Power generation costs	GHG emissions	Investment costs
+125.4 TWh per year (+5%)	-3.6 Billion EUR per year (-7%)	-11.7 $MtCO_2eq$ per year (-8%)	+3.9 Billion EUR per year

FIGURE 18 2040 POWER GENERATION MIX, SFE SCENARIO VS GAS RETIREMENT SENSITIVITY



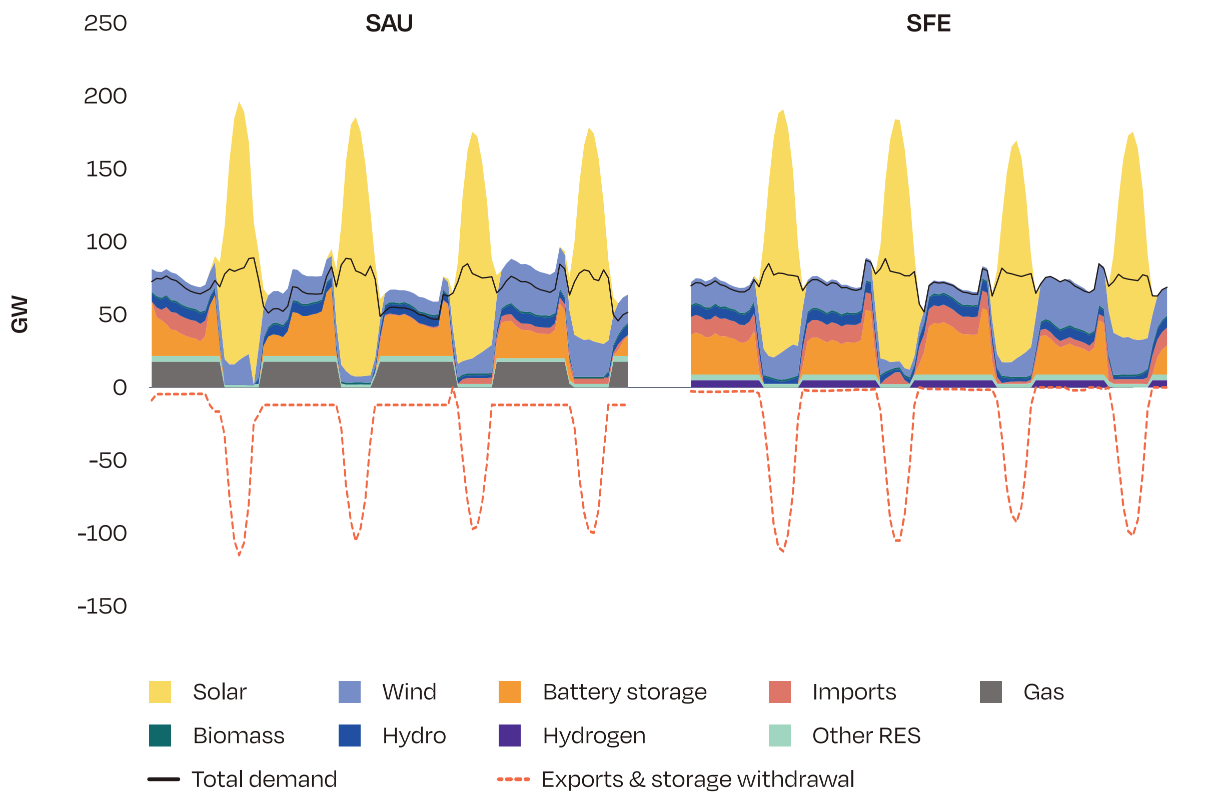
Main results

The re-optimisation of gas-fired capacity leads to increased deployment of solar capacity and battery storage. Battery installations increase by 265 GW (44%) to 871 GW, while gas capacity decreases by 10% or 30 GW to 270 GW. In addition, 75 GW of additional solar capacity is installed, bringing the total solar fleet up 3% to 2,510 GW. Despite this growth, solar curtailment drops from 11.5% to 10.2%, thanks to the additional availability of flexibility capacity. The share of solar power increases by 5% or 125 TWh to 2,486 TWh, while its share in the electricity mix grows by 2.1 percentage points to 40.8% (see Fig. 19). At the same time, gas-fired generation is reduced by 11% or 38 TWh to 314 TWh.

This shift from gas to solar contributes to an 8% reduction of power system carbon emissions, which drop by 112 $MtCO_2eq$ per year. By contrast, total power system costs remain comparable to the SFE Scenario. While the solar and battery capacity additions increase annualised investment costs by 3.9 billion EUR, the savings in operational power generation amount to 3.6 billion EUR, which is a 7% decrease compared to the baseline.

Figure 18 depicts the impact of gas retirement on the hourly electricity dispatch for a representative winter week in the Spanish electricity system in 2040, compared to the SFE Scenario. Gas-fired power generation, which in the SFE Scenario meets demand in times of low variable renewable generation, is replaced by a combination of solar PV generation and flexibility services from batteries and cross-border interconnections.

FIGURE 19 2040 POWER GENERATION AND CONSUMPTION PROFILES IN A REPRESENTATIVE WINTER WEEK IN SPAIN, SFE SCENARIO VS GAS RETIREMENT SENSITIVITY



ANNEX

General modelling approach

The Artelys Crystal Super Grid modelling platform was used to perform simulations of the three scenarios of the study in the timeframes 2030 and 2040.[9] Each simulation consists in the joint optimisation of investment and hourly operations of the European power system over a full year (8760 consecutive time-steps), for a perimeter that covers all EU-27 countries and relevant non-EU countries (CH, NO, UK, Western Balkans). Results include the hourly dispatch and price formation of wholesale electricity markets over a full year, and provide the optimal dimensioning of key infrastructure and generation assets – including additional solar capacities.

All modelling runs are performed over a full year. Investment decisions are therefore based on annuities computed according to investment parameters presented in the following paragraphs.

Main power system modelling assumptions

Inputs from TYNDP22

The baseline power system model is built according to the 2030 and 2040 Distributed Energy scenarios from ENTSO-E's Ten-Year Network Development Plan 2022.[10] This includes capacities and main techno-economic parameters from all generation technologies except solar, as well as timeseries for power demand and renewable generation.

Baseline solar capacities

Baseline solar capacities at national level are based on current and foreseeable market trends under SolarPower Europe's Medium Scenario from the EU Market Outlook 2023-2027.[11] According to this scenario, EU solar capacity stands at 576 GW by 2027 and is projected to reach 902 GW by 2030. An extension of the scenario until 2040 projects 2,090 GW of solar installed in the EU, with a conservative CAGR of 9% in the timeframe 2030-2040. National solar generation profiles from ENTSO-E's TYNDP were rescaled in order to meet average national capacity factors published by the JRC on the PVGIS platform.[12]

Commodity prices and gas supply

The commodity prices used in the study were aligned with 2030 and 2040 projections from up-to-date sources, as shown in Table 6.

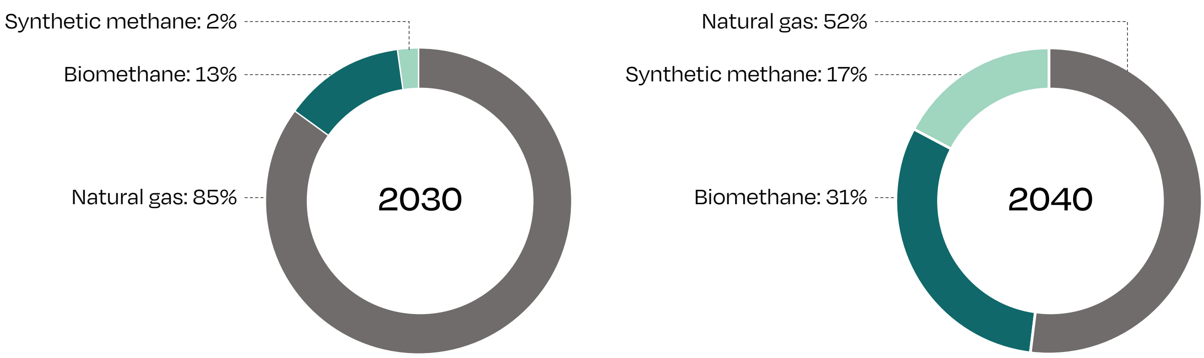
9 Artelys (2023): Artelys Crystal Super Grid.
10 ENTSO-E and ENTSOG (2022): TYNDP 2022 Scenario Report & TYNDP 2022 Scenario Building Guidelines.
11 SolarPower Europe (2023): EU Market Outlook for Solar Power 2023-2027.
12 Huld, T., Müller, R. and Gambardella, A. (2012): A new solar radiation database for estimating PV performance in Europe and Africa.

TABLE 6 STUDY ASSUMPTIONS ON COMMODITY PRICES

COMMODITY	2030 PRICE	2040 PRICE	SOURCE
Natural gas (EUR/MWh)	37	37	REPowerEU[13]
Biomethane (EUR/MWh)	75	61	TYNDP 2022 - DE[14]
Synthetic methane (EUR/MWh)	104	84	TYNDP 2022 - DE
Coal (EUR/MWh)	10	11	REPowerEU
Oil (EUR/MWh)	51	53	REPowerEU
CO_2 (EUR/t)	104	112	IEA WEO 2023, Stated Policies scenario[15]

In addition, gas supply assumptions for power generation were aligned with the TYNDP-DE gas supply mix (see Fig. 20). The gas-based power generation has been distributed accordingly between fossil gas and other renewable-based power generation.

FIGURE 20 GAS SUPPLY MIX FROM TYNDP 2022 DISTRIBUTED ENERGY SCENARIO



13 European Commission (2022): REPower EU plan (SWD/2022/230 final).
14 ENTSO-E and ENTSOG (2022): TYNDP 2022 Scenario Building Guidelines.
15 IEA (2023): World Energy Outlook 2023.

Other investment assumptions

Other investment assumptions were adapted from TYNDP 2022 Scenario Building Guidelines or, in the case of batteries, are based on current and foreseeable market trends according to industry stakeholders (see next section).

Technology and cost assumptions for stationary batteries and electrolysers are provided in Table 7. Assumptions for stationary batteries are based on industry stakeholders' experience, while electrolyser assumptions are based on TYNDP 2022.

As the implemented scenarios imply significant amendments of demand profiles and generation fleets, OCGT capacities are recalibrated by the model for each run to avoid loss of load.

Counterfactual for electrification

The SFE Scenario does not deliver the same energy services than other scenarios. As power demand in the SFE Scenario is higher than in SAU and SE Scenarios, an estimation of cross-sectoral costs and GHG emission savings was performed based on the following counterfactuals:

1. For the additional power consumption from heat pumps, it was assumed a situation where the equivalent heat demand is met with gas boilers (considering a 90% efficiency).
2. For the additional demand from electric vehicles, it was assumed a situation where an equivalent cumulated distance is covered by a thermal passenger car, considering IEA data on fuel consumptions in Europe.[16]
3. For the additional hydrogen demand, it was compared with the emissions and costs associated with generating additional hydrogen by CCS-equipped steam-methane reforming (SMR CCS), using TYNDP 2022 assumptions regarding SMR and CCS efficiency.

TABLE 7 TECHNOLOGY AND COST ASSUMPTIONS FOR STATIONARY STORAGE AND ELECTROLYSERS

TECHNOLOGY	2030		2040		LIFETIME	WACC
	CAPEX (EUR/kW)	FIXED OPEX (EUR/kW/Y)	CAPEX (EUR/kW)	FIXED OPEX (EUR/kW/Y)		
Li-ion battery (3h)	210	4	140	3	20	7%
Electrolyser	366	11	290	11	25	6%

16 IEA (2021): Fuel Economy in the European Union.

Representation of solar PV investments

Solar technologies and investment parameters that have been used in the SFE Scenario, in which the model is free to invest in additional solar capacities, are provided in Table 8. All investment costs are then annualised in the model.

Solar generation profiles from ENTSO-E'S TYNDP have then been rescaled to match technology-specific average capacity factors at national level and per technology, as available in publications from the ENSPRESO 2020 European project.[17]

In order to preserve realistic technology breakdowns for new solar additions, ad-hoc investment options have been designed at national level, notably SolarPower Europe's EMO 2023 Medium Scenario data regarding solar installations at country level for the 2023-2027 period and projections towards the years 2030 and 2040.

The corresponding investment options therefore present investment parameters and generation profiles that are representative of country specific mixes of technologies, with the following EU-27 breakdowns:

1. Rooftop vs utility-scale: 59-41% in 2030, 40-60% in 2040 (EU-27 average)
2. Residential vs C&I rooftop: 38-62% in 2030 &2040
3. Utility-scale with vs without tracker: 30-70% in 2030, 50-50% in 2040

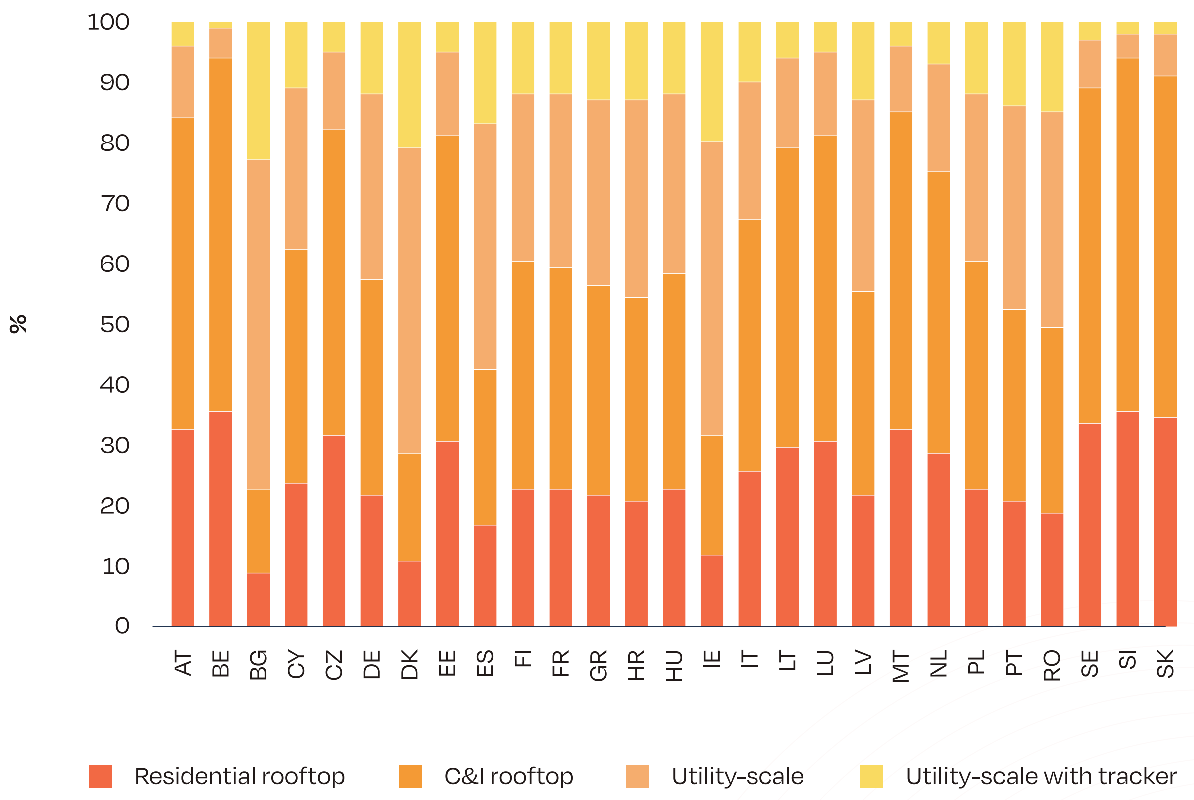
The country-specific technology combinations for 2030 investment options in solar PV are presented in Figure 21 on the following page.

TABLE 8 SOLAR PV TECHNOLOGY AND INVESTMENT ASSUMPTIONS

TECHNOLOGY	2030		2040		LIFETIME	WACC
	CAPEX (EUR/kW)	FIXED OPEX (EUR/kW/Y)	CAPEX (EUR/kW)	FIXED OPEX (EUR/kW/Y)		
Residential rooftop	1,130	6	870	5	30	4%
C&I rooftop	560	7	430	6	30	6%
Ground-mounted	330	11	260	9.5	35	6%
Ground-mounted + tracker	350	12	280	10.5	30	6%

17 JRC (2020): ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials.

FIGURE 21 SEGMENTATION OF EU-27 SOLAR PV ADDITIONS 2030



Note: the values illustrate the segmentation of the additional installed capacity in the SFE scenario.

Integration of key flexibility solutions

This subsection describes more in details the modelling approach that was adopted for the main flexibility solutions in this study.

Flexible technologies

Stationary batteries

While TYNDP scenarios make a distinction between front-of-the-meter (FTM) and behind-the-meter (BTM) units, stationary batteries were modelled as battery fleets aggregated at national level in this study, participating in the supply-demand equilibrium of wholesale electricity markets. As a result, this model makes no distinction between FTM and BTM battery capacities. This is a limitation of the study, which is unable to capture the self-consumption dynamics at the BTM level.

In line with TYNDP scenarios, a 3h discharge time (GWh/GW) was assumed for all assets.

Power interconnectors

Cross-border interconnections are modelled in the form of net transfer capacities (NTC) aligned with TYNDP scenarios.

Flexible demand

Electric vehicle fleet

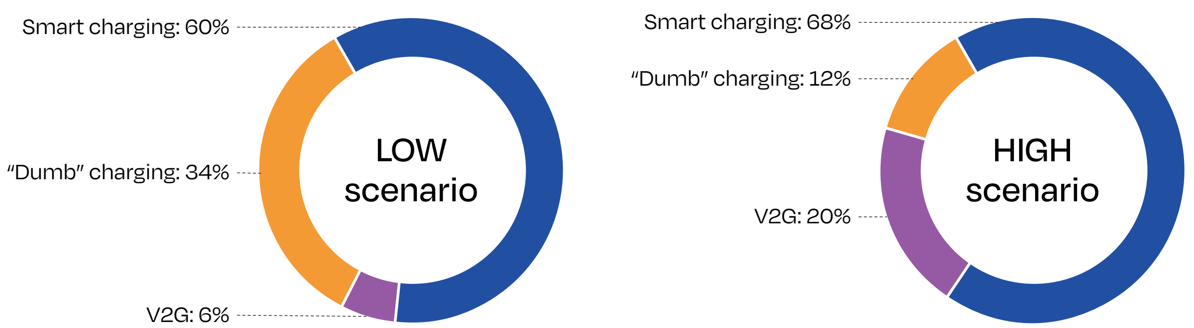
Electric vehicles are represented in the form of aggregated fleets in each modelled country, which differ by fleet-specific distributions of arrivals and departures, as well as their charging behaviour.

Each fleet is modelled as a storage asset, with injection/withdrawal capacities and storage volume depend on departure and arrival profiles. Three charging behaviours are represented in the model:

- "Dumb" charging, where the vehicle charges as soon as it is plugged in (no control);
- Smart charging (V1G), where vehicle charging is co-optimised with the operation of the electrical system to minimise system costs;
- Smart charging with the possibility of injection (V2G), where the potential charging and discharging of the vehicle is also co-optimised with the operation of the electrical system in order to minimise system costs.

The EU-27 penetration of V2G and V1G vehicles represented in the model are presented in Figure 22. The Low Scenario is used in the SAU and SF Scenarios; the High Scenario is used in the SFE Scenario. Assumptions on EV charging mode shares are based on RTF data.[18] In each scenario, the size (i.e., the number of vehicles) in each fleet is calibrated to correspond to the annual power demand from EVs in the scenario.

FIGURE 22 EV CHARGING MODE SHARES IN LOW AND HIGH SCENARIO



18 Réseau de Transport d'Electricité (2021): Energy Pathways to 2050.

Heat pump fleet

The power demand from domestic heat pumps is modelled in the form of heat demand profiles corresponding to different fleets, distinguished by their flexibility. Three types of individual heat pumps are considered:

- Unflexible heat pumps that meet the heat demand at any time. These heat pumps don't include storage;
- Short-term flexibility heat pumps that include thermal storage to provide short-term flexibility;
- Long-term flexibility heat pumps. These heat pumps derive their flexibility from a hybrid system (gas/electricity). The gas back-up can be activated for heating peaks to avoid electricity peaks.

The assumptions regarding the demand and the flexibility share for the different scenarios, based on RTE data, are outlined in Figure 23.

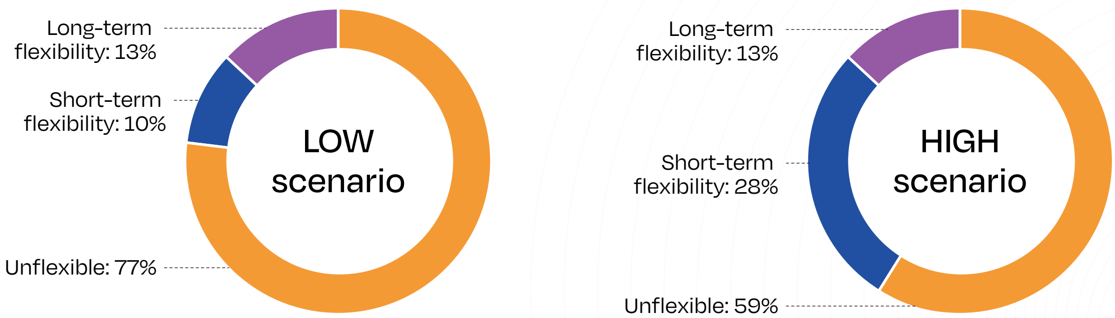
Hydrogen demand

Power-to-hydrogen sector coupling is represented in the model. Power consumption by electrolysers is therefore linked to an explicit hydrogen demand. Electrolysis capacities are modelled along with virtual hydrogen storage assets that allow for a flexible operation of the fleet. Electrolyser efficiencies are taken from TYNDP 2022.

For each scenario, national demand volumes are obtained through a calibration of national demand volumes from the TYNDP 2022 Distributed Energy scenario in order to match the specific EU-27 volume target.

The demand for hydrogen represented in the model corresponds to the EU-27 supply via electrolysis. Other sources of supply like extra-EU imports or steam-methane reforming are not represented. All hydrogen demand profiles are considered flat, i.e., non-thermosensitive. Flexibility needs for hydrogen supply is therefore driven by supply and demand dynamics in the power system.

FIGURE 23 HEAT PUMP SHARES IN LOW AND HIGH SCENARIO



SolarPower Europe

SolarPower Europe

SolarPower Europe - Leading the Energy Transition
Rond-Point Robert Schuman 3, 1040 Brussels, Belgium
T +32 2 709 55 20 / F +32 2 725 32 50
info@solarpowereurope.org / **www.solarpowereurope.org**

ISBN NUMBER 9789464669183