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How To Make Europe's Energy System Climate-Neutral Before **2050**

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FOREWORD: Claude Turmes

Dear Readers,

On 4 March 2020, the European Commission made a fundamental move by submitting a proposal for the "Climate Law", pledging to become the first climate-neutral continent. This vision is much needed at a point in time where our traditional vision of growth and industrial development is being challenged by the depletion of earth's resources, collapse of our natural ecosystems, staggering levels of global warming and an unprecedented health crisis putting in question our production and consumption models.

European citizens and civil society are leading the way, starting with our youth – in 2019, thousands of climate strikes took place across nearly every European country.

As a Member of the European Parliament for 19 years, I have carried out the fight against climate change, and proudly contributed to the adoption of the 2009 Energy and Climate Package that established a vivid home market for an exponential growth of renewables and made the EU a global leader. The Clean Energy Package is a critical milestone in boosting the deployment of renewable energies and energy efficiency in the next decade, as the most cost-efficient solutions to tackle climate change. The Clean Energy Package placed Europe on the right path to achieving climate neutrality by 2050, but the size of the challenge requires us to step-up our ambitions.

In my current role as Energy Minister of Luxembourg, I have teamed up with colleagues from Austria, Denmark, Ireland, Lithuania, and Spain, calling on the European Commission to include a 100% renewable energy scenario in the Commission's 2050 energy and climate projections. On 14 April 2020, together with 180 ministers, MEPs, CEOs, NGOs and Trade Unions, we launched the European alliance for a green recovery after the corona crises that should act as an accelerator of the transition towards climate neutrality. As political leaders, we must demonstrate to the younger generations that they have been heard, and that the most ambitious scenarios possible are being seriously considered to help fight climate change and create a more resilient and sustainable Europe.

SolarPower Europe and LUT University's ground-breaking modelling demonstrates that it is possible for the EU to become fully climate neutral by 2040, complying with the ambitious 1.5°C Paris Agreement target, and without any tricks, like carbon sinks, but by implementing ambitious energy efficiency policies and going 100% renewables. In addition, the study highlights the critical advantage of a 100% renewable pathway, as the most cost-effective way of achieving climate neutrality before 2050 and to make the European energy system less dependent and more resilient. It also shows the crucial role solar power has in the energy transition. That's why we in Luxembourg have launched first solar auctions to support and utilize lowest-cost ground-mount solar and improved the regulatory framework for solar rooftop applications. In our national plan, we foresee to multiply by a factor 6 our power generation from photovoltaic by 2030.

This study comes at an important point in time and will spark useful conversations on the ongoing European climate negotiations and recovery plans. To face the challenge of climate change, the EU must consider all possible options with the utmost level of transparency and with credible technology cost and carbon price assumptions. Only then will we be able to make an enlightened choice, and succeed in the unprecedented, yet exciting challenge, of becoming the first climate-neutral continent.

CLAUDE TURMES
ENERGY MINISTER
OF LUXEMBOURG

FOREWORD: SolarPower Europe and LUT University

Welcome to SolarPower Europe & LUT's 100% Renewable Europe Report.

It's possible for the EU to become fully climate neutral by 2040, complying with the ambitious 1.5°C Paris Agreement target, and without any tricks, like carbon sinks, but just by going 100% renewable. This is the main message of SolarPower Europe and LUT University's modelling of a cost-optimal energy transition in Europe. Our results are good news for the European Green Deal, indicating that the European Commission's climate ambition can be achieved, even before the 2050 deadline.

The key to achieving a 100% renewable Europe is a high electrification rate of around 85%, which enhances sectoral integration and results in significant efficiency gains for the energy system. It also paves the way for renewable hydrogen to contribute as of 2030 to the full decarbonisation of the heat and transport sectors. A core technology for the heat segment are heat pumps. With transport having the longest way to go to 100% renewables, from 8% today, this transformation relies on batteries that are crucial to electrify vehicles, and even more on hydrogen, but in this case as a base for synthetic fuels that have a prime role to play in the large marine and aviation application field of the transport sector. The key part of batteries in a 100% renewable powered Europe is energy storage. As the share of flexible solar and wind grows significantly beyond 2030, batteries contribute up to 70% of electricity storage, backing up to 20% of European energy demand.

A major news of this report is that a 100% renewable system in Europe will be primarily a solar story. Solar PV and wind represent the two main pillars of the energy transition, supplying over 90% of power demand in the long run. Due to its unique versality – capable of being installed in any size for distributed and centralised applications – and combined with its strong cost-competitiveness, solar generates over 60% of the electricity in both 100% renewable scenarios, modelled for 2040 (Leadership) and 2050 (Moderate). At this penetration level, solar would create over 4 million jobs in Europe by 2050.

Such an ambitious energy transition will require significant efforts. Just considering the sheer volume of solar installations, at least 7.7 TW by 2050 in the Moderate scenario from 150 GW today, means an annual installed capacity of around 250 GW/year in average – that's a factor 10 from what was installed last year.

If the EU takes the European Green Deal and Paris Agreement seriously, policymakers **must utilise this decade to focus on creating the right policy and financing frameworks to enable this unprecedented growth of renewables**. We need to enshrine the climate neutrality target into law, and change the EU 2030 Greenhouse Gas reduction goal to a level that complies with the 1.5°C Paris Agreement target. Only if renewable-based electrification is prioritised by 2030, can the pathway towards the development of competitive and sustainable hydrogen solutions be paved. In this context, it is essential to upgrade, expand, and modernise Europe's electricity grids, as well as other infrastructure, in order to enable the rapid deployment of distributed flexibility resources and demand response, such as EV charging stations, heat pumps, and battery storage.

With solar potentially generating up to two thirds of Europe's power by 2050 or before, the EU must push for the technologies needed to bring forward this transition to originate also in Europe to ensure its energy security in the long-term. This study clearly shows that we need a roll-out of a solar industrial strategy today, to truly benefit from solar power generation tomorrow. The European solar PV industry needs to be strengthened as a cornerstone of the European Green Economy, complementing existing industry alliances for batteries and hydrogen.

Clearly the transition to a climate-neutral energy system comes at a cost; however, perhaps surprisingly, moving slowly does not make it any less costly. The most cost-effective way of achieving climate neutrality by 2050 is a 100% renewable energy system. According to the modelling in this study, the total cost of achieving 100% by 2050 is 6% lower than the cost of inadequate action in the less ambitious Laggard scenario, which only reaches 62% renewables by 2050, thus missing both the targets of the European Green Deal and the Paris Agreement.

Moving forward, any kind of European stimulus package offers the opportunity not only for economic recovery from COVID-19, but if done sustainably, the possibility of accelerating the energy transition and to set the pathway for becoming the world's first climate neutral continent powered by 100% renewables by 2050, or even before.

Enjoy reading our 100% Renewable Europe Report,

WALBURGA HEMETSBERGER
CEO

MICHAEL SCHMELA
EXECUTIVE ADVISOR

AURÉLIE BEAUVAIS
POLICY DIRECTOR

CHRISTIAN BREYER
PROFESSOR FOR SOLAR ECONOMY

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KEY FINDINGS & POLICY RECOMMENDATIONS

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Key Findings

1. A 100% renewable energy system enables the EU to become climate neutral before 2050, complying with an ambitious 1.5°C Paris Agreement target, and without resorting to carbon sinks.

   SolarPower Europe and LUT's modelling shows that it is possible for Europe to reach 100% renewables by 2050 in a Moderate scenario, and by 2040 in a Leadership scenario.

2. A 100% renewable energy system is the most cost-effective way of becoming climate neutral by 2050.

   The cumulative costs of achieving a 100% renewable energy by 2050 in the Moderate scenario are 6% lower than the cost of inadequate action in the less ambitious Laggard scenario, which reaches only 62% renewables by 2050, thus missing both the targets of European climate neutrality and the Paris Agreement.

3. A 100% renewable energy system is primarily a solar story.

   In both of the modelled 100% renewable scenarios, solar generates more than 60% of EU electricity by 2050. In the long run, solar and wind are the two main pillars of the European energy transition. Due to its higher capacity factors, wind energy provides the highest shares of electricity generation up to 2030, however, solar's versatility and cost-competitiveness will make it the main source of electricity generation from 2030 onwards.

4. **A 100% renewable transition triggers the sharpest decline in GHG emissions.**

   Following the path of the 100% renewable scenarios (Moderate and Leadership), GHG emissions will decline by over 60% (from 1990) by 2030, and down to zero in 2050, or even 2040 in the Leadership scenario. In the least ambitious Laggard scenario, Europe reaches only 53% CO_2 emission reductions in 2030, and still emits approximately 800 million tonnes of CO_2 ($MtCO_{2eq}$) per year.

5. **A high rate of electrification is essential to achieving a 100% renewable and integrated energy system.**

   The drive towards electrification of about 85% in the 100% renewable scenarios enhances sectoral integration, resulting in significant system efficiency gains, thus lowering the cost of the transition.

6. **Electrolysers for hydrogen production are a crucial technology for a 100% renewable energy system.**

   From 2030 onwards, renewable hydrogen contributes to the full decarbonisation of the heat and transport sectors, becoming Europe's second key energy carrier. In the Leadership scenario, by 2040 Europe can even become an exporter of renewable hydrogen's product, synthetic fuels.

7. **Batteries provide the bulk of electricity storage in a 100% renewable energy system.**

   As the share of solar and wind increases significantly beyond 2030, electricity storage becomes crucial in providing an uninterrupted energy supply, backing up to 24% of European electricity demand. As the most cost-efficient storage technology, batteries will contribute up to 98% of electricity storage.

8. **A 100% renewable transport sector needs significant synthetic fuels for marine and aviation.**

   From an only 8% share of renewables today, the transport sector has the longest way to go to reach 100% renewables in Europe. Direct electrification emerges as the most efficient solution to decarbonise road transport, but the aviation and marine sectors will rely heavily on renewable synthetic fuels (hydrogen, methane and power-to-liquids).

9. **Heat pumps emerge as core part of a 100% renewable energy system, with over 60% share of heat generation by 2050.**

   While final heat demand will grow most compared to the other sectors, by 2050, European heat generation capacity is dominated by heat pumps and direct electric heating solutions.

BOX WHAT SOLAR NEEDS BY 2030 AND BEYOND

- **Establish "Clean Energy Package Implementation Body"**

  Inappropriate regulatory and administrative frameworks remain the principal barrier to the deployment of solar in Europe, including limited grid and land access, lengthy permitting requirements. The EU has a responsibility to secure the collective achievement of the 2030 climate and energy targets, paving the way for a climate-neutral economy by 2050.

- **Unlock the huge potential of large-scale solar involving citizens**

  Utility-scale solar installations are essential to drive the cost-efficient achievement of a climate-neutral EU, and provide the volumes needed to power the energy system with 100% renewable energy. In addition, utility-scale installations provide valuable grid services, with a positive impact on biodiversity. For optimal use, floating solar and agri-solar solutions need to be taken into account. To unlock the full potential, the EU needs a new 'social pact', scaling-up the concept of "citizen-energy" and enabling local authorities and communities to take part and ownership in the deployment of large-scale solar projects.

- **Develop pan-European solar rooftop program as part of upcoming renovation wave**

  With over 90% of European rooftops unused, there needs to be regulation that encourages all new and renovated residential, commercial, and industrial buildings in the EU to include solar PV. Finally, by 2050, solar needs to be installed on every appropriate rooftop to enable all citizens to become active consumers.

Policy Recommendations

A clear commitment towards achieving climate neutrality before 2050 and complying with the ambitious Paris Agreement targets is a necessary signal to accelerate investments in renewable energy technologies across all sectors of the EU economy. Taking into account the massive volume of solar and wind that needs to be installed to achieve 100% renewables by 2050 – at least 7.7 TW solar and 1.7 TW wind – policy makers must in this decade focus on creating the right policy and financing frameworks to enable this unprecedented growth.

1. Enshrine objective of climate neutrality into law and review EU 2030 GHG target to comply with the 1.5°C Paris Agreement.
2. By 2030, prioritise renewable-based electrification of the EU economy, paving the way to development of competitive and sustainable hydrogen solutions.

   The massive deployment of low-cost solar and wind power as prime energy carriers sets the direction towards a truly decentralised, flexible, and demand-driven energy system. From 2030 onwards, renewables will enable the emergence of diversified and competitive renewable energy solutions such as hydrogen, methane, and power-to- liquids.
3. Invest in upgrading, expanding, and modernising Europe's electricity grids.

   Electricity grids are crucial to enabling high levels of electrification and sectoral integration, and the cost-efficient achievement of a 100% renewable energy system in Europe. In the review of the TEN-E regulation, the concept of Projects of Common Interest (PCI) must evolve to address the need for smart, distributed infrastructure, and electricity grid upgrades (lower voltage, DSO/TSO participation).
4. Accelerate deployment of decentralised flexibility resources.

   The roll-out of smart and efficient decentralised solutions and demand response such as EV charging stations, heat pumps, and battery storage support a more flexible and efficient energy system. It is essential to reduce the need for electricity grid investments and optimise the utilisation of local renewable resources to meet annual energy demand.
5. Roll-out solar industrial strategy.

   By 2050, solar energy might power nearly two thirds of Europe's electricity generation, which forms the basis of most of the energy system. Supporting large-scale industrial deployment of existing, innovative European solar solutions and technologies are essential to enable long-run energy security. Solar PV manufacturing needs to be strengthened as a cornerstone of the European green economy and must be a major element in Europe's industrial strategy, complementing existing industry alliances on batteries and electrolysers.
6. Develop skills and training program to unlock potential of solar jobs.

   The lack of a skilled EU workforce in clean energy technologies has become a critical bottleneck, hampering the deployment of renewables. Solar is the most job-creating renewable technology and could deliver over 4 million jobs in Europe by 2050.

EXECUTIVE SUMMARY

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In light of the European Commission's 2050 climate neutrality vision for a European Green Deal to meet the Paris Agreement targets, SolarPower Europe and LUT University (LUT) developed a research project to better understand solar's role in the European energy transition. While the share of solar in the EU's electricity supply is currently less than 5%, the technology is the most versatile and often lowest-cost clean power generation source, with a rapid cost reduction trajectory. In 2019, more new solar capacity was installed in the European Union than any other power generation technology.

The overall aim of the project was to present an assessment demonstrating the lowest cost feasible energy mix with the transitioning of the power, heat, and transport sectors towards an integrated energy system across Europe up to 2050. The project uses a novel technology-rich, multi-sectoral, multi-regional and cost-optimal analysis, with a high spatial (20 sub regions) and temporal (hourly) resolution of energy transition pathways for Europe.

The energy transition across Europe is explored in the modelling of three distinct scenarios with the following boundary conditions and main results (see Fig. 0.1):

- **Laggard scenario:** A slower energy transition up to 2050 results in only in a renewable energy share of 62% and approximately a 90% reduction in GHG emissions by 2050, missing the EC's climate neutrality and Paris Agreement targets.
- **Moderate scenario:** A medium pace energy transition towards 100% renewables by 2050, meeting the EC's climate neutrality vision with zero GHG emissions and the 2°C Paris Agreement target.
- **Leadership scenario:** A rapid energy transition in the next two decades resulting in 100% renewables and zero GHG emissions in the energy system by 2040, achieving the ambitious 1.5°C Paris Agreement target.

FIGURE 0.1 SCENARIO OVERVIEW

	LAGGARD	MODERATE	LEADERSHIP
RE energy share	62% by 2050	100% by 2050	100% by 2040
Paris Agreement	⊗	Achieved 2.0°C	Achieved 1.5°C
GHG emissions in the energy system	-90% in 2050	-100% in 2050	-100% in 2040
Fossil fuels phaseout	⊗	Achieved in 2050	Achieved in 2040
Nuclear phaseout	⊗	⊗	Achieved in 2040

Source: SolarPower Europe.

The key trends and insights that emerge from the research include:

High rate of electrification is essential to achieving a 100% renewable and integrated energy system.

A fundamental shift towards high levels of electrification will shape the European energy transition, which is currently based on 85% fossil fuels and nuclear. Electrification across the energy sector – comprised of power, heat, and transport – results in the highest electrification share of 86% for the Leadership scenario, and the relatively low share of 51% for the Laggard scenario (see Fig. 0.2). Despite an overall increase in the demand for energy services across the power, heat and transport sectors, the primary energy demand declines with higher shares of electrification due to increased efficiency. This indicates a highly sector-coupled and efficient energy system based on renewable power in the future.

In summary, the drive towards low-cost electrification and enhanced sectoral integration leads to **strong electricity demand growth by 2050, with renewable electricity emerging as the prime energy carrier in future energy systems**, reaching 100% by 2040 in the Leadership scenario and almost 100% in the Moderate scenario by 2050 (with a few nuclear power plants still in phase out mode) (see Fig. 0.3).

FIGURE 0.2 ELECTRIFICATION RATES AND PRIMARY ENERGY DEMAND IN 2050

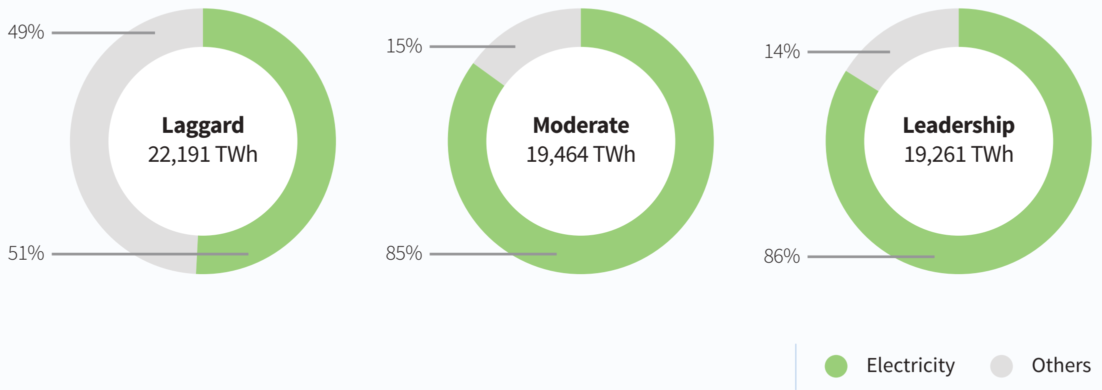
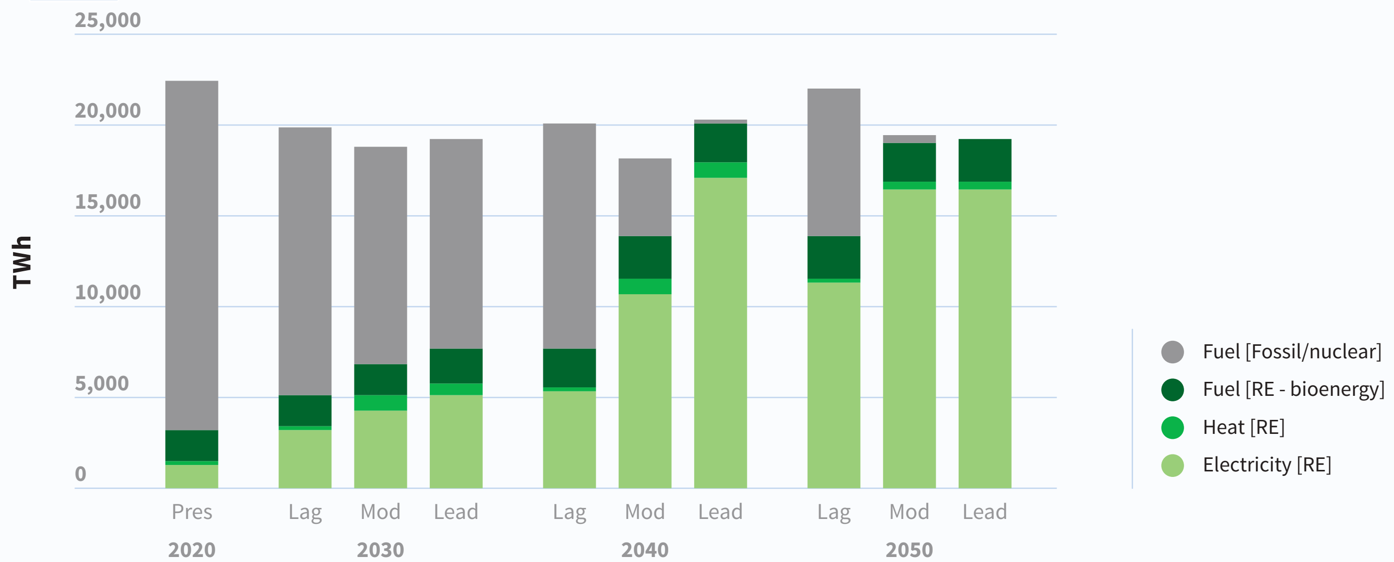


FIGURE 0.3 PRIMARY ENERGY DEMAND - FUEL USE



Source: SolarPower Europe.

Power: A 100% renewable European energy system is primarily a solar story.

Due to its cost competitiveness, solar PV will become the dominant source of electricity generation across the three scenarios. Solar provides the largest capacities over the course of the energy transition, reaching 4.7–8.8 TW in 2050; as of 2040, solar will represent the largest generation shares, and by 2050 it will reach at least 48% in the Laggard scenario and 63% in the Leadership scenario. By 2050, the other power pillar of the energy transition, wind energy, will, depending on the scenario, account for 28–33% of generation shares, and 1.1–1.9 TW of capacity.

Heat: Heat pumps emerge as a core part of a 100% renewable energy system, with over 60% share of heat generation by 2050.

Whereas today's heat market is dominated by fossil gas, which takes up a nearly 50% market share, a combination of direct and indirect electric heating will take over by 2050, reaching 62–68% in all scenarios, owing to the substantial efficiency gains of these electricity-based solutions. Renewable-based electric heating (direct) and heat pumps (indirect) will form the majority of heat generating capacities by 2050, complemented by a small but steady share of other renewables, such as sustainable bioenergy. All three scenarios also face a notable portion of renewable-based synthetic fuels – namely, hydrogen and methane – which contribute towards industrial process heat in the later stages of the transition.

FIGURE 0.4 ELECTRICITY SHARE 2050

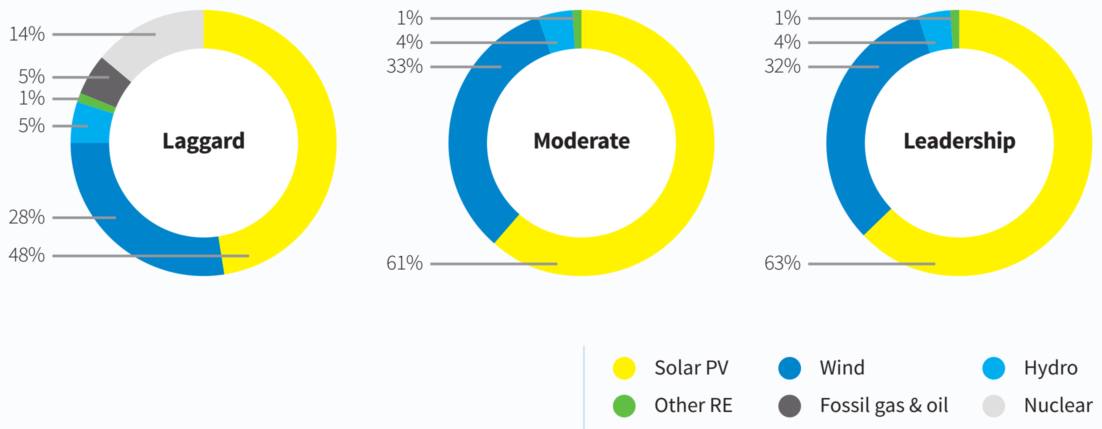
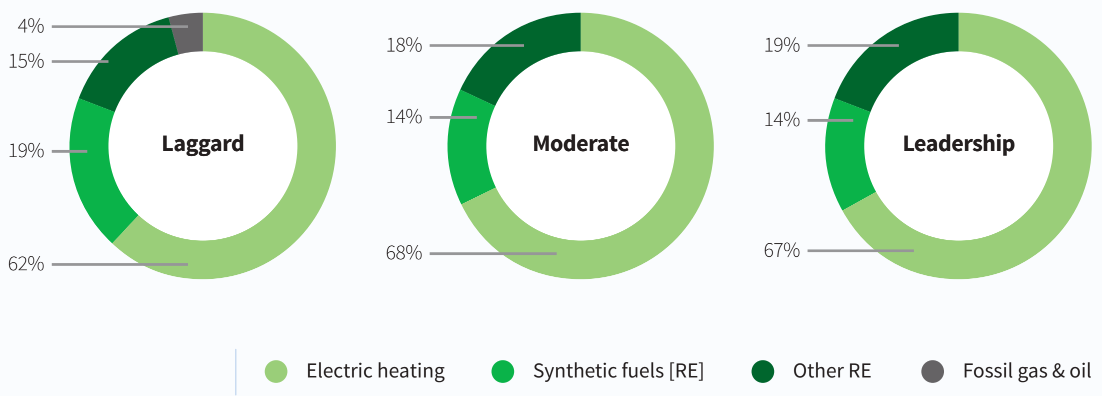


FIGURE 0.5 HEAT SHARE 2050

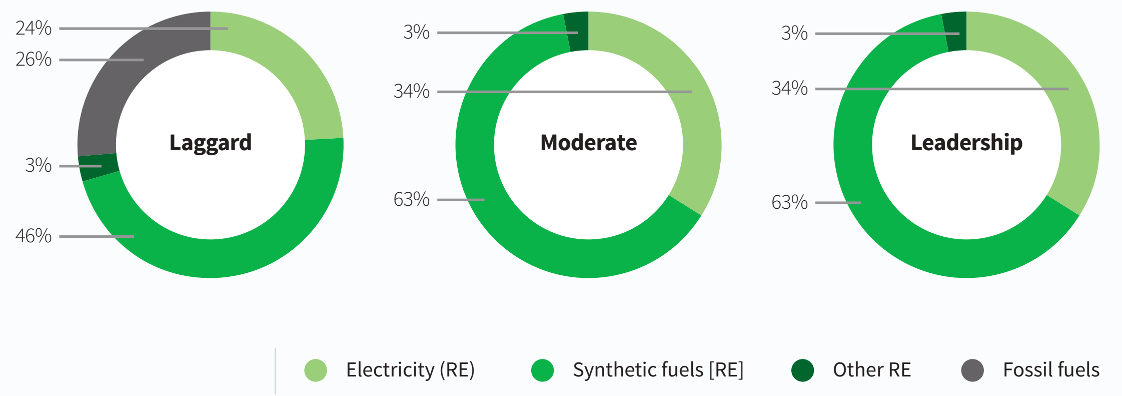


Source: SolarPower Europe.

Transport: A 100% renewable transport sector requires significant synthetic fuels for marine and aviation.

Responsible for almost a quarter of the European GHG emissions, the transport sector shows the lowest renewable energy shares compared to its peers. Only 5% of the energy needed for transport in Europe is provided by renewables in 2020. Direct electrification emerges as the most efficient solution to decarbonising road transport. On the other hand, in 2050, the aviation and marine sectors will heavily rely on renewable synthetic fuels (hydrogen, methane, and power-to-liquids) in the two 100% renewable scenarios, resulting in nearly two-thirds of final energy demand in that sector along with exports, while the Laggard scenario will still be sourcing over a quarter of its energy needs from fossil fuels.

FIGURE 0.6 TRANSPORT SHARE 2050

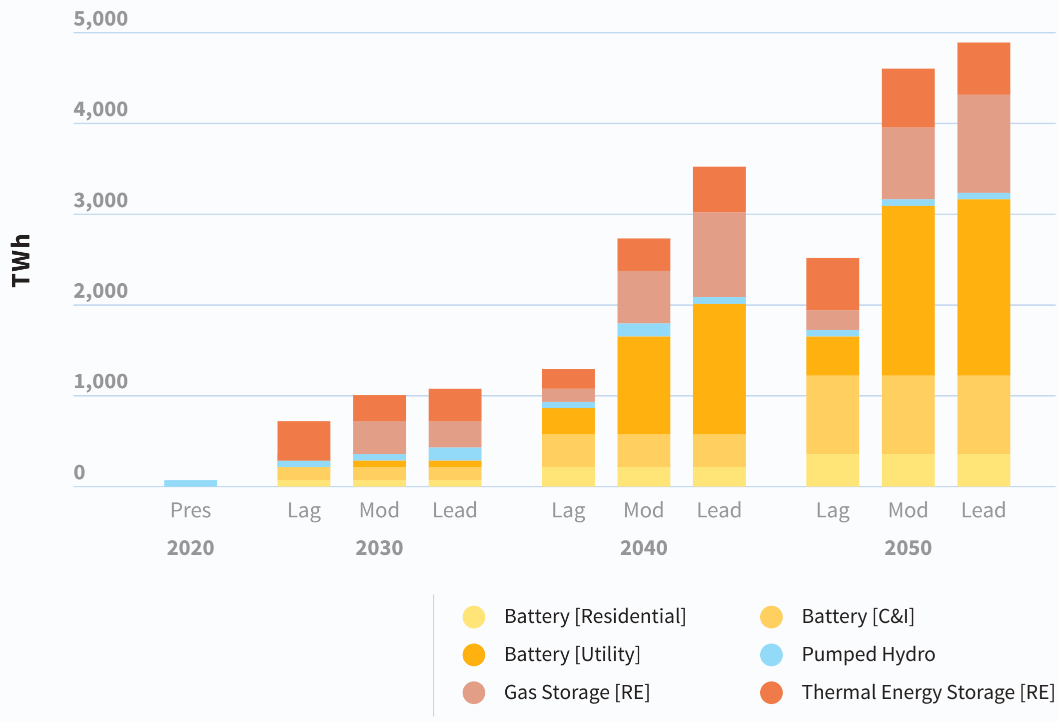


Source: SolarPower Europe.

Batteries provide the bulk of energy storage in a 100% renewable energy system.

Storage plays a critical role in the transition of the energy system towards high shares of renewables by providing stability and flexibility, and reducing curtailment to an economic minimum. Combinations of storage technologies cover the energy demand throughout the transition period, with batteries providing the bulk of storage needs, reaching shares between 67–70% depending on the scenario. Whereas gas and thermal storage technologies are mainly used in the heat sector, batteries are primarily used in the power sector. Storage technologies are an indispensable part of the energy transition, however, a highly integrated approach with full sector coupling and high electrification rates will deliver the most efficient and cost-effective energy system, keeping the growth of storage output up to approximately 25% of demand in 2050.

FIGURE 0.7 STORAGE OUTPUT



Source: SolarPower Europe.

A 100% renewable energy system is the most cost-efficient way to become climate neutral by 2050.

The cost of energy is a key deciding factor for determining the viability of energy scenarios and roadmaps. The vital question that remains is how much an ambitious energy transition to a system based on 100% renewables will cost. In short, it can overall be less expensive than a less ambitious scenario. The cumulative cost of achieving 100% renewable energy by 2050 in the Moderate scenario is 6% lower than the cost of inadequate action in the less ambitious Laggard scenario, which reaches only 62% renewables by 2050 and misses both the targets of European climate neutrality and the Paris Agreement.

However, the energy transition is not only about direct investments but also per-unit-generation cost. When looking at the levelised cost of energy in 2050, the two 100% renewable scenarios have LCOEnergy at €47/MWh, that is about 5–6% below the Laggard scenario's average level of €50/MWh, and at the same time about 7% more competitive than today's €51/MWh, showing that an accelerated energy transition towards 100% renewables is more cost effective than moving slowly. Capital costs increasingly dominate the LCOEnergy in all three scenarios, as fuel costs become less important throughout the transition period. In 2050, only the Laggard scenario cost structure contains a notable portion spent on fuels and costs for GHG emissions, as both of the other scenarios have reached the 100% renewable level.

FIGURE 0.8 CUMULATIVE ANNUAL SYSTEM COSTS

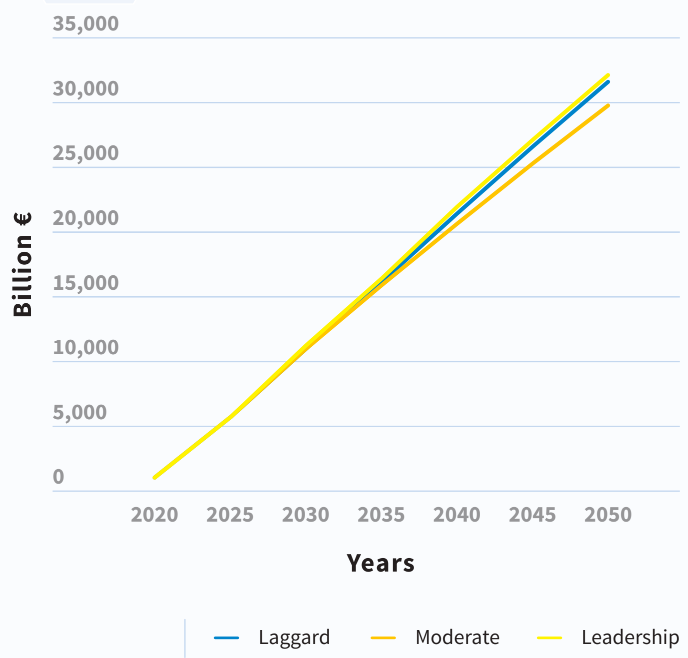
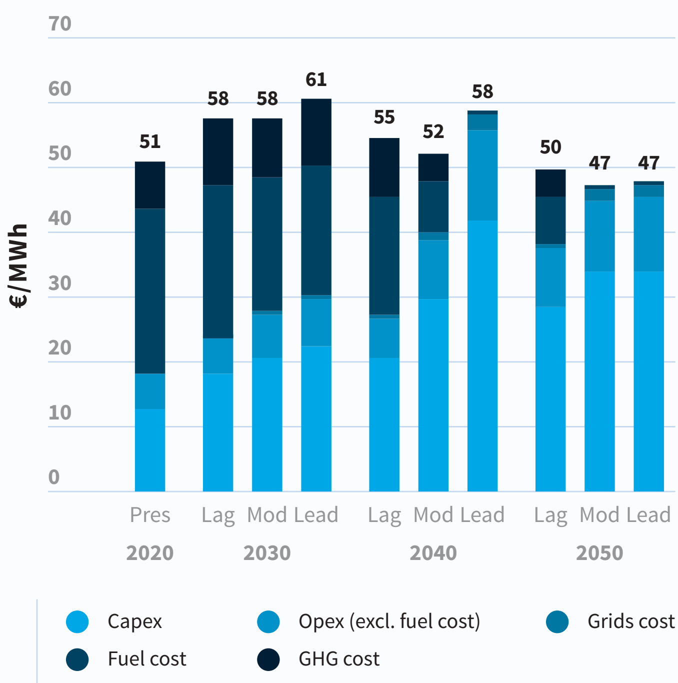


FIGURE 0.9 LEVELISED COST OF ENERGY



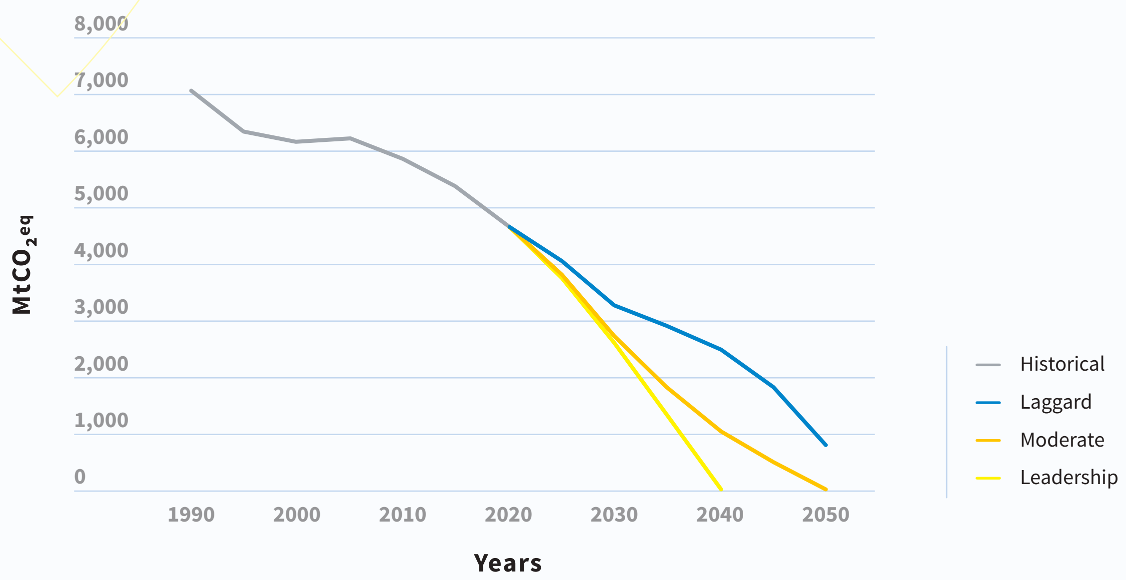
Source: SolarPower Europe.

A 100% renewable transition triggers the sharpest decline in GHG emissions.

An accelerated energy transition to a 100% renewable scenario not only means a faster decrease of power generation costs, but also results in a more important benefit: there will be a lower level of GHG emissions in Europe. Following the path of the 100% renewable scenarios (Moderate and Leadership), GHG emissions will decline by over 60% (from 1990) by 2030, and will be down to zero in 2050, or even 2040 in the Leadership scenario, which meets the EC's climate neutrality and Paris Agreement targets. In the least ambitious Laggard scenario, Europe reaches only 53% CO_2 emission reductions in 2030 and still emits around 800 million tonnes of CO_2 ($MtCO_{2eq}$) per year, thus missing both climate targets.

In summary, the results from this research project indicate that a low ambition pathway in Europe is a burden for society, from both a climate change and economic perspective. **The Moderate scenario modelling zero GHG emissions by 2050 appears to be the most economic pathway.** A highly ambitious climate change mitigation pathway is possible, which would result in 30% higher investments than for the Laggard scenario, but with the benefit of lower per unit energy costs as of 2050, and the promise of meeting the 1.5°C Paris Agreement target since no more GHGs will be emitted from 2040. Parts of the investments will even lead to energy exports and effectively result in negative CO_2 emissions.

FIGURE 0.10 GHG EMISSIONS



Source: SolarPower Europe.

1 INTRODUCTION

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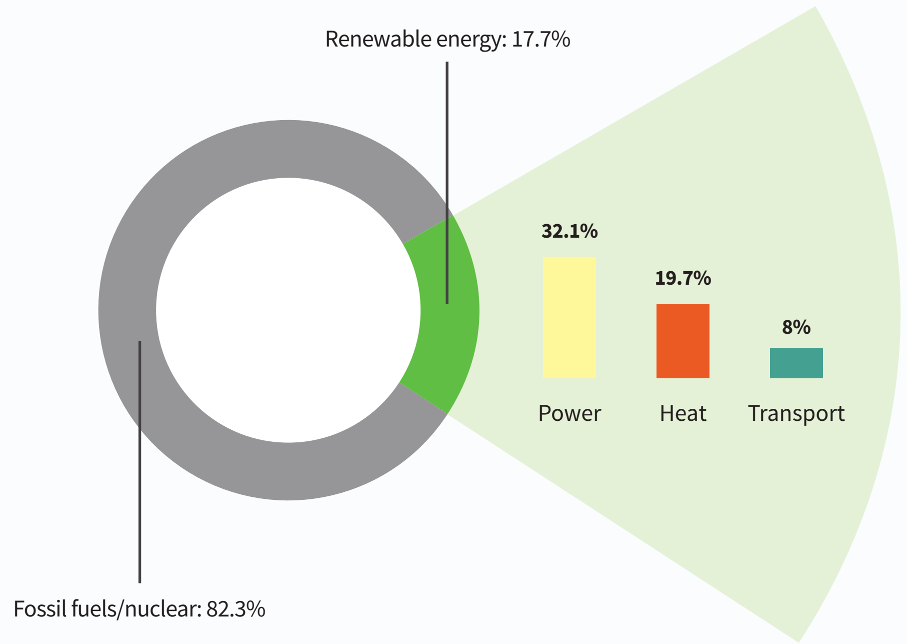
In her announcement of a Green Deal for Europe as the flagship initiative of European Commission (EC), President Ursula von der Leyen underlined the fact that the fight against climate change is a top priority for the European Union's executive body. As a longstanding pioneer in advancing the energy transition in previous years, Europe now strives to become the first climate-neutral continent by 2050. The Green Deal includes a large package of measures for which the details are currently being worked out, including a European 'climate law', the revision of Europe's 40% GHG reduction target by 2030 to 50-55%, and up to €100 billion in financing for the just transition to transform the EU economy in service of the EU's citizens and environment, in line with the ambitious objectives of the Paris Agreement. The EC also reaffirmed the crucial role of renewable energies in the Green Deal framework but did not specify clear targets for the development or deployment of renewable technologies. So far, the EC has examined nine scenarios that were modelled internally in 2018, well before the Green Deal was a core topic, and none of them target full climate neutrality of the energy system without resorting to carbon sinks.[1]

SolarPower Europe and LUT University (LUT) have set up a research project to better understand the role of solar in powering Europe's energy and industrial transition. Solar's share in Europe's electricity supply is only 5% today, but the technology's high versatility, strong public support, and rapidly increasing cost-competitiveness makes it a game changer.[2,3] With solar being the lowest-cost power generation source in many parts of Europe today, it already beats wholesale power prices in northern countries such as Finland, and has won many of the recent technology-neutral tenders across the continent. In 2019, more new solar capacity was installed in the EU than any other power generation technology, and newly added annual solar capacities more than doubled year-on-year.[4]

Recently, an increasing number of cities, states, and countries have committed to becoming climate neutral, and have even targeted 100% renewables. While the support to reach 100% renewables has grown in momentum – with over 60 countries and 300 regions around the world in 2019 – their time horizons to achieve this goal varies, as do their ambitions.[5] Most look at 2050 as a target year, some for 2040, and even a few for 2030. There are already over 50 sub-national regions that have reached their 100% renewables targets. However, the 100% renewables ambition is often not further specified, and if it is, it mostly refers only to the electricity sector, which is usually the most advanced, where progress is comparatively easy. A 100% renewables target that also includes transport, heating, and cooling is much less common.

However, no economy with the size of the EU has agreed to transition its entire energy system towards climate neutrality; this is a gigantic task taking into account the status of renewables in the EU (see Fig. 1.1). Despite the growth of renewables in the power sector across the EU to around 32% in 2018, the remaining energy sectors are lagging far behind. Heat consumption remains heavily based on fossil fuels, primarily gas, resulting in a renewables heat share of around 20%, of which the bulk, around 15%, comes from bio resources. In the transport sector, the renewables share is even lower, at 8%.* Energy for the transport sector – including road, rail, marine, and aviation – makes up nearly 40% of the EU's final energy demand. Despite gains in efficiency, the transport sector accounts for two-thirds of overall oil consumption, since all dominant transport technologies rely on fossil oil-based fuels. Moreover, it is both the largest individual sector in terms of overall EU GHG emissions, and the only sector with rising emissions.

FIGURE 1.1 EU RENEWABLE ENERGY SHARE IN 2018



Source: SolarPower Europe.

* These values slightly differ from the 2020 renewable energy shares in power, heat and transport used in the study because the energy system model used in this study looks at Europe as a whole continent.

However, there are several technical solutions available for decarbonising the heat and transport sectors that are being increasingly applied. For the heat sector, renewable energy can serve thermal demand when supplied by electricity, either directly or using heat pumps.[6] Further, the electrification of heating is on the rise – for example, using wind electricity for Power-to-Heat applications or heat pumps in district heating. There is also the trend of using electricity from solar PV for heat to increase self-consumption rates in the face of reductions in feed-in tariffs and rising retail electricity prices.[6] District heat systems supply about 11% of global space and domestic hot water heating and are particularly suitable for use in densely populated regions.

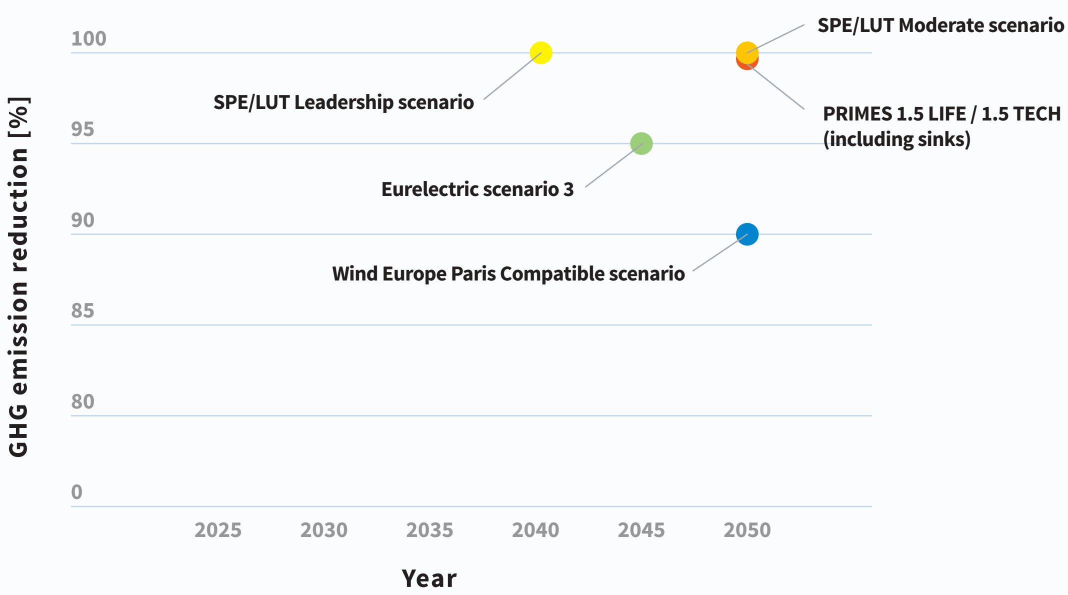
The movement towards electrification in the transport sector is also starting to gain momentum.[7] Global sales of electric vehicles (EVs) reached over 2.2 million in 2019, translating into an average of 2.5% market share (1 in 40 new cars), which indicates that the growth of EV sales is accelerating.[8] Likewise, the marine sector has options to replace existing fuels with a range of increasingly available alternative fuels, such as biofuels in the near term, and renewable electricity-based synthetic fuels – such as synthetic natural gas, Fischer-Tropsch-based fuels or hydrogen – in the long term (for technology explanations, see Box 3, p. 38).[9] The production and use of sustainable aviation fuels, specifically bio-based jet fuel or synthetic jet fuel, apart from direct electrification for short-distance flights, can propel the aviation sector towards greater sustainability.[10] The rail sector already has a high share of electricity use, and is well underway of reaching maximum electrification.[11] In addition, synthetic fuels, including hydrogen and biofuels, could cover the non-electrified rail transport.

The research study by LUT and SolarPower Europe envisions different energy system transition pathways for Europe as a continent, with varying levels of ambition. It analyses the development of the European energy system in three scenarios: (1) Laggard scenario, modelled on one of the earlier EC scenarios in which GHG emissions from the energy sector are reduced by 80-95% below 1990 levels in 2050; (2) a Moderate scenario, in which GHG emissions reach zero by 2050; and (3) the Leadership scenario, in which GHG emissions reach zero by 2040.

This report also offers a new perspective to the discussion on how to enable a true European Green Deal. No other report that has modelled decarbonisation scenarios for the European energy system has been as ambitious as this one; no existing study explores a 100% renewable energy scenario in Europe without carbon sinks, nor models a 100% renewable energy scenario for Europe by 2040.

SolarPower Europe and LUT hope this report offers new insights and provides a valuable contribution to the ongoing critical policy debates on the energy transition, thus ensuring that the European Green Deal truly delivers on a fully climate-neutral EU.

FIGURE 1.2 EU BENCHMARK

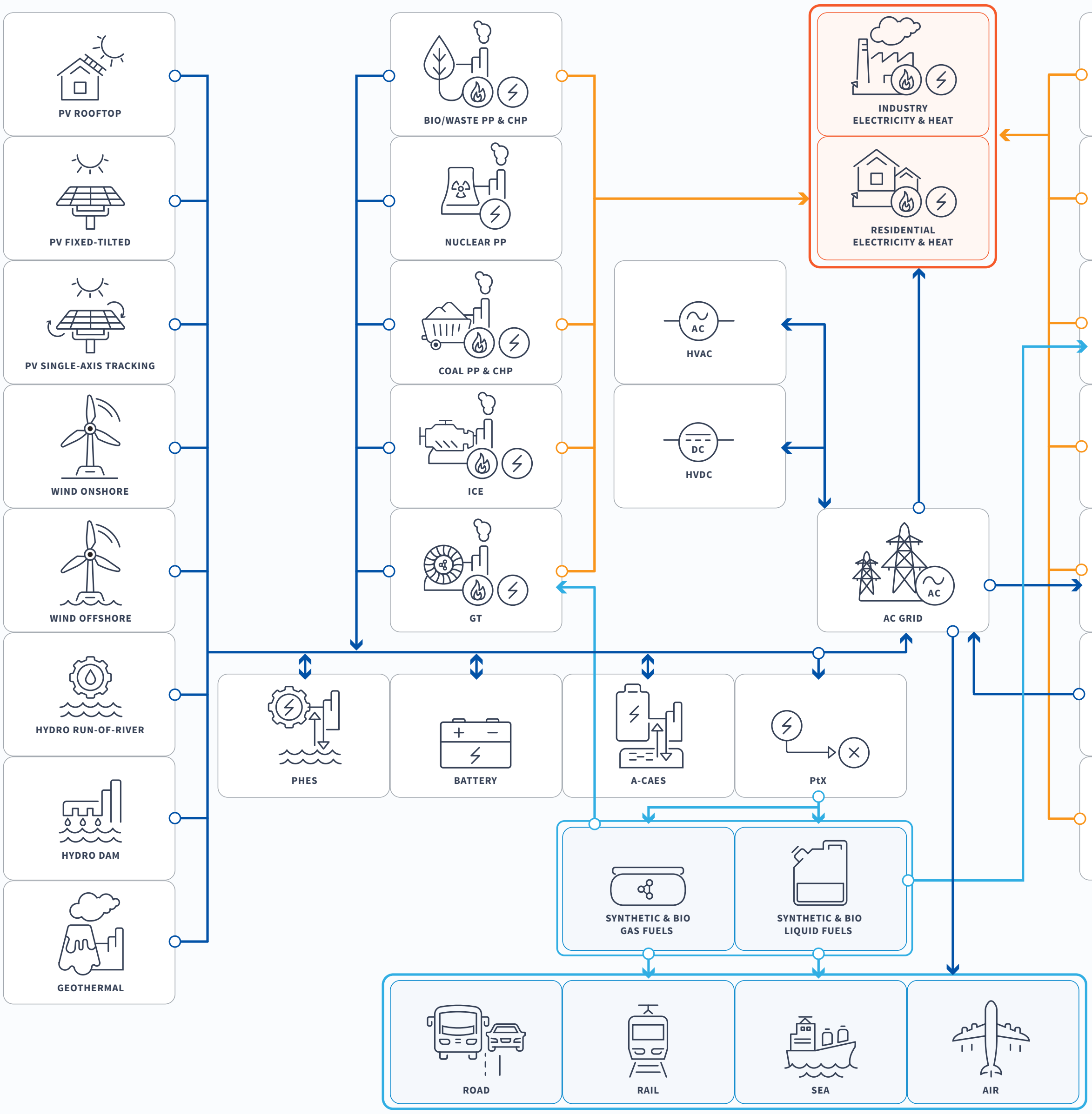


Source: SolarPower Europe.

2 METHODOLOGY: MODELLING THE INTEGRATED EUROPEAN ENERGY SYSTEM TRANSITION

The LUT Energy System Transition model[12,13] is applied across an integrated energy system covering demand from power, heat, and transport sectors (see Fig. 2.1), which enables **the modelling of cost-optimal energy system transition pathways on high levels of geo-spatial (20 regions in Europe) and temporal (hourly) resolutions**. The capability to model in an hourly resolution for an entire year allows for crucial insights to be uncovered, particularly with respect to storage and flexibility options. In order to reflect the versatility of solar PV, the model includes distributed PV rooftop systems and utility-scale PV installations, both using fixed tilted mounting structures and single-axis tracking technology, which is today frequently applied in sunny regions as it enables solar modules to follow the course of the sun in one direction, thus significantly increasing yield.

FIGURE 2.1 SCHEMATIC REPRESENTATION OF THE LUT ENERGY SYSTEM TRANSITION MODEL



Source: SolarPower Europe.

The simulations are carried out in a two-stage approach. In the first stage, the prosumer simulations determine a cost-effective share of prosumers across Europe through the transition from 2020 to 2050, in five-year intervals.[14,15] In the second step, the energy modelling takes place: the model integrates all crucial aspects of the power, heat, and transport sector demands, while the non-energetic feedstock for industry is not included. For every time-step, the model defines a cost-optimal energy system structure and operation mode. The target of the optimisation is minimising the total system cost.

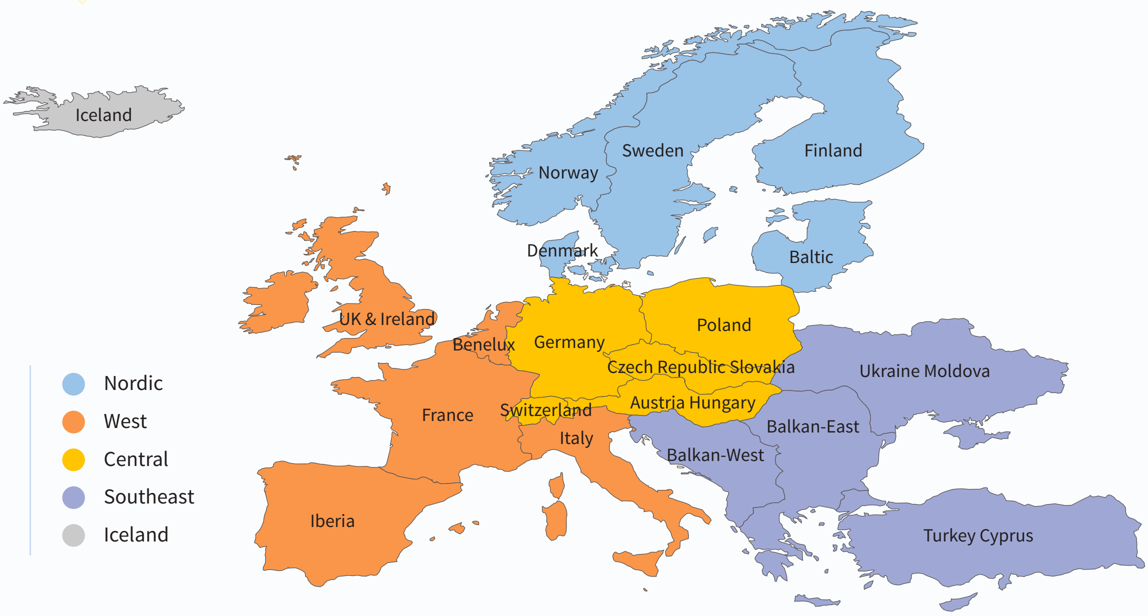
Regional setup: Europe

The energy system transition has been carried out for Europe (except Russia and Belarus), which is structured into 20 sub-regions consisting of smaller countries that have been merged with larger countries to form sizeable local units, as the energy transition is envisioned on a regional basis. The sub-regions are further grouped into four macro regions and Iceland. The composition of the regions is as follows:

- Nordic: Norway, Denmark, Sweden, Finland, and a Baltic region that includes Estonia, Latvia, and Lithuania;
- West: Iberian Peninsula region – with Portugal, Spain and Gibraltar; France, together with Monaco and Andorra; Italy, together with San Marino, Vatican City, and Malta; British Isles region – comprised of the United Kingdom and Ireland; Benelux region – comprised of Belgium, the Netherlands, and Luxembourg;
- Central: Germany, Poland, a region comprising Czech Republic and Slovakia, a region with Austria and Hungary, and a region with Switzerland and Liechtenstein;
- Southeast: A region that includes the Western Balkan countries – Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Kosovo, and Albania; a region including the Eastern Balkan countries – Romania, Bulgaria and Greece; a region with Ukraine and Moldova, and a region with Turkey and Cyprus;
- Iceland, as an isolated region.

The 20 regions are interconnected with optimised transmission networks and Iceland is considered as an isolated region. Cost optimised transition pathways for an integrated European energy system are modelled for three distinct scenarios.

FIGURE 2.2 EUROPE – REGIONAL COMPOSITION



Source: SolarPower Europe.

Scenarios: Laggard, Moderate, and Leadership

The objective of this project is to highlight energy scenarios for Europe, in the context of achieving the goals of the Paris Agreement – reaching net zero GHG emissions from the energy sector – in a technically-feasible and economically-viable manner. Three distinct scenarios are envisioned for an integrated energy sector, combining the power, heat, and transport demands for the case of Europe, from the current system in 2020 towards cost-optimal energy systems with varying features by 2050 (see Fig 2.3).

Laggard scenario:

- In this scenario, the European energy system is set on a minimum ambition pathway.
- Current and upcoming fossil fuels and nuclear power plants are not phased out and continue operating until end of technical lifetime.
- In the transport sector, a slower rate of electrification of road transport leads to longer presence of internal combustion engines (ICE) in road transport by 2050. Fuels for marine and aviation transportation are still 50% fossil by 2050 due to delayed transition.
- Substantial new nuclear power plants, but also new fossil plants are added to the system according to scenarios of the European Commission (EC).[16]
- The EC's vision of climate neutrality by 2050 is not achieved.
- Medium GHG cost development is considered with present values in 2020 to €150/tCO_2 by 2050.
- Finally, the ambitious goal of the Paris Agreement – limiting mean global temperature rise to below 1.5^{0}C – is not achieved.

.

Moderate scenario:

- In this scenario, the European energy system is set on a medium ambition pathway.
- Current fossil fuel power plants are phased out by 2050 and no new nuclear power plants are considered, with existing and under construction plants operating until the end of their technical lifetimes.
- New coal plants are not allowed due to climate regulation, whereas new gas-fired power plants are allowed, but with the obligation to switch to non-fossil fuels during the transition.
- The EC's vision of climate neutrality by 2050 is achieved, as GHG emissions are zero in 2050.
- Medium GHG cost development is considered with present values in 2020 to €150/tCO_2 by 2050.
- Finally, the less ambitious goal of the Paris Agreement – limiting mean global temperature rise to below 2^{0}C – is more likely achievable than the more ambitious target of 1.5^{0}C.

Leadership scenario:

- In this scenario, the European energy system is set on a high ambition pathway.
- Current fossil fuels and nuclear power plants are phased out by 2040, and no new plants are considered.
- New gas-fired power plants are allowed, but with the obligation to switch to non-fossil fuels before 2040.
- The EC's vision of climate neutrality by 2050 is achieved a decade early, as GHG emissions are down to zero by 2040.
- High GHG cost development is considered with present values in 2020 to €200/tCO_2 by 2040. Finally, the ambitious goal of the Paris Agreement – limiting mean global temperature rise to below 1.5^{0}C – is likely to be achieved.

FIGURE 2.3 SCENARIO OVERVIEW

	LAGGARD	MODERATE	LEADERSHIP
RE energy share	62% by 2050	100% by 2050	100% by 2040
Paris Agreement	⊗	Achieved 2.0°c	Achieved 1.5°c
GHG emissions in the energy system	-90% in 2050	-100% in 2050	-100% in 2040
Fossil fuels phaseout	⊗	Achieved in 2050	Achieved in 2040
Nuclear phaseout	⊗	⊗	Achieved in 2040

Source: SolarPower Europe.

3

RESULTS

3.1 Integrated energy system transition across Europe

Looking at the state of Europe's energy system in 2019, we see a continent that is still in the early stages of its energy transition. To become climate-neutral by 2050, Europe must transition from today's decoupled state of the power, heat, and transport sectors, largely based on non-renewable energy sources, towards an integrated energy system with renewable electricity at its core. This report assumes an increasing rate of sector coupling over the next 30 years, leading to a highly integrated energy sector by 2050, though with varying levels of efficiency gains across the three scenarios.

In all three cases, the evolution of European energy demand from 2020 to 2050 depends on several key factors:

- The **level of sector coupling** between the power, heat, and transport sectors depends on the adoption of different technologies. The greater the amount of Power-to-X technologies (power to heat, fuel, gas) the higher the degree of sector coupling.
- The **rate of electrification** in the heat and transport sectors depends on the adoption of heat pumps with electric heating, and a technological shift from ICE engines to electric powertrains.
- The **adoption rate of synthetic fuels** (methane, hydrogen, and FT fuels) is primarily based on electricity and thus on the electrification level.[17]

Primary Energy Demand

In 2020, primary energy demand in Europe is covered to a large extent by fossil fuels with an estimated share of 86%, while the rate of renewable electricity is very small (for definitions of primary energy supply, demand, see Box 1, p. 28). As the energy system transitions toward larger shares of renewables over time and 100% for two of the scenarios by 2050, a strong electrification trend can be observed across all three scenarios (see Fig. 3.1). In the Laggard scenario, the energy sector reaches 51% electrification by 2050, while in the Moderate scenario, the energy sector is 85% electrified by 2050. In the Leadership scenario, rapid electrification of 85% is already achieved in 2040, and continues to increase beyond then. This enables Europe to become an exporter of renewable-based synthetic fuels once the 100% renewables level is reached as of 2040, adding to the primary energy demand and raising the level of electrification to 86% by 2050.

On the contrary, energy from fossil fuels and nuclear decline to zero by 2040 in the Leadership scenario, and nearly zero by 2050 in the Moderate scenario, as a few nuclear power plants will be still in service. In comparison, the Laggard scenario will have a considerable amount of fossil and nuclear power plants in operation, contributing to a share of around 38%.

From a sectoral point of view, the primary energy demand for the transport sector grows across the three scenarios through the transition – around 1,200 TWh for the two 100% scenarios but over 3,100 TWh for the Laggard scenario (see Fig. 3.2). This is mainly due to the demand for synthetic fuels in the aviation and marine sectors; the larger demand for the least ambitious scenario is due to the existing fossil fuel-based transport options. At the same time, primary energy demand for the heat and power sectors declines across the board because of the higher efficiency of electrification, whereas the reduction is much more significant for the 100% scenarios in 2050 due to a higher electrification rate.

FIGURE 3.1 PRIMARY ENERGY DEMAND - FUEL USE

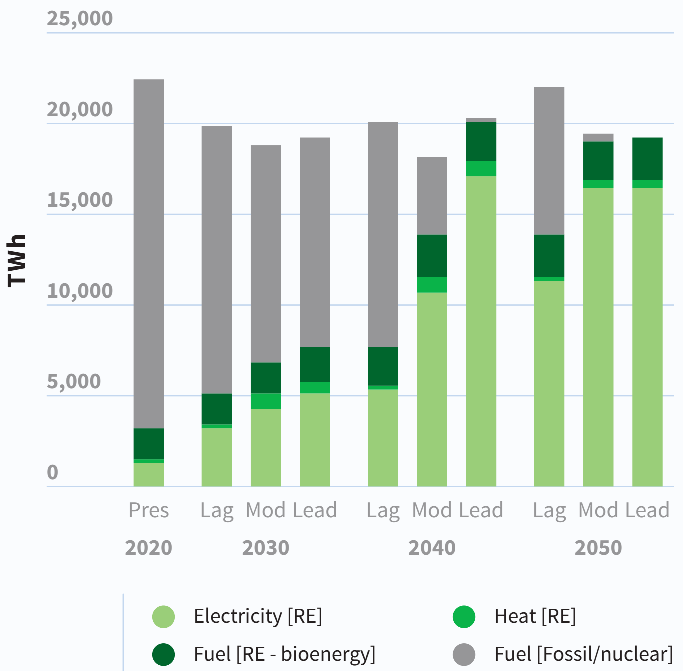
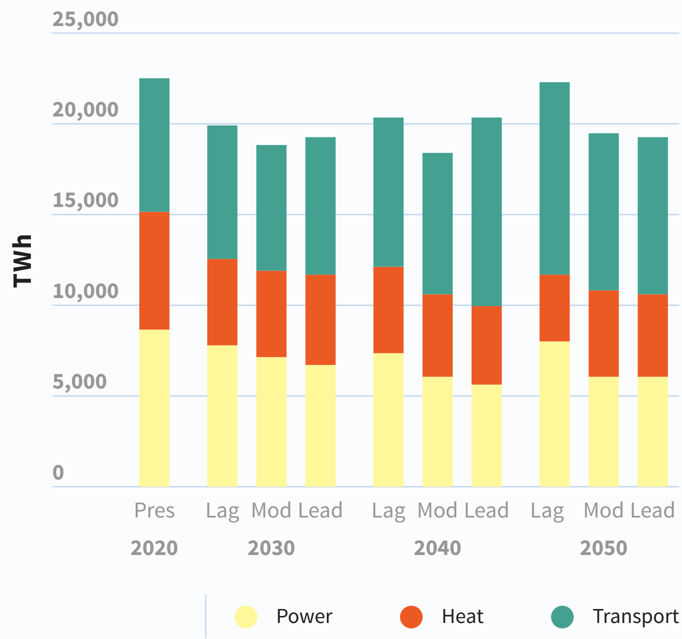


FIGURE 3.2 PRIMARY ENERGY DEMAND - SECTOR



Source: SolarPower Europe.

BOX 1. THE EVOLUTION OF PRIMARY AND FINAL ENERGY DEMAND OF THE EUROPEAN ENERGY SYSTEM OVER THE COURSE OF THE ENERGY TRANSITION

Up until today, **primary energy demand** (see Fig. 3.1) in Europe is represented largely by a **fragmented energy system**, which is dominated by fossil fuels that are inefficiently converted to electricity for the power sector, heat for applications in the heat sector, and as combustible fuels for energy in the transport sector. Over the course of the energy transition, primary energy demand evolves to represent an **increasingly integrated energy system** enabled by electrification and sector coupling.

Electrification is primarily driven by the switch from fossil fuels and nuclear based electricity generation to renewable-based electricity in the power sector, internal combustion engines to electric powertrains in the transport sector, and electric heating coupled with geothermal heat pumps in the heat sector. Sector coupling enhances the efficient operation of the energy system, which is driven by power-to-gas, power-to-heat, and power-to-fuels.

Renewable-based electricity, which is a primary source of energy, emerges as the key energy carrier. It is utilised for electricity in the power sector, generating heat applicable in the heat sector and providing electricity for direct use as well as production of synthetic fuels (hydrogen, methane, and FT fuels, which are liquid fuels such as diesel and kerosene) for the transport sector and high temperature applications in the heat sector.

Renewable electricity-based hydrogen emerges as the second most important energy carrier through the transition, mainly used for the production of synthetic fuels. Natural heat from the environment in the form of geothermal heat, and bioenergy from biomass and organic waste, also provide some shares of primary energy for electricity, heat, and transport use.

High levels of efficiency gains from electrification and sector coupling enable a decrease in the primary energy demand of an integrated energy system by 2050. This is captured by the **final energy demand** (see Fig. 3.3), which represents the energy needs of consumers. In the current decoupled and fossil fuel-heavy energy system, a higher level of primary energy is required to meet final energy demand, whereas in a highly electrified and integrated energy system, a lower level of primary energy is required to satisfy final energy demand, which in 2050 will be essentially at the same level as today.

Final Energy Demand

The efficiency is significantly higher for power-based applications: an electric vehicle, for example, has a power-to-wheel efficiency of up to 85% compared to an internal combustion engine car with a fuel-to-wheel efficiency of up to 30%. (see Box 2, p. 30). **In other words, the penetration of renewables is not just a matter of replacing hydrocarbons with zero-carbon sources of energy supply, it also represents a significant change in resource efficiency**. This is illustrated in the development of final energy demand in Europe, where an increasing electrification rate across the power, heat, and transport sectors, keeps energy demand almost steady in the high electrification/100% renewable energy scenarios through the entire transition phase until 2050 (see Fig. 3.4 b).

Final energy demand can be kept stable despite a continous growth in energy services, which is reflected by the growth in power and heat demand. In contrast, final energy demand from the transport sector decreases, despite a 2.2% annual growth in terms of passenger and 1.5% annual growth in freight travel over the next 30 years (see Fig. 3.4). The explanation for this decreasing demand is the high effiency of electrification, which is represented in the transport sector through the large share of electric vehicles in 2050.

The changing shares in the final energy demand for the different energy carriers ('fuel use') is also influenced by growing electrification rates, directly and indirectly (see Fig. 3.3). While the final energy demand for electricity and heat grow their shares across the three scenarios, there is less need for fuels, as gasoline and other fossil fuels will be replaced by renewable energy-based electricity and heat, sustainable synthetic fuels, and some shares of biofuels.

FIGURE 3.3 FINAL ENERGY DEMAND - FUEL USE

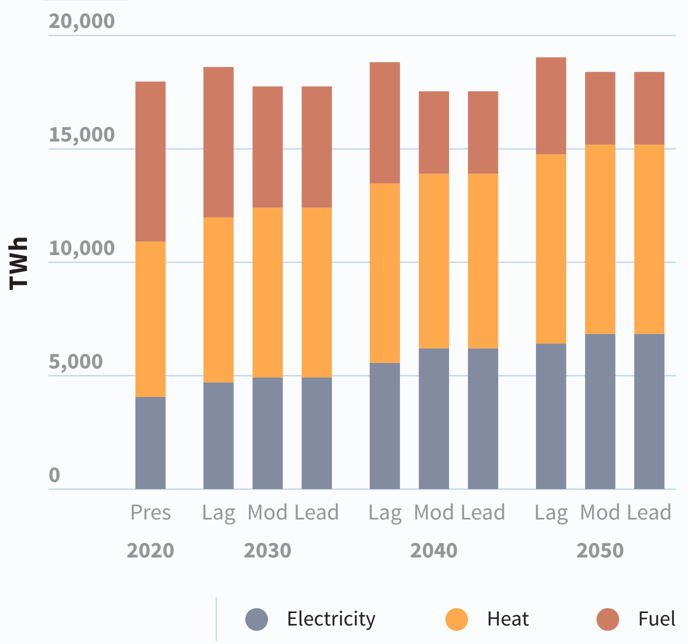
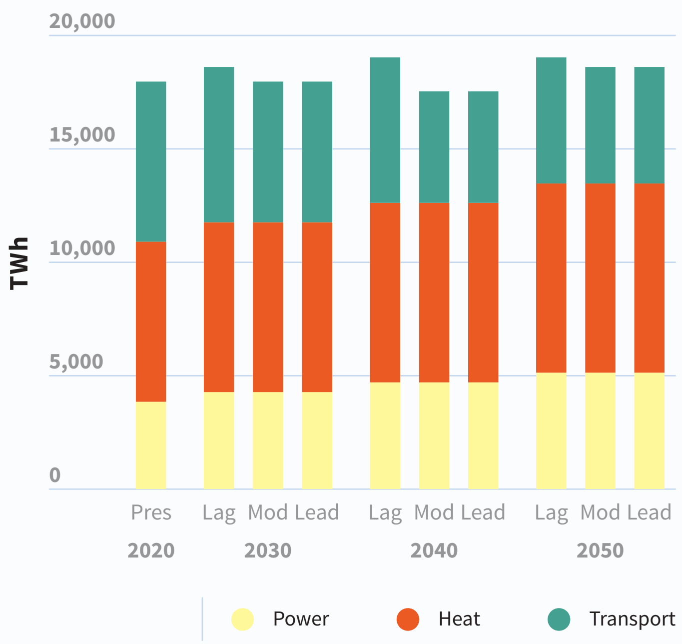


FIGURE 3.4 FINAL ENERGY DEMAND - SECTOR



Source: SolarPower Europe.

BOX 2. UNDERSTANDING THE EFFICIENCY GAINS FROM ELECTRIFICATION AND SYSTEM INTEGRATION

Switching from today's energy system dominated by fossil fuels to a fully renewable-based energy system means unlocking a tremendous efficiency potential.

In the **power sector**, fossil-fuelled power plants are inefficiently converting hydrocarbons into electricity. Their efficiencies typically range from 37% to 60%, depending on the fuel and power plant type. Similarly, uranium enrichment for nuclear electricity production is a highly inefficient process, in which only 35% of the energy in the uranium fuel is transformed into electricity, while the remaining 65% is lost, and further energy is required in mining and processing uranium, which finally increases the total loss. Conversely, renewable-based electricity allows for a more efficient use of energy compared to using conventional sources. The energy output of direct renewable electricity sources, such as solar PV, wind electricity, and hydropower, is 100% primary energy, according to international standards.

In the **heat sector**, conventional energy supply achieves higher efficiencies – combined heat and power (CHP) can go beyond 80% efficiency, whereas a gas boiler has an efficiency close to 100%. However, the use of heat pumps allows for much higher efficiencies, referenced to the electricity input, since additional heat is taken from the environment as part of the process. For this reason, their efficiency, called coefficient of performance, is usually in the range of 3 to 4 (or 300 to 400%), as the heat supplied is higher by this factor than the electricity required.

Electrification is a strong efficiency trend also in the **transport sector**. Internal combustion engines (ICE) used in conventional cars have an average annual efficiency of 20-30%, because a significant portion of energy is lost as waste heat. In contrast, electric vehicles achieve a much higher efficiency than conventional cars – the efficiency of an electric motor is around 85%, with regeneration allowing energy to be saved from deacceleration (so called regenerative braking), which not only further increases efficiency, especially in urban terrains, but also has the positive side effect of increasing the lifespan of the car's brakes as the mechanical parts wear out more slowly. Electricity-based production of synfuels enables indirect electrification of the heat and transport sectors. Electricity, water, and air can be converted to synthetic hydrocarbon fuels, such as jet fuel, for an average efficiency of around 50%, which is only slightly less than converting raw biomass into refined biofuels.

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To highlight the efficiency gains from increased levels of electrification, the three scenarios are compared to a low electrification scenario where primary energy demand grows through the transition with the same levels of energy use and technologies as of 2020. While the Laggard scenario with a significantly lower electrification rate shows a 29% reduction in primary energy demand by 2050 compared to the low electrification scenario, the highly – and in 2050 almost equally – electrified Moderate and Leadership energy systems need 38% and 39% less primary energy, respectively (see Fig. 3.5).

The operational efficiency of highly electrified systems can be also be shown indirectly by the ratio of final energy demand to primary energy demand (see Fig. 3.6). From the current levels of around 80% (based on system efficiency), the Laggard scenario reaches a ratio of 86% by 2050, whereas the Moderate scenario reaches a level of 95% by 2050. The most electrified Leadership scenario also achieves the highest efficiency ratio of 96% by 2050. This means that energy systems with high shares of renewables will have higher conversion efficiencies, delivering a multitude of energy services with lower levels of primary energy input.

FIGURE 3.5 EFFICIENCY GAINS FROM INCREASED ELECTRIFICATION

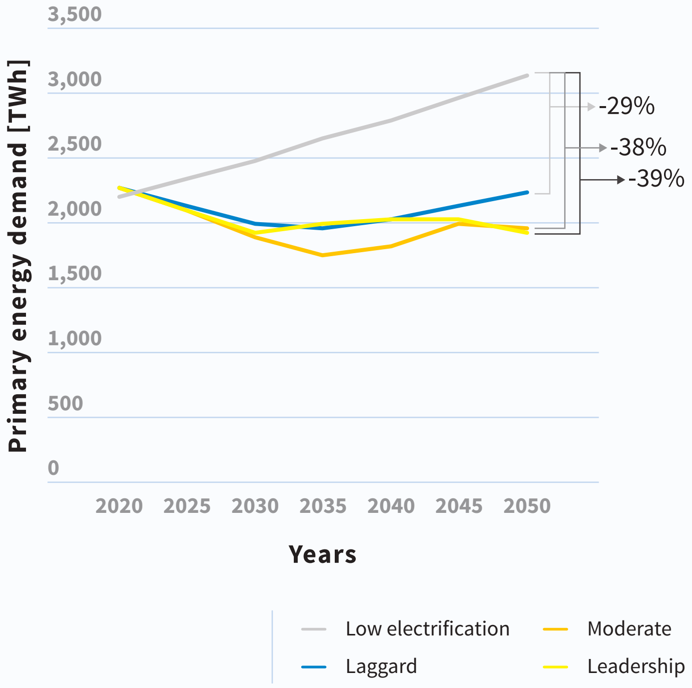
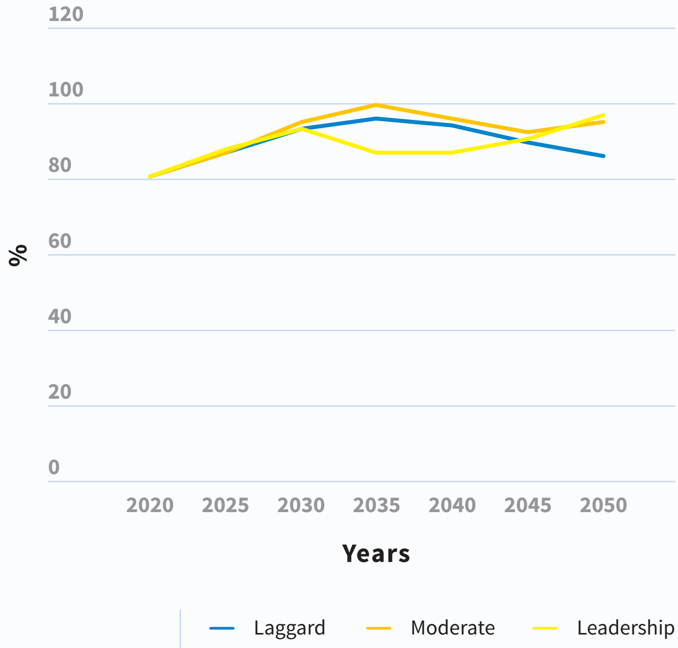


FIGURE 3.6 RATIO OF FINAL ENERGY TO PRIMARY ENERGY



Source: SolarPower Europe.

Primary energy supply

A view on the energy supply side shows Europe's share of renewable energy is only around 14%, or 3,200 TWh, today. Europe is heavily dominated by fossil fuels in 2020, which provide around 72% of the energy output, equal to 16,300 TWh per year. In line with the rapidly increasing electrification of the energy system, the share of renewable energy grows substantially – up to 100% through the transition period – but with varying pathways across the three scenarios.

The Leadership scenario displays a rapid transition pathway for Europe, in which renewables supply 100% of energy by 2040. From that year, renewables continue to provide Europeans with clean energy in a fully integrated energy system through to 2050 and beyond. In the Moderate scenario, the share of renewable energy grows at a steady rate to almost 100% by 2050. In fact, the share will be 99% in 2050 as there will be a few remaining nuclear power plants that will gradually be phased out. In contrast, the Laggard scenario shows renewable energy being on a low-growth trajectory, reaching a primary energy supply share of around 62% by 2050, with the remainder of energy coming from nuclear and fossil fuels.

Sectoral Outlook

Renewable penetration is very different for the power, heat, and transport sectors in Europe, and so are the trends that will emerge over the next 30 years in the three scenarios. As all energy sectors transition towards higher shares of renewables in the energy supply mix, different technologies take on different roles and responsibilities in ensuring the operational stability of the integrated energy system.

FIGURE 3.7 PRIMARY ENERGY SUPPLY - FUEL USE

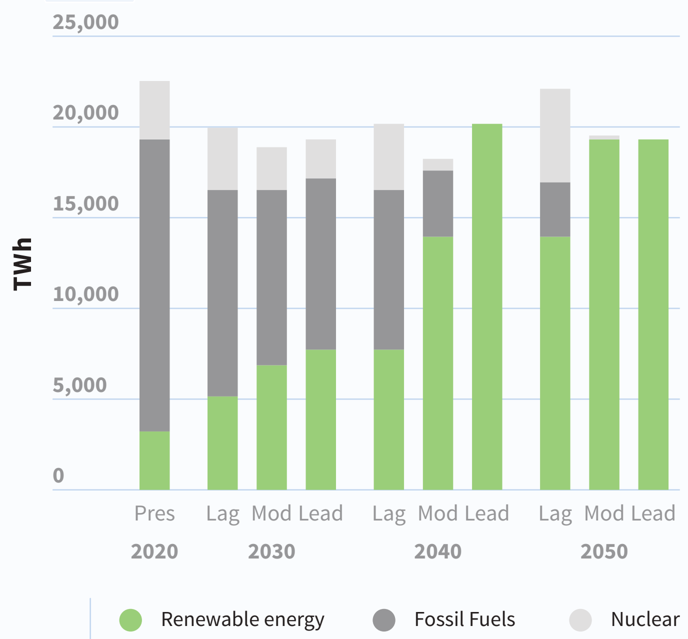
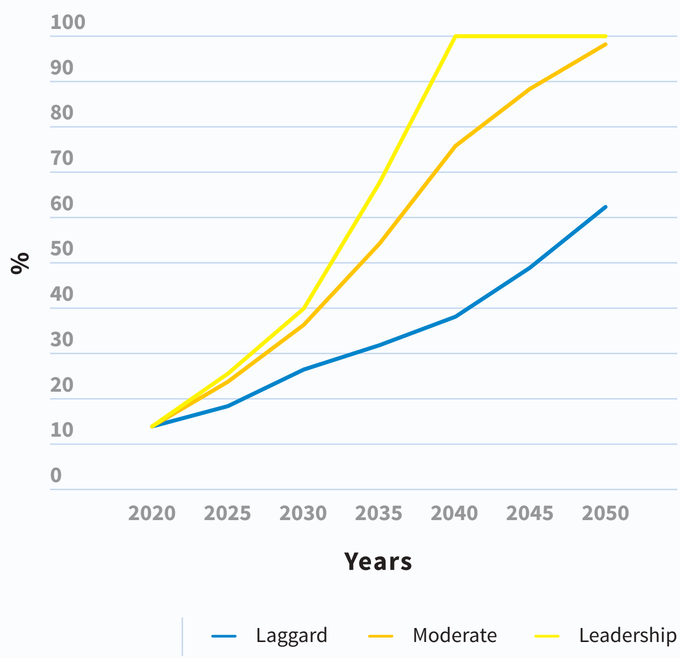


FIGURE 3.8 RENEWABLE ENERGY SHARE OF PRIMARY ENERGY SUPPLY



Source: SolarPower Europe.

Power

The power sector is a shining example in the energy transition across Europe, with around 34% of electricity being generated by renewables in 2020. According to the modelling results, the growth of renewable energy continues across all scenarios, though in varying levels of installed capacities and electricity generation.

Increased levels of electrification will lead to higher levels of renewable power generation and corresponding generation capacities for all scenarios, and the two pillars will be solar and wind. Already in the last few years, solar and wind were responsible for adding the largest volumes of all power generation sources in the EU-28; last year, solar overtook wind, adding nearly 17 GW, compared to 13 GW of wind. The modelling results of this report assume this trend will continue, but at a dramatically higher speed.

In 2050, solar PV alone has installed capacities between 4.7 TW in the Laggard scenario, 7.7 TW in the Moderate scenario and 8.8 TW in the Leadership scenario. This would mean solar capacity will reach shares of 72%, 78%, and 77% (see Fig. 3.10).

Whereas solar capacities are already much higher than wind in 2030 across all scenarios, wind energy still delivers the highest share of electricity in 2030 in two out of three scenarios, due to better capacity factors. Backed by its cost competitiveness, versatile solar PV emerges as the prime source of electricity as of 2040. Ten years later, solar PV will generate across all scenarios at least half of the power – that is, 48% of electricity in the Laggard scenario, around 61% in the Moderate scenario, and over 63% in the Leadership scenario (see Fig. 3.9).

FIGURE 3.9 ELECTRICITY GENERATION

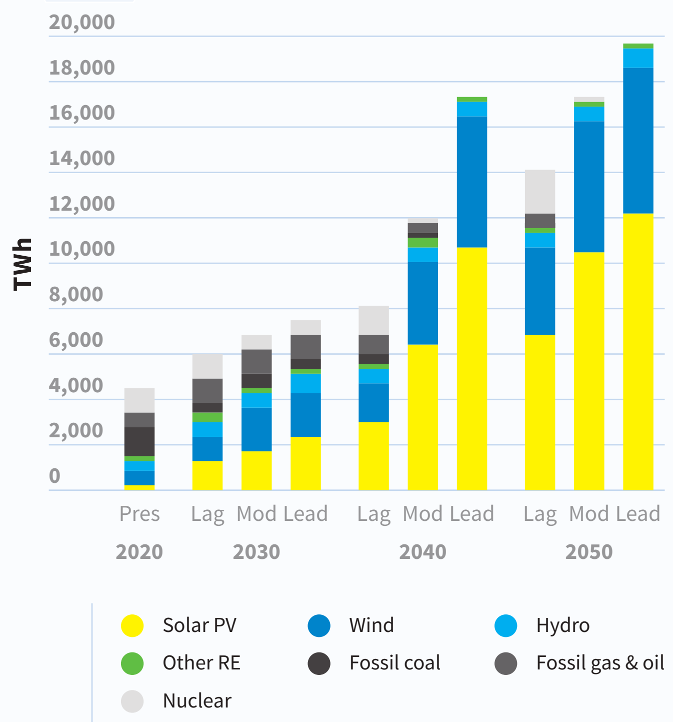
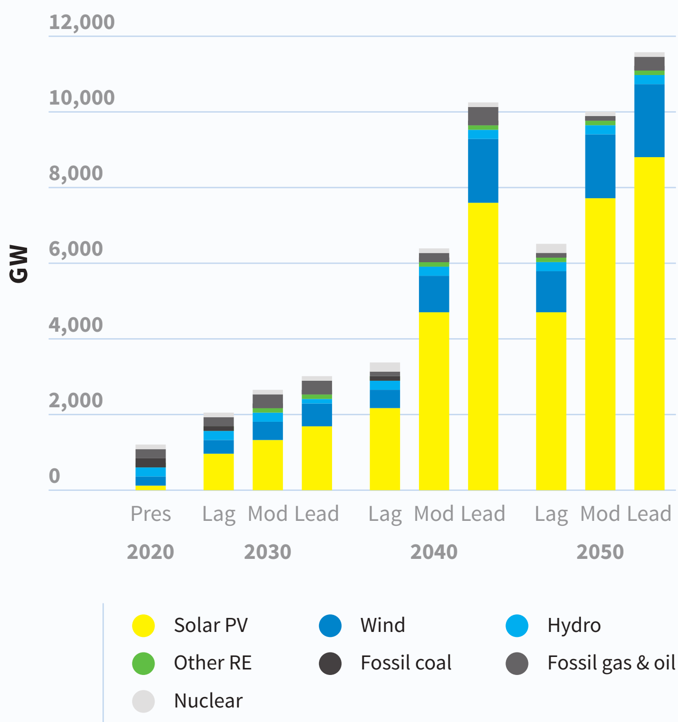


FIGURE 3.10 ELECTRICITY INSTALLED CAPACITY



Source: SolarPower Europe.

Electricity Storage

As the share of variable energy sources (solar and wind) increases significantly beyond 2030, the role of electricity storage becomes crucial in providing an uninterrupted energy supply; this is the case across all scenarios, although the needs are higher for the two 100% scenarios in 2050. This is documented through the ratio of electricity demand covered by electricity storage, which increases through the transition to 15% in the Laggard scenario, 24% in the Moderate scenario, and about 20% in the Leadership scenario by 2050. At first glance it is surprising that the Leadership scenario needs less storage than the Moderate scenario. However, this is due to the much faster uptake of renewables and the phasing out of fossil fuels and nuclear with a higher level of sectoral integration (see Fig. 3.13).

The bulk of electricity storage output will be supplied by prosumer and utility-scale batteries with over 97% by 2050, while pumped hydro energy storage (PHES) will contribute only minor shares (see Fig. 3.12).

FIGURE 3.12 ELECTRICITY STORAGE OUTPUT

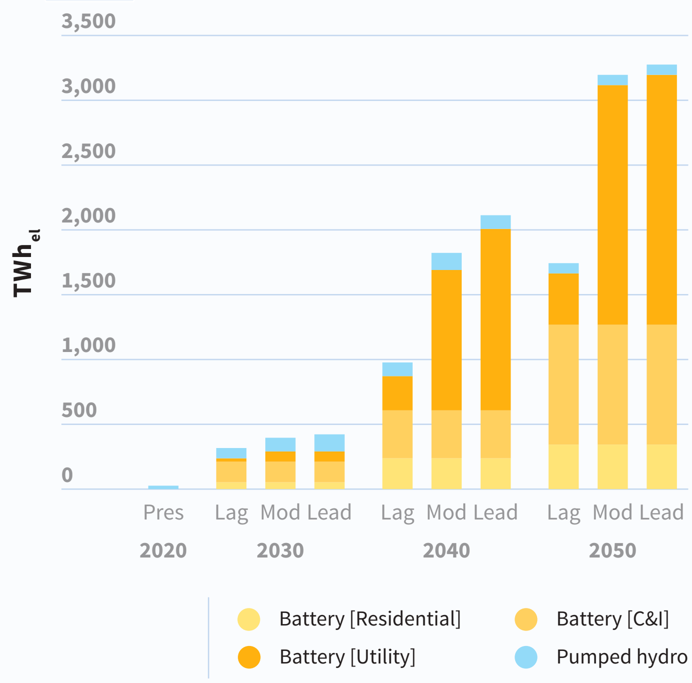
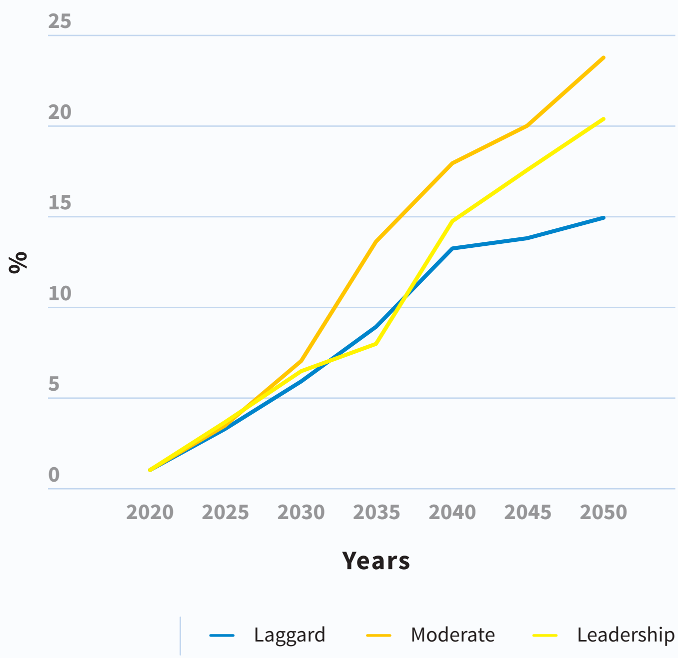


FIGURE 3.13 RATIO OF ELECTRICY STORAGE OUTPUT TO DEMAND



Source: SolarPower Europe.

Heat

Heat is mainly used for space heating, domestic hot water, and industrial processes in Europe. The share of renewables in the heat sector is much less than for power – in 2020, only about 23% of heat is provided by renewables, mostly from bioenergy. Today's heat market is strongly dominated by fossil gas with a 48% share (see Fig. 3.14). However, a combination of direct and indirect electric heating will increase its shares in many European countries owing to the substantial efficiency gains of these electricity-based solutions that will also be affordable alternatives to fossil gas. Renewable-based electric heating (direct) and heat pumps (indirect) will form the majority of heat generating capacities by 2050, complemented by a small but steady share of other renewables, primarily sustainable bioenergy.

While fossil fuel-based heat declines across the three scenarios to zero in the Leadership scenario by 2040 and in the Moderate scenario by 2050, there will be minor shares of fossil gas and oil based industrial process heat left in the Laggard scenario. However, all three scenarios also face a notable portion of renewable-based synthetic fuels – namely hydrogen and methane – which contribute towards industrial process heat in the latter stages of the transition.

FIGURE 3.14 HEAT GENERATION

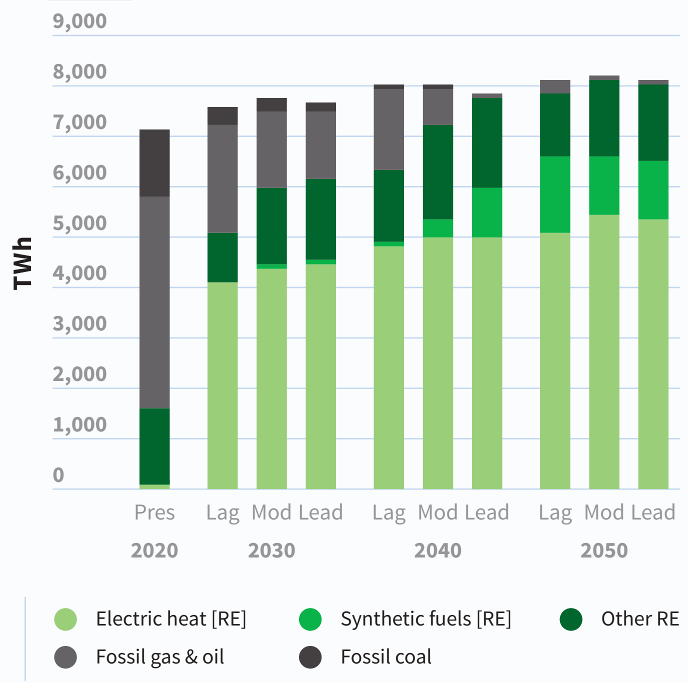
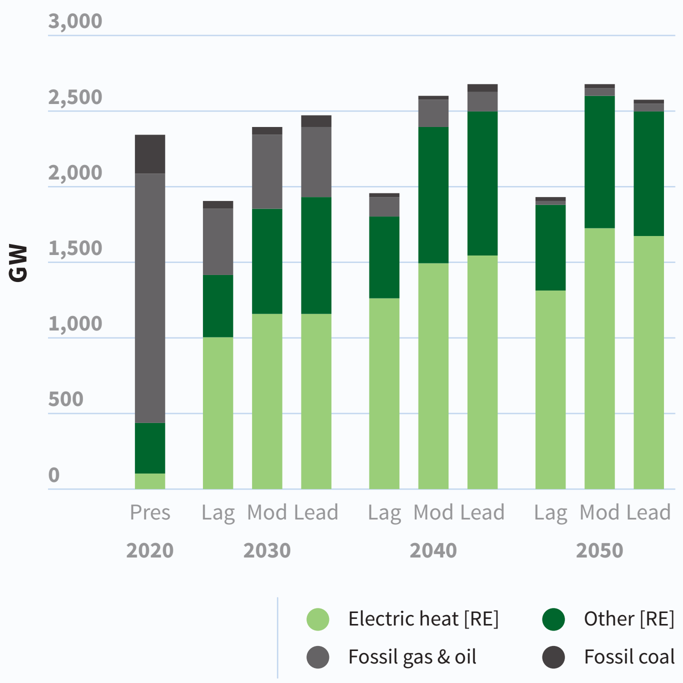


FIGURE 3.15 HEAT INSTALLED CAPACITY



Source: SolarPower Europe.

Heat Storage

Heat storage plays a vital role in covering heat demand across the three scenarios, through the energy transition phase. The largest needs for heat storage are seen in the Leadership scenario, followed by the Moderate, with renewable-based synthetic methane providing the majority of the output across the three scenarios until 2030 (see Fig. 3.16). Another share will come from thermal energy storage (TES), which becomes the primary source of heat storage in the later stages of the transition for the Moderate and Leadership scenario, providing up to 59% and 63% respectively. The reasons for this are the rapid transition and the role of Power-to-Heat, which converts electricity to heat in the form of thermal energy storage (e.g. prosumers store their electricity as heat in hot water tanks, which is then utilised for heating).

The need for heat storage to fulfil heat demand is significantly lower than for electricity storage, but still increases across the three scenarios. In the Leadership scenario heat storage supplies 12% of heat demand by 2040, enabling a rapid transition towards 100% renewable energy (see Fig. 3.17). In the Moderate and Laggard scenarios, the ratios are somewhat lower, at around 9% and 2% respectively, by 2050. Heat storage is mostly critical to supply seasonal demand as fossil gas is phased out of the European heating system.

Transport

Responsible for almost a quarter of Europe's GHG emissions, the transport sector shows the lowest renewable energy shares compared to its peers. Only 5% of the energy needed for transport is provided by renewables in 2020. With electrification, digitalisation, automation, and the sharing economy rapidly shaping the transport sector, numerous service business models have entered the market.[18,19] Driven by increasing electrification rates and efficiency gains, energy demand for road transport will strongly reduce until 2040; this applies to the freight segment and even more to passengers, who will all use electric vehicles at that time (see Fig. 3.18). In contrast, the final energy demand for aviation passenger transport increases through the transition across all scenarios, as additional electricity is required for the production of synthetic fuels, while final energy demand for marine, mainly freight, remains stable through the transition.

FIGURE 3.16 HEAT STORAGE OUTPUT

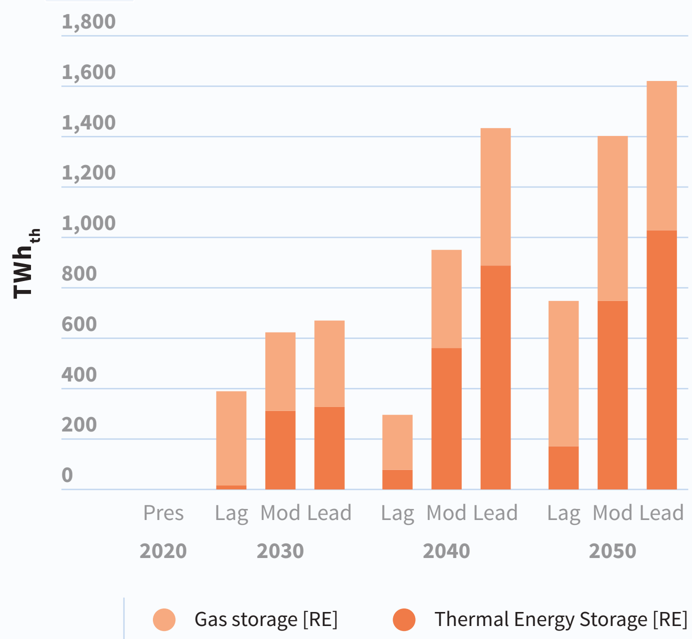
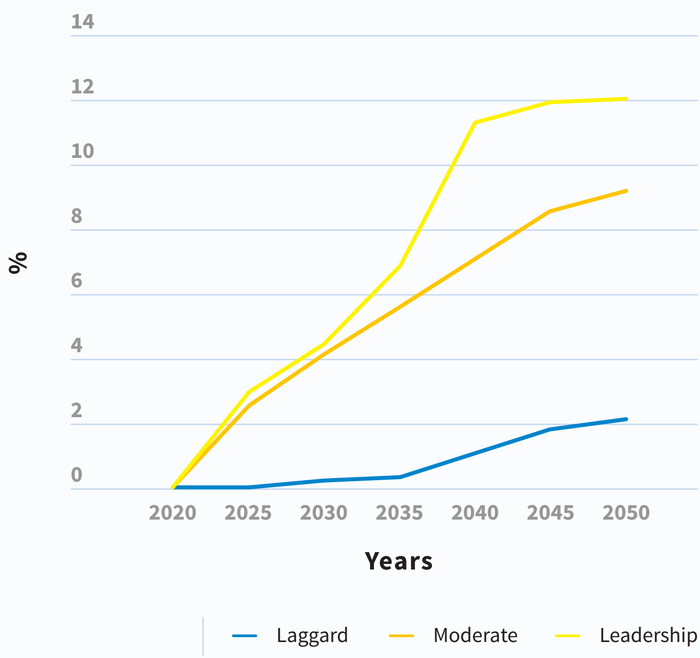


FIGURE 3.17 RATIO OF HEAT STORAGE OUTPUT TO DEMAND



Source: SolarPower Europe.

In general, the opposing trends in the development of the final energy demand in the transport sector can be explained by the various levels of direct electrification that are possible depending on the transport modes. While road transport has a high level of direct electrification in the Leadership and Moderate scenarios, slightly lower levels in the Laggard scenario result in a slightly higher final energy demand. On the other hand, very little direct electrification in marine and air transport applications means basically no efficiency gains and thus reduces effects on final energy demand.

Unlike in the power and heat sector, the share of fossil fuel consumption in the transport sector across the three scenarios is still very high in 2030, also for the two 100% renewable scenarios (see Fig. 3.19). Even the most progressive Leadership scenario shows a 78% fossil fuel use share in 2030, compared to 95% in 2020.

The rapid decrease down to zero in the Leadership scenario will take place almost entirely in the 2030 decade, when on top of renewable-based direct electrification synthetic fuels that are indirectly produced with renewable power will also reach their full potential. Here, the main contributor to replace fossil fuels will be Fischer-Tropsch (FT) fuels. These are made using the FT Power-to-Liquid technology for synthetic fuels, such as diesel, gasoline, jet fuel from hydrogen, and CO_2 (see Box 3, p. 38). Hydrogen can also be used directly for electricity production in gas turbines or as fuel for transport, which will be one of three major pillars with electricity and FT fuels in final energy demand in 2050 in 100% renewable scenarios. Although the Laggard scenario in 2050 sees large parts of final energy demand in transport coming from renewable electricity, FT, and hydrogen, the main share of 26% will still be based on fossil fuels.

FIGURE 3.18 FINAL ENERGY DEMAND FOR TRANSPORT

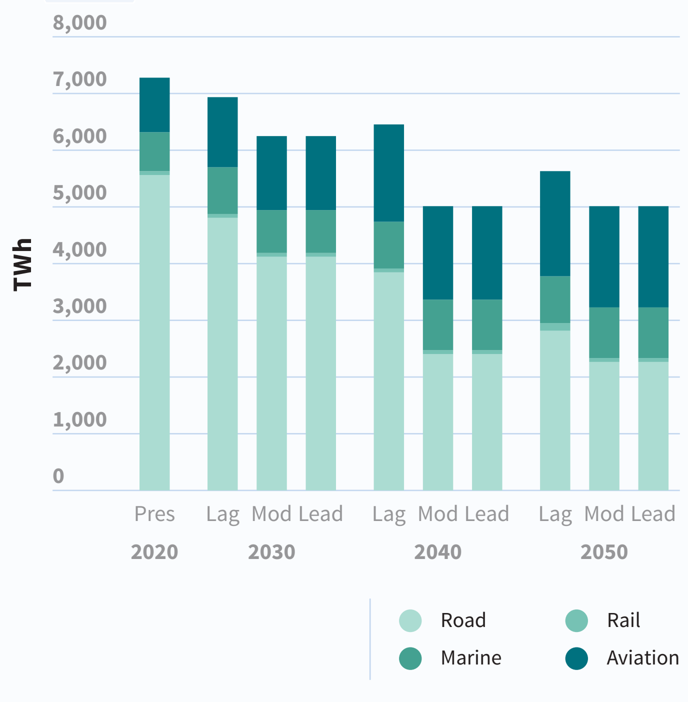
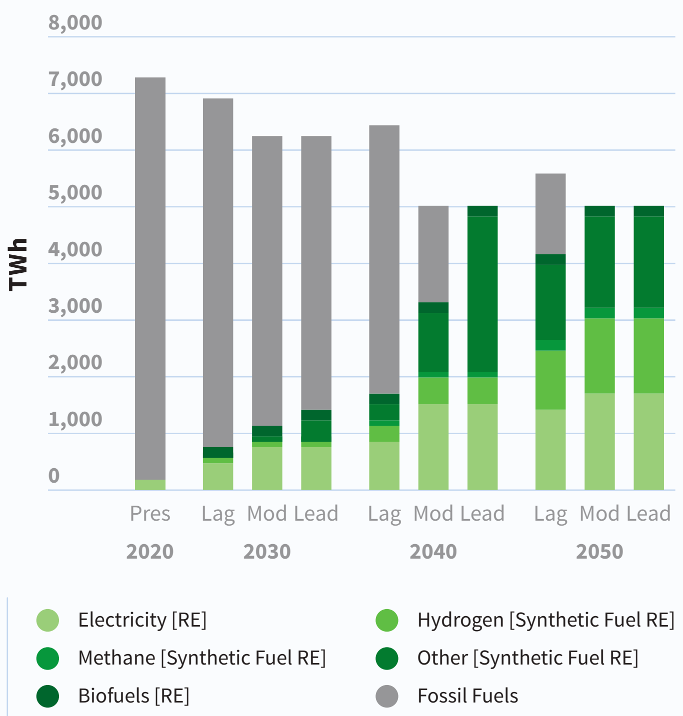
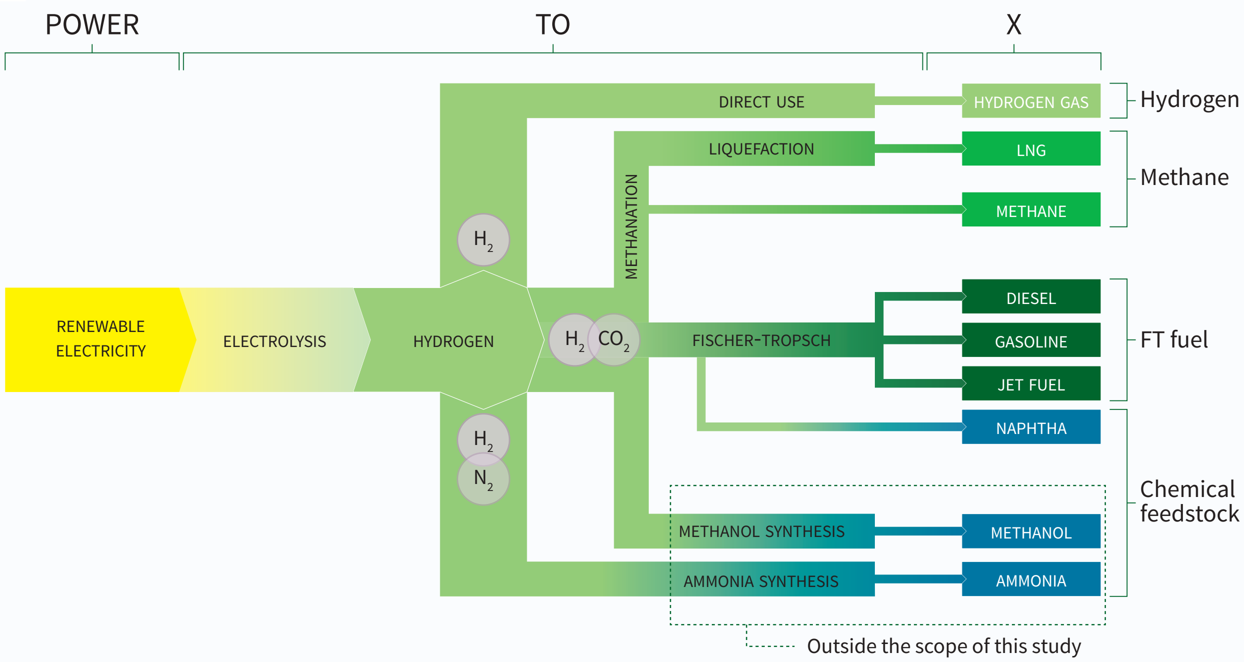


FIGURE 3.19 FINAL ENERGY DEMAND FOR TRANSPORT - FUEL USE



Source: SolarPower Europe.

BOX 3. POWER TO HYDROGEN TO X



A fully integrated energy system depends on employing renewable electricity in the heat and transport sectors, in applications that today mostly rely on hydrocarbon fuels. While using direct electricity is a cost-efficient solution in a number of cases, it could prove difficult to completely replace fuel use in certain applications, such as high temperature industrial heating, aviation and maritime transport. Also, the current road fleet is largely based on ICE engine vehicles, and it will take some time to replace them with electric vehicles.

To overcome this challenge, a variety of chemical processes were discovered in the twentieth century: various synthetic fuels with equivalent features to hydrocarbon fuels can be produced from just renewable electricity, water, and air. Hydrogen plays a crucial role as an energy carrier for the creation of synthetic fuels and chemicals.

The first, fundamental step is **water electrolysis** (1), a process that uses direct electricity to split water molecules into hydrogen (H_2) and oxygen (O). Hydrogen gas can be used directly (2) as a fuel, or undergo further treatments to produce a wider range of products. These additional steps use carbon oxides (CO or CO_2) as raw materials that, combined with hydrogen, are processed into synthetic hydrocarbon compounds. In this model, the CO_2 needed for these processes is taken from the ambient air through direct air capture (DAC). Sustainable or non-avoidable CO_2 point sources are also useful, such as waste incinerators, pulp and paper mills, and limestone-based CO_2 emissions from cement plants.

Methanation (3) converts carbon dioxide and hydrogen to methane (CH_4), producing synthetic methane, and, through liquefaction (4), synthetic LNG (Liquified Natural Gas).

The **Fischer-Tropsch process** (5) converts, through a series of chemical reactions, carbon dioxide and hydrogen into synthetic crude, which is refined into various liquid hydrocarbons: diesel, gasoline, jet fuel, and naphtha. The former three are used as liquid fuels, while the latter is a key feedstock for the chemical industry.

A third route of combining hydrogen with carbon oxides is **methanol synthesis** (6), which can be used to produce methanol and subsequently various other chemicals. Methanol is assumed to become the major chemical feedstock. Moreover, hydrogen can be also coupled with dinitrogen (N_2) for the **production of ammonia** (7), an important feedstock for the chemical industry that is mainly used in agriculture as a fertiliser. Methanol and ammonia are not included in the scope of this study. The additional energy demand for a sustainable chemical industry, considering all demand is supplied within Europe, requires about 16.0% and 19.3% higher installed capacities of PV and wind energy than the reported capacities in this study.

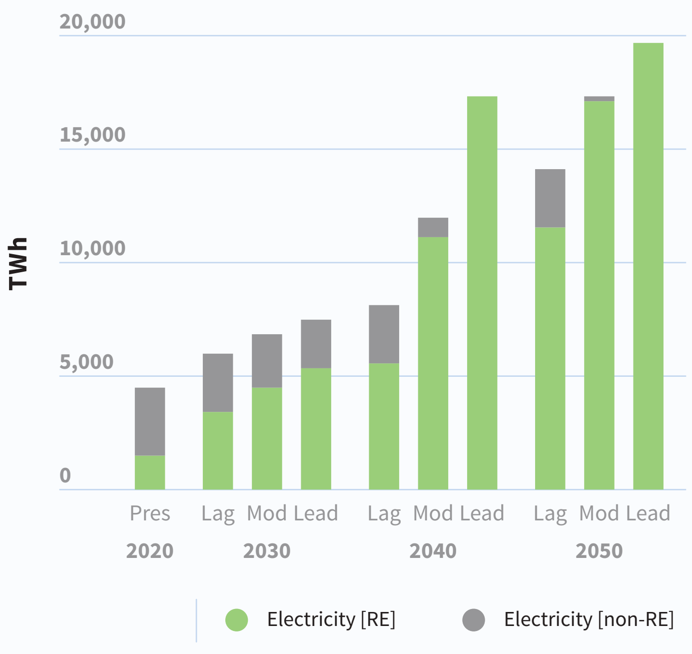
Electrification and decarbonisation through renewables across the power, heat, and transport sectors

Our modelling shows that a high electrification rate through direct and indirect substitutions of fossil fuels and nuclear is key for the decarbonisation of all sectors with renewables.* Direct substitution involves the proliferation of electric vehicles in the transport sector and the adoption of electric heating systems like heat pumps in buildings and some parts of industry. On the other hand, indirect substitution involves a switch to synthetic fuels, which are produced by electrolysis, methanation, and FT synthesis using renewable electricity, to provide energy for heat, transport, and as many industrial processes as possible, that otherwise would rely on fossil fuels.

However, the current level of electrification across the power, heat, and transport sectors in Europe is approximately 6% in 2020 (see Fig. 3.20). In the Laggard scenario, lower levels of electrification only lead to about 51% electrification, or 14,000 TWh by 2050, with 62% of the electricity coming from renewables. In the Moderate scenario, a steady increase in electrification occurs to a much higher level of up to 85%, or about 17,000 TWh by 2050, with nearly 100% of the electricity from renewables. The Leadership scenario leads only to a slightly higher level of 86% or around 17,000 TWh, but that takes place 10 years earlier than in the moderate scenario, so that Europe is supplied with 100% electricity from renewables in 2040. In 2050, the fully electrified Leadership scenario's further augmented renewable power generation capacities supply to almost 20,000 TWh, as additional electricity of nearly 3,000 TWh will be utilised in the production of synthetic fuels for export.

FIGURE 3.20 ELECTRIFICATION RATE

FIGURE 3.21 RENEWABLE ENERGY SHARE IN ELECTRICITY GENERATION



Source: SolarPower Europe.

* The graphs in this study consider electricity as 100% renewable. Although that is the case for the Leadership scenario since 2040 and for the Moderate scenario in 2050, it is important to highlight that a significant share of non-renewable energy sources contributes to the electricity mix, especially in the early phases of the transition.

With low-cost renewable electricity emerging as the prime energy carrier in Europe's future energy system and in line with increasing electrification rates, the continent also faces enhanced sectoral integration. Direct and indirect renewable electricity usage in the power, heat, and transport sectors increase through the transition across the three scenarios. While the direct and indirect electricity needs are likely to be the highest in transport, up to 10,000 TWh in the Leadership scenario; the possible maximum is up to 7,000 TWh in the power sector and up to 3,000 TWh in the heat sector.

In the **Heat sector**, for the Leadership and Moderate scenarios, renewable electricity is mostly used for direct heating, before renewable-based hydrogen kicks-in in 2040, while electricity-based methane delivers up to 12%, mostly for the purpose of switching from natural to renewable gas-fuelled heating in 2050. In the Laggard scenario, renewable electricity and renewable electricity-based hydrogen deliver most of the heat through the transition, but the absolute amounts are about one third less, as some fossil fuel-based heat is still in use as shown in Fig. 3.22.

In the **Transport sector**, renewable electricity drives electrification in the initial periods of the transition, while from 2030 onwards renewable electricity-based hydrogen and FT fuels are technologically and cost-wise ready to take over and provide the majority of the energy across the three scenarios (see Fig. 3.23). The use of electricity for transport rises most rapidly in the Leadership scenario, more steadily in the Moderate scenario, and at slower pace in the Laggard scenario, in line with the respective ambitions towards high renewable energy rates. The role of renewable electricity-based FT fuels is vital for the transition of energy in transport modes that cannot be directly electrified – in particular, marine and aviation, as shown in Fig. 3.18 – and further enables integration of the power and transport sectors.

FIGURE 3.22 ELECTRICITY DEMAND FOR SUSTAINABLE HEAT

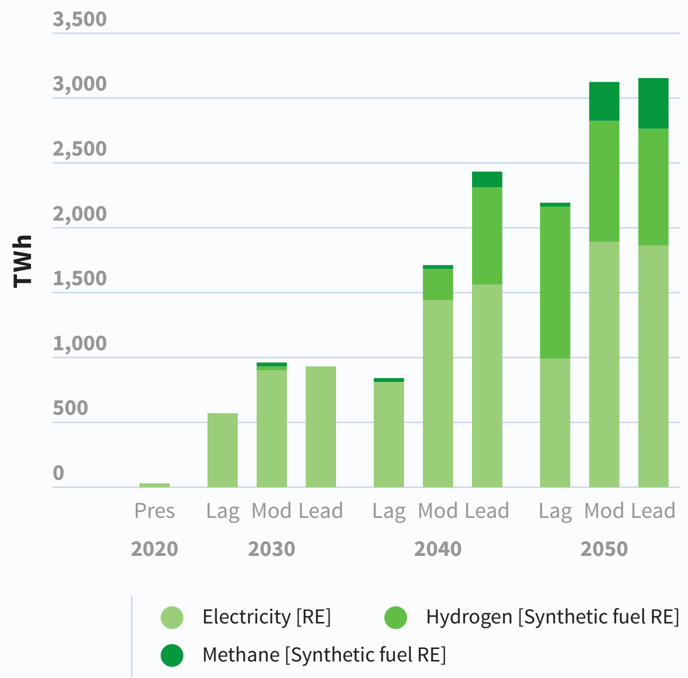
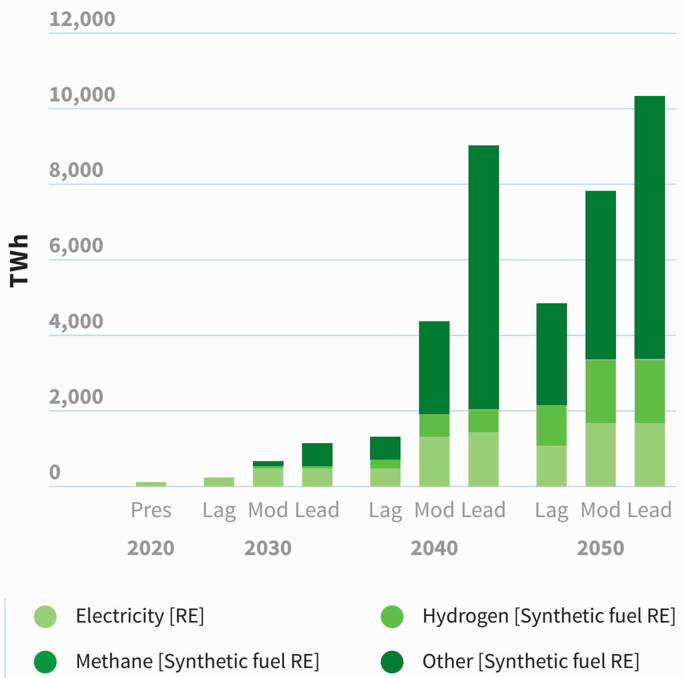


FIGURE 3.23 ELECTRICITY DEMAND FOR SUSTAINABLE TRANSPORT



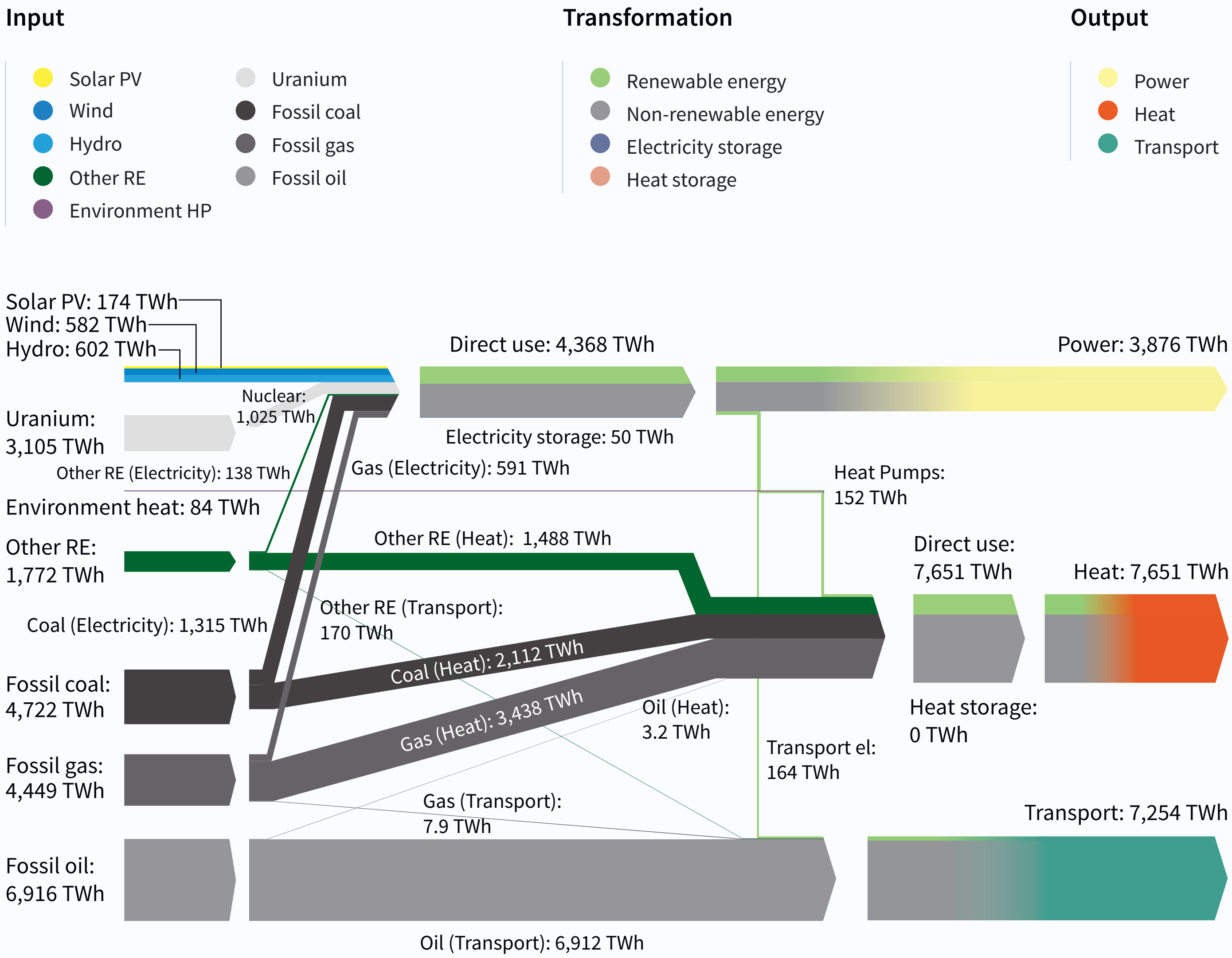
Source: SolarPower Europe.

BOX 4. SECTOR COUPLING AND FLEXIBILITY IN THE ENERGY SYSTEM

Sector coupling or energy system integration is considered by many experts as a key enabler to reduce GHG emissions in the European energy sector.[20,21] Moreover, it can be a cost-efficient means of integrating the energy system by valuing synergy potentials and interlinkage between different uses, applications, and sectors.

In this report, sector coupling includes the integrated use of different energy infrastructures and carriers, in particular electricity, heat, synthetic gas, and synthetic liquid fuels. This energy system is enabled both on the supply side (input), with the conversion of renewable electricity to heat, hydrogen, methane, and FT fuels, and on the demand side (output), with electrification of end-use and storage for cost effective management of energy use. Several studies[13,21–24] show that sector coupling can lower the overall costs of the energy transition, which is validated by the results of this study.

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020



BOX 4. SECTOR COUPLING AND FLEXIBILITY IN THE ENERGY SYSTEM / CONTINUED

Today, the European energy system is supply-driven, centralised and largely decoupled as it still depends on imported fossil fuels and nuclear (see Fig. 3.24). The energy flows in 2020 are highly resource-intensive and inefficient; there is a significant portion of energy, around 18%, lost on the way to produce final energy, but even more wasteful is the step from final energy to energy services, particularly in the transport sector, where around 69% is lost. While the power sector is the most diversified in terms of energy sources, with different renewables already contributing nearly one third, transport is the least diversified sector, relying almost exclusively on fossil oils. Although the heat sector shows some diversification using biomass, with a share of 20%, it still heavily depends on fossil gas.

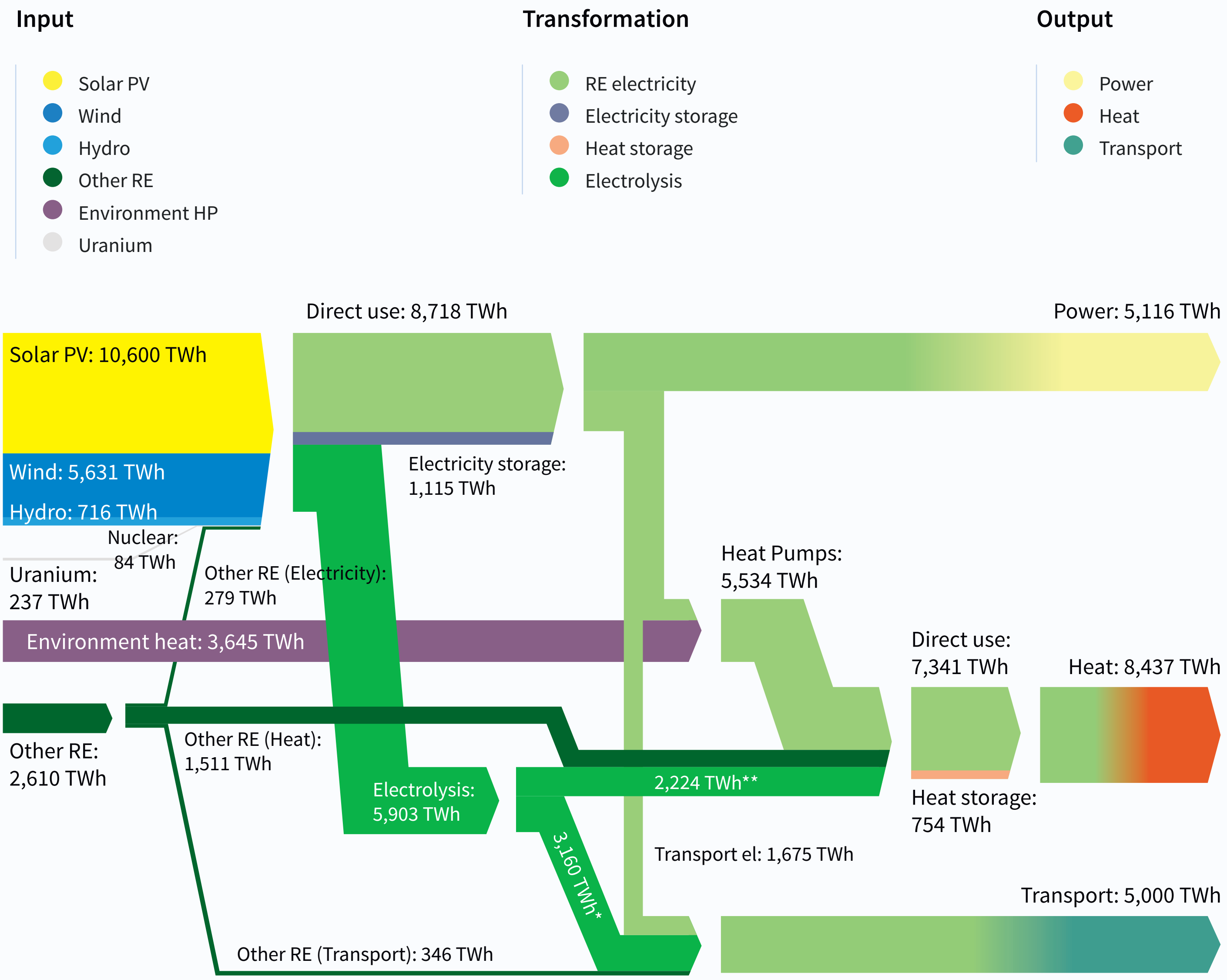
However, recent developments in the power sector and the emergence of low-cost renewable electricity as the prime energy carrier have set the path towards a more decentralised, integrated, flexible, and demand-oriented energy system.[25] The impacts of sector coupling in the Moderate scenario are highlighted in Fig. 3.25, which show the energy flows of a fully sector-coupled European energy system in 2050, compared to its decoupled status in 2020.

In the Laggard scenario, the energy system in 2050 is highly integrated, with flexible storage options. However, it still has some shares of nuclear and fossil fuels that contribute to an energy loss of 27%. The high level of diversification of energy sources is evident across the power, heat, and transport sectors, as shown by an increasing complexity in energy flows. Compared to 2020, most of the energy for the heat and transport sectors does not come from fossil fuel sources, but rather from direct electricity use or from indirect electricity in the form of synthetic fuels.

Unlike the Laggard scenario, the Moderate scenario results in an almost completely integrated energy system in 2050, as it is nearly entirely based on renewable electricity (see Fig. 3.25). The energy system includes a variety of flexibility options – batteries for short-term storage, gas storage for seasonal variations, and a mix of power-to-heat, power-to-gas, and power-to-liquid fuels. The power, heat, and transport sectors are based on highly diversified energy sources. Major losses can be seen as a result of the electrolysis and synthetic fuel production processes, although a share of energy is retrieved in the form of recovered heat. Total system losses in this scenario account for 13%; a minor share of these losses is due to the remaining share of nuclear in the system, which results to about 80 TWh of electricity production.

Although not too different from the Moderate Scenario, a fully integrated system based on 100% renewables is only represented in the Leadership scenario in 2050. What mostly differs is that the majority of heat is coming from highly efficient heat pumps that use naturally available heat and renewable electricity-based synthetic fuels to satisfy large parts of transport energy demand. Storage technologies play a vital role in providing flexibility to the system, which enables a higher level of electrification and sector coupling. In comparison to the Moderate scenario, the Leadership system features higher flexibility coming from an additional 550 GW of electrolyser capacities, which are needed for hydrogen, synthetic methane, and FT fuels, mainly for the transport sector, but also for high-temperature applications; these energy carriers can be stored until they are used. Thus, curtailment rate is below 5% across both scenarios. However, the high flexibility of electrolysers enables the efficient uptake of variable electricity generation from solar PV and wind energy, which effectively reduces the demand for electricity storage.

FIGURE 3.25 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN THE MODERATE SCENARIO IN 2050



*RE synthetic fuels for transport.

**RE synthetic fuels for heat, recovered heat.

Storage Output

The more renewable electricity is generated, the more complementary storage technologies are needed to enhance its penetration in energy systems, as renewables are inherently variable in nature due to their reliance on weather conditions. In this context, various storage technologies provide stability, flexibility to the energy system, and even enable a wide range of grid services.[15,26] With their rapidly decreasing cost, batteries emerge as the most cost-effective electricity storage option in all three scenarios, contributing the largest storage shares as of 2040 (see Fig. 3.26). In addition, gas storage becomes critical to cope with seasonal variations in demand and renewable energy supply. Renewable electricity-based synthetic gas (methane) is used in gas-fired power plants, providing electricity when other renewable energy resources are unavailable. Some shares of thermal energy storage also provide short-term flexibility, and coupled with power-to-heat, they can supply both critical electricity as well as heat. Pumped hydro, which is currently the most widely used electricity storage option in Europe, continues to provide shares, although decreasing throughout the transition across all three scenarios; its job is to serve as a short-term storage option, very similar to batteries. The storage output increases through the next 30 years across the three scenarios by 50 to 100 times.

The largest storage output is needed in the Moderate and Leadership scenarios, ranging around 4,600 to 4,900 TWh in 2050, while in the Laggard scenario it reaches around 2,500 TWh at that time. While the growth of storage is considerable, the high levels of electrification and the integration of the energy system with other sectors reduces the requirement for larger volumes of storage across all three scenarios. Storage output with respect to energy demand in 2050 is around 11% in the Laggard scenario, about 24% in the Moderate scenario, and reaches the highest level at around 25% in the Leadership scenario (see Fig. 3.27). Storage technologies are an indispensable part of the energy transition, which provide necessary stability and flexibility. However, a highly integrated approach between sectors and very high electrification rates delivers the most efficient and cost effective energy system, keeping the growth of storage output up to about one fourth of demand in 2050.

FIGURE 3.26 STORAGE OUTPUT

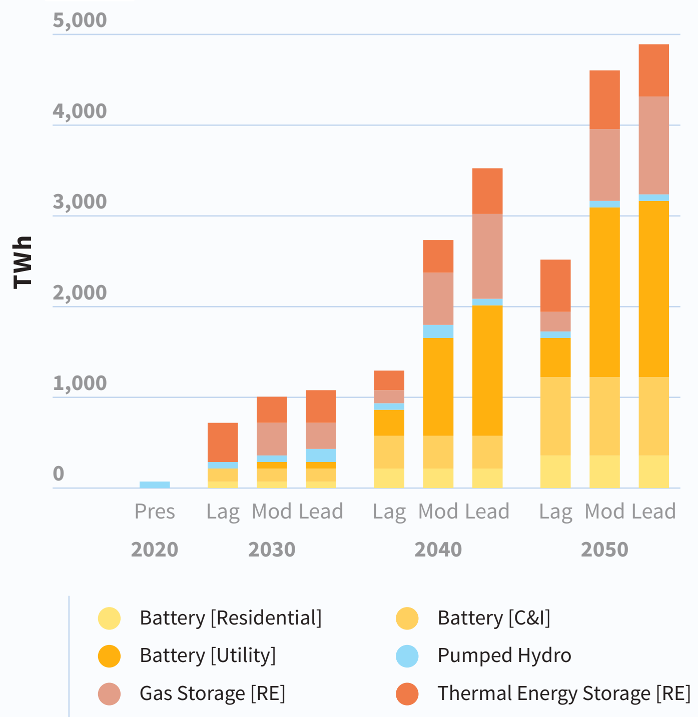
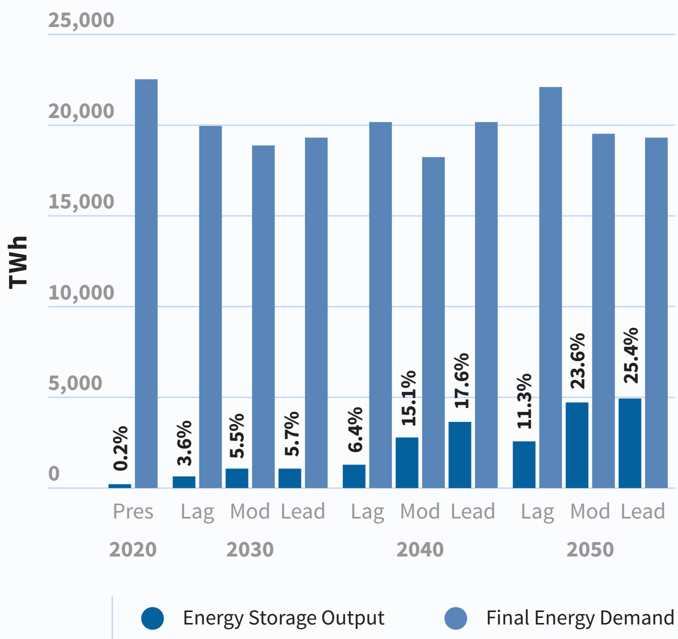


FIGURE 3.27 STORAGE OUTPUT TO ENERGY DEMAND



Source: SolarPower Europe.

3.2 Cost and benefits of the integrated European energy system transition

The cost of energy is a key factor for determining the viability of energy scenarios, roadmaps, and pathways. As renewable energy generation sources, electricity and heat storage technologies - along with renewable electricity-based synthetic fuels - evolve to become key elements of Europe's energy supply system by 2050. The vital question that remains is how much an ambitious transition to a 100% renewable energy system will cost. In short, it can be less costly overall and remains more affordable than a business as usual mode.

Annual System Costs

When taking into account total annual system costs – representing the annualised costs of the entire energy sector averaged for 5-year time intervals – the costs for the Moderate scenario are consistently lower than for the other two scenarios until 2050, as the model shows the best ratio of new investments and operating costs during the transition (see Fig. 3.28). While the Leadership scenario requires massive investments as it strives for a 100% renewable level in 2040, its annual system costs will drop massively in the years up to 2050, when the system will operate to a large extent on power plants producing electricity with a marginal cost of zero. In contrast, the fossil fuel-heavy Laggard scenario shows the highest annual cost in 2050. However, taken altogether, the cumulative annual system cost for the Moderate scenario by 2050 will reach €30 trillion, which is 6-7% below the other scenarios; Leadership at €32.3 trillion and Laggard at €31.9 trillion (see Fig. 3.29).

FIGURE 3.28 ANNUAL SYSTEM COSTS

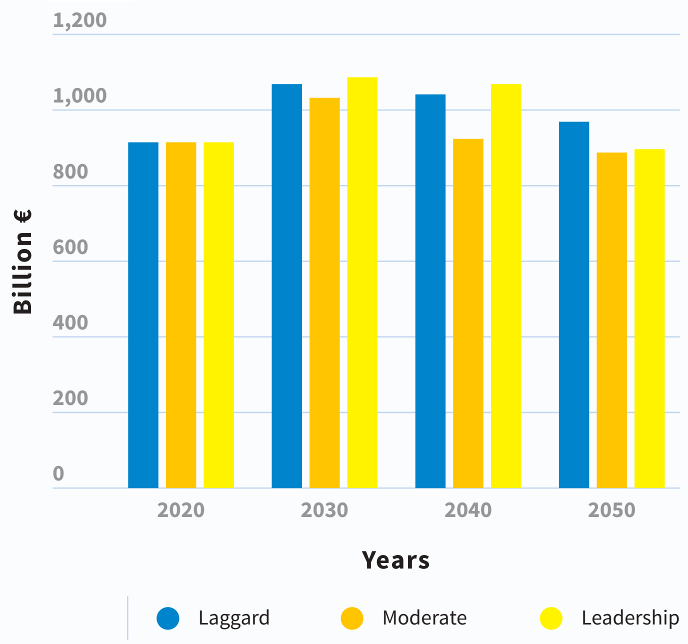
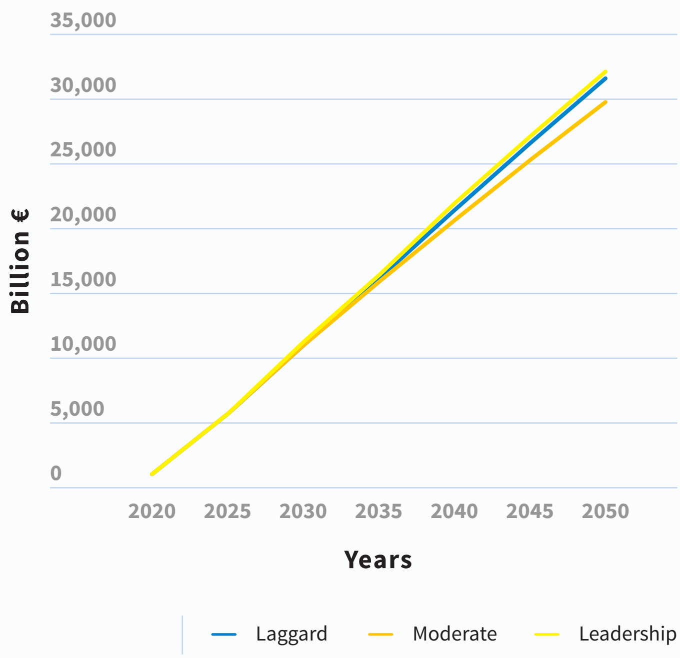


FIGURE 3.29 CUMULATIVE ANNUAL SYSTEM COSTS



Source: SolarPower Europe.

Capital Expenditures

When looking solely at capital expenditures (for installed capacities of energy technologies that occur in every 5-year time period) the modelling for the three scenarios clearly shows that the more ambitious the scenario, the earlier the bulk of the investment needs to be taken (see Fig. 3.30). The Leadership scenario requires massive investments in the short-term, in particular in the 2030s decade to achieve the 100% renewables target by 2040, while the Moderate scenario allows for more time for investments in the later stages of the transition from 2040 onward, as it reaches close to 100% renewables 10 years later. With the lowest time pressure, the Laggard scenario investments peak even later, in the mid to late 2040s, though at absolute lower levels as the final renewables share in 2050 is only 62%.

The highest cumulative expenditures are needed for the ambitious Leadership scenario – an amount of close to €8.3 trillion until the 100% target is reached in 2040, after which it only slightly increases up to €8.37 trillion by 2050 (see Fig. 3.31). Investments in the form of capital expenditures are mainly spent for solar PV, wind energy, batteries, heat pumps, and technologies in the value chain of renewable-based synthetic fuels production, such as electrolysers. Capital investment for the least ambitious Laggard scenario is the lowest of the three scenarios, €6.45 trillion Euros, but that is only half a trillion below the spending needed for the Moderate scenario. In other words, to reach a 100% renewable-based Europe by 2050, there needs to be only 8% higher investment than a scenario targeting 62% renewables by the same point in time.

FIGURE 3.30 CAPITAL EXPENDITURES IN EVERY 5-YEAR INTERVAL

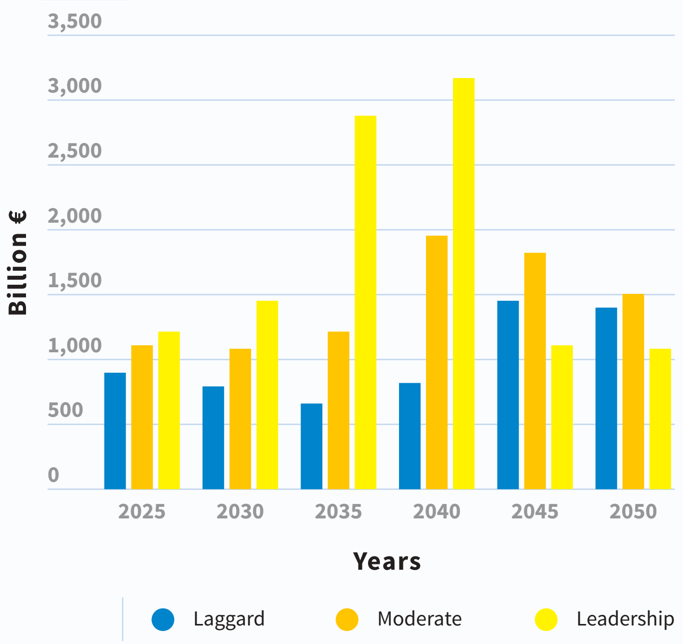
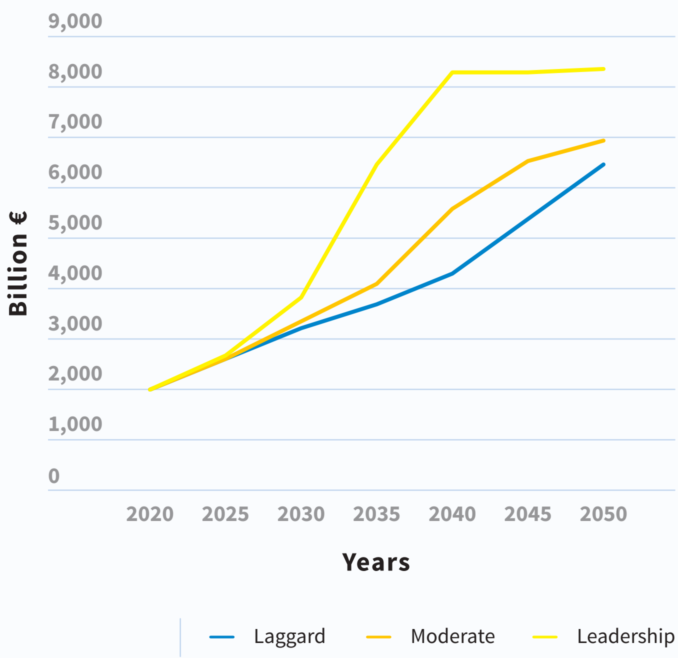


FIGURE 3.31 CUMULATIVE CAPITAL EXPENDITURES



Source: SolarPower Europe.

Levelised cost of energy

In the end, the energy transition is not only about direct investments but also per-unit-generation cost, or the levelised cost of energy, electricity, and heat. After a short peak for each of the scenarios in this decade, the LCOEnergy declines across all three scenarios through the transition up to 2050 (see Fig. 3.32), confirming the positive effects of system integration. The total system wide LCOEnergy is the lowest in the Leadership and Moderate scenario in 2050. At €47/MWh, that is about 5-6% below the Laggard scenario's average level of €50/MWh, and at the same time about 7% more competitive than today's €51/MWh. It shows that an accelerated energy transition towards 100% renewable energy is an economically attractive proposition. Capital cost increasingly dominate LCOEnergy in all three scenarios, as fuel costs lose importance through the transition period. In 2050, only the Laggard scenario cost structure contains a notable portion spent on fuels and GHG, as both of the other scenarios have reached the 100% renewable level.

FIGURE 3.32 LEVELISED COST OF ENERGY DEVELOPMENT

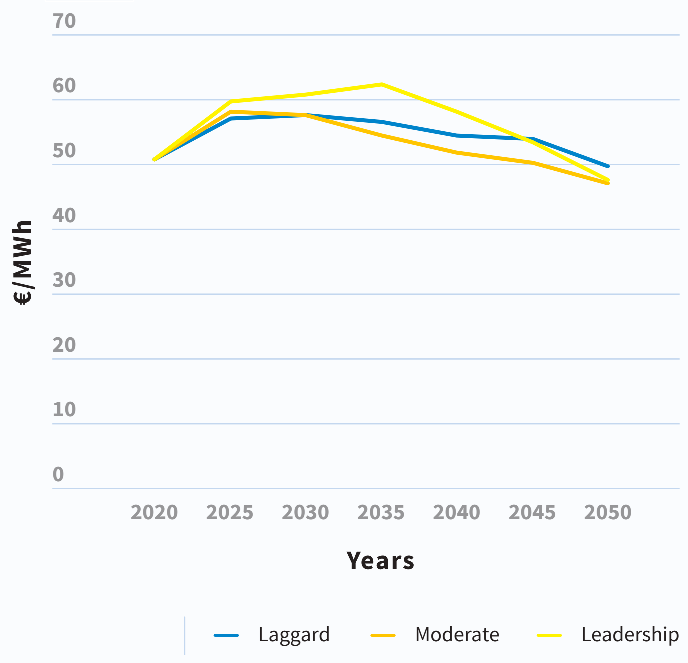
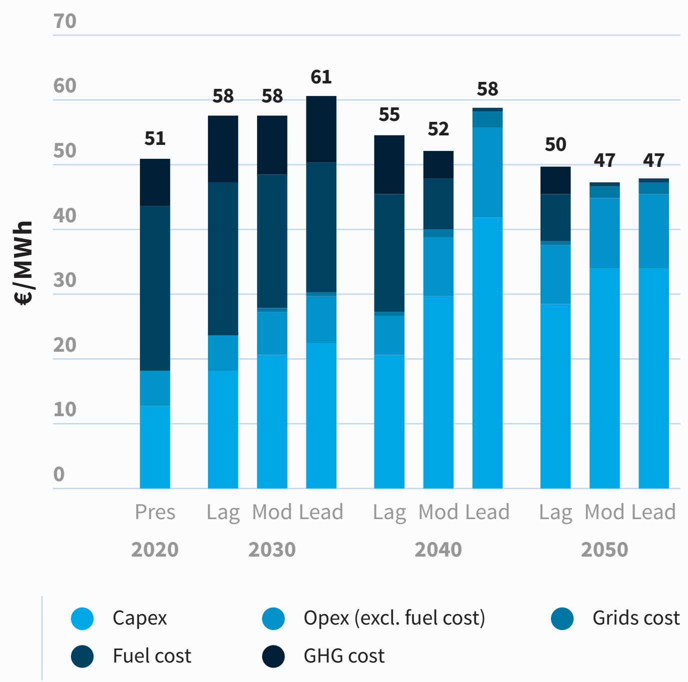


FIGURE 3.33 LEVELISED COST OF ENERGY



Source: SolarPower Europe.

Levelised cost of electricity and heat

The LCOEnergy consists of all aspects of the energy system, including electricity and heat as the primary sources of energy generation, which are the two vital cost indicators of the energy transition. The trends for both electricity and heat costs follow similar patterns, decreasing substantially by up to 45% for power and up to 27% for heat compared to today, as the share of fuel and GHG costs declines with systems getting increasingly electrified and resulting in capital expenditure-driven energy system costs. The only difference is grid costs, which are only relevant for the power sector; although very modest on a per-unit basis over time, the total amounts are significant as expansion of the grid is key for a sector coupled energy system with high electrification rates.

The levelised cost of electricity (LCOE) of the power sector, which averages around €71/MW today, declines most for the Moderate and Leadership Scenarios, reaching almost €39/MWh in 2050, while the Laggard scenario reaches €48/MWh (see Fig. 3.34). Beyond the modelling horizon of 2050, it is anticipated that the LCOE further decreases, mainly as a consequence of reinvestments, with capital costs per unit seeing further cost reductions.

The levelised cost of heat (LCOH) declines for all scenarios from around €37/MWh in 2020, to about €27/MWh in the Moderate and Leadership scenarios, €25/MWh in the Laggard scenario (see Fig. 3.35). This reduction takes place despite a substantial increase in heat demand across Europe, mainly due to industrial process heat and increased space heating, which are driven by more space used per person. However, the increased levels of electrification easily compensate for that growth in demand in the heating sector.

FIGURE 3.34 LEVELISED COST OF ELECTRICITY

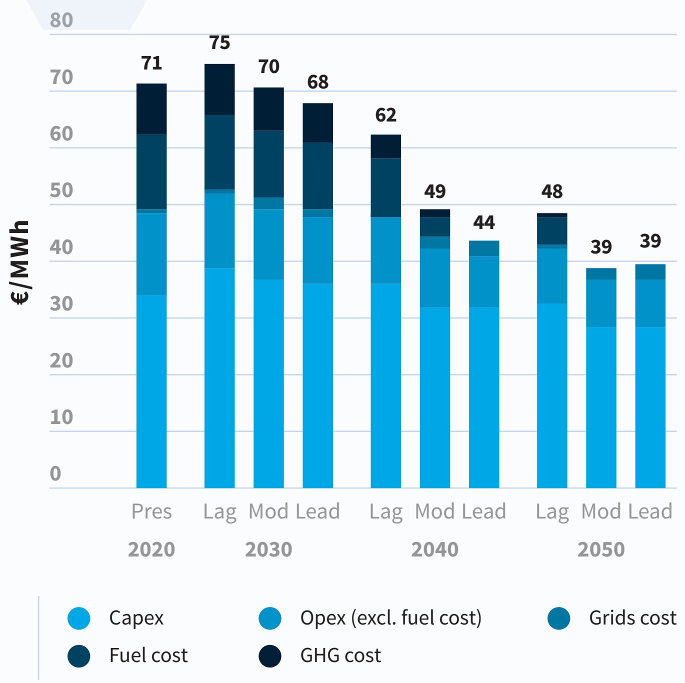
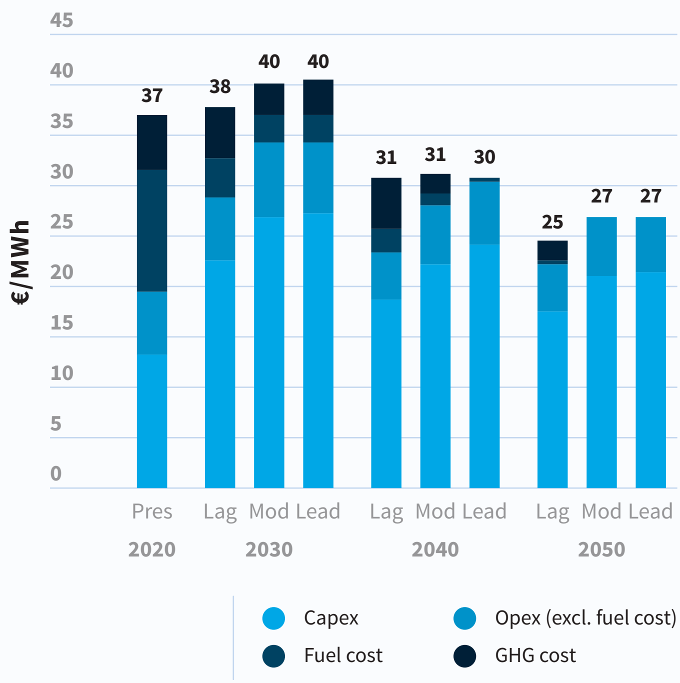


FIGURE 3.35 LEVELISED COST OF HEAT



Source: SolarPower Europe.

Greenhouse gas emissions

An accelerated energy transition to a 100% renewable scenario not only means faster decrease of power generation cost, it also brings another huge benefit: the air gets cleaner faster, as less GHG will be emitted.

All scenarios show a sharp decline in GHG emissions until 2050 in the power, heat, and transport sectors (see Fig. 3.36). Today's GHG emissions across Europe of around 4,700 million tons CO_2 ($MtCO_{2eq}$) decrease steadily to zero by 2040 in the Leadership scenario, and by 2050 in the Moderate scenario. The Laggard scenario still emits around 800 $MtCO_{2eq}$ of greenhouse gases in 2050. That means that following the Laggard's pathway would burden the European society with 89 gigatons CO_2 ($GtCO_{2eq}$) over the coming 30 years (see Fig. 3.37), whereas the Moderate scenario results in about 64 $GtCO_{2eq}$ or 28% less GHG compared to the Laggard scenario. The Leadership Scenario has the most positive impact on the climate, resulting in remaining cumulative GHG emissions of only 53 $GtCO_{2eq}$ and down to zero over the next 20 years. In comparison to the Laggard scenario, the Leadership scenario emits 41% less up to 2050.

FIGURE 3.36 GHG EMISSIONS BY SECTOR

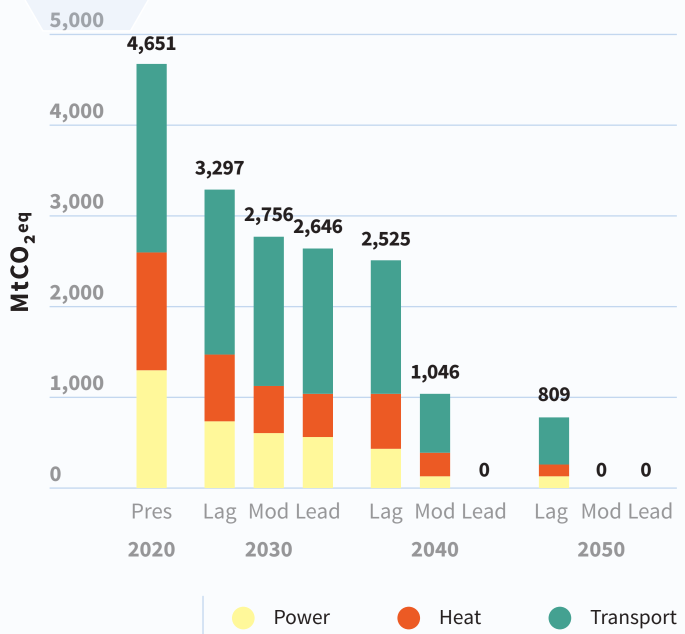
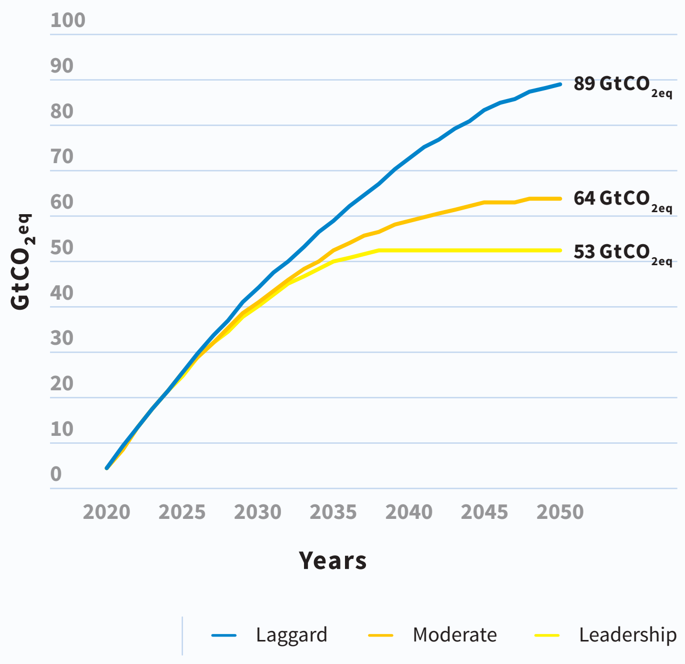


FIGURE 3.37 CUMULATIVE GHG EMISSIONS



Source: SolarPower Europe.

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REGIONAL AND SEASONAL VARIATIONS: FULL SECTOR COUPLING PROVIDES ENERGY SECURITY FOR EUROPE

4.1 Regional variation

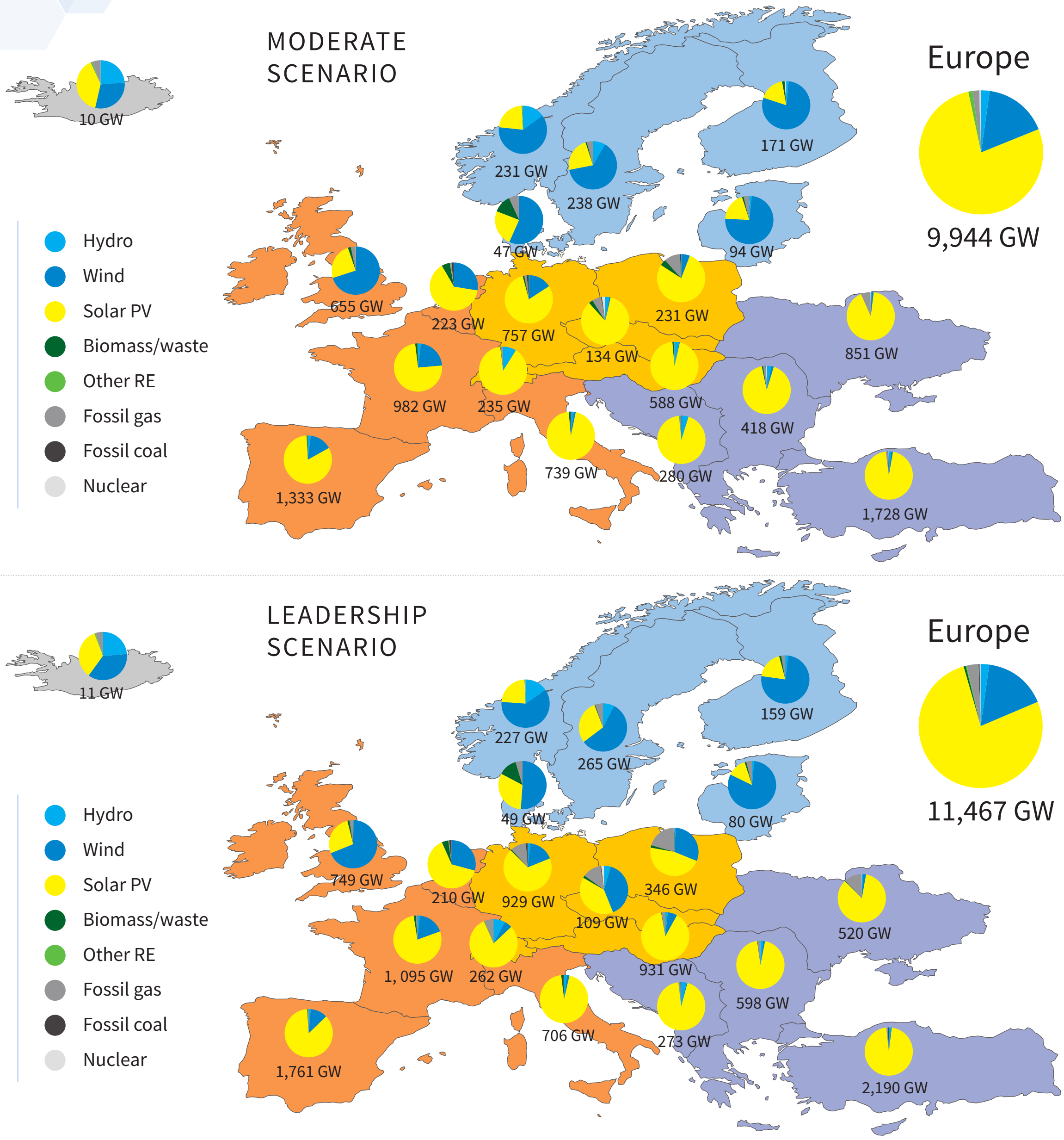
Europe is one of the most interconnected regions in the world, with robust energy infrastructure connecting the different member states. As far as renewable energy resources are concerned, Europe offers a good mix of significant wind potential in the northern and western regions (including the UK and Ireland), complemented with excellent solar potential in its southern regions. Other forms of renewable resources, such as hydro power and biomass, are also well distributed throughout the continent, which influence the regional energy mix of the various countries within Europe.

This section explores the regional breakdown for the different technologies used in the Moderate and Leadership scenarios to achieve 100% renewable energy levels by 2050.

Massive **electricity generation capacities** are installed across Europe to satisfy energy demand for power, heat, and transport up to 2050. Overall, solar PV and wind constitute the bulk of installed capacity in 2050 across Europe, along with minor shares of hydropower in both the Moderate and Leadership scenarios (see Fig. 4.1). Solar PV capacities are predominantly located in the southern regions of Europe that have high solar resources throughout the year, while wind energy systems are mainly installed in the northern and western regions of Europe, where good wind conditions prevail. The only difference between the two scenarios is volume: in 2050, close to 9.4 TW of wind and solar PV is installed in the Moderate scenario, with solar PV's share reaching 78%, while around 10.7 TW is installed in the Leadership scenario, where solar PV accounts for 77% of the capacities. As the Leadership scenario achieves 100% renewables already by 2040, further capacity additions are used to power the production of synthetic fuels that can be exported beyond 2040.

The distribution of **electricity generation output** follows the pattern of capacity installations. The major portion of solar PV generation takes place in the southern regions, while higher shares of wind energy are produced in the northern and western regions of Europe (see Fig. 4.2). This could enhance the complementarity of solar PV and wind energy in an interconnected European energy system. What differs is the higher percentage of wind generation compared to capacity as wind energy's capacity factors are overall higher. Solar

FIGURE 4.1 REGIONAL ELECTRICITY GENERATION CAPACITIES IN 2050 ACROSS EUROPE

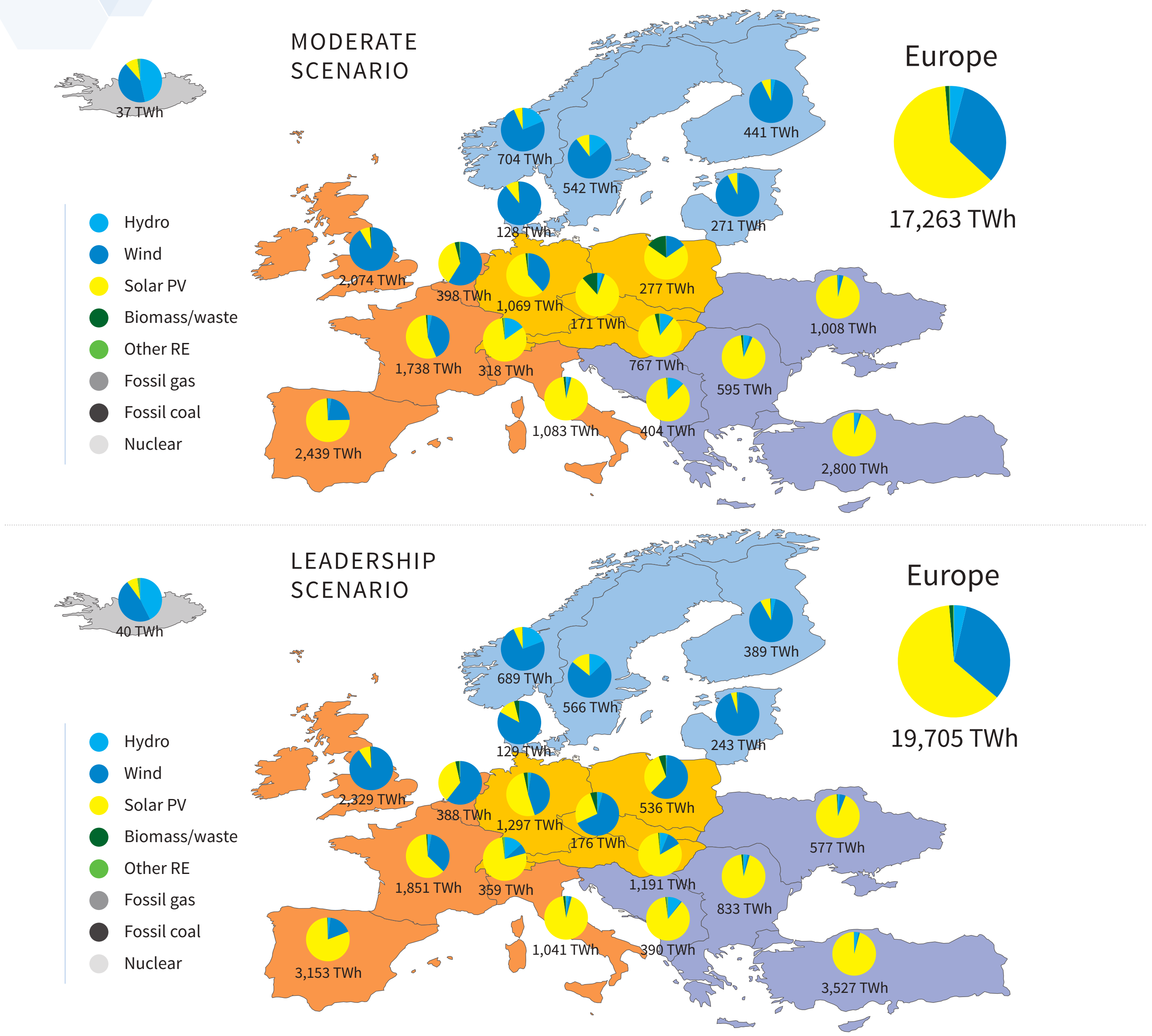


Source: SolarPower Europe.

PV supplies an average of 61% in the Moderate scenario and 63% in the Leadership scenario. Wind energy, on the other hand, contributes an average of 33% in both the Moderate and the Leadership scenario. In both scenarios, solar PV and wind energy generate over 90% of the electricity needed across Europe by 2050. However, in line with larger installed capacities, the Leadership scenario leads to around 2,500 TWh more electricity generation.

Europe's flexible energy system in 2050 relies on **electricity storage output** across the fully integrated power, heat and transport sectors. The storage output comes predominantly from batteries, including utility-scale, residential, commercial, and industrial prosumers, and a minor share of up to 3% from pumped hydro. Utility-scale batteries, which supply the major shares of of electricity storage output across Europe, with an average of up to 59%, are higher in the southern regions

FIGURE 4.2 REGIONAL ELECTRICITY GENERATION IN 2050 ACROSS EUROPE

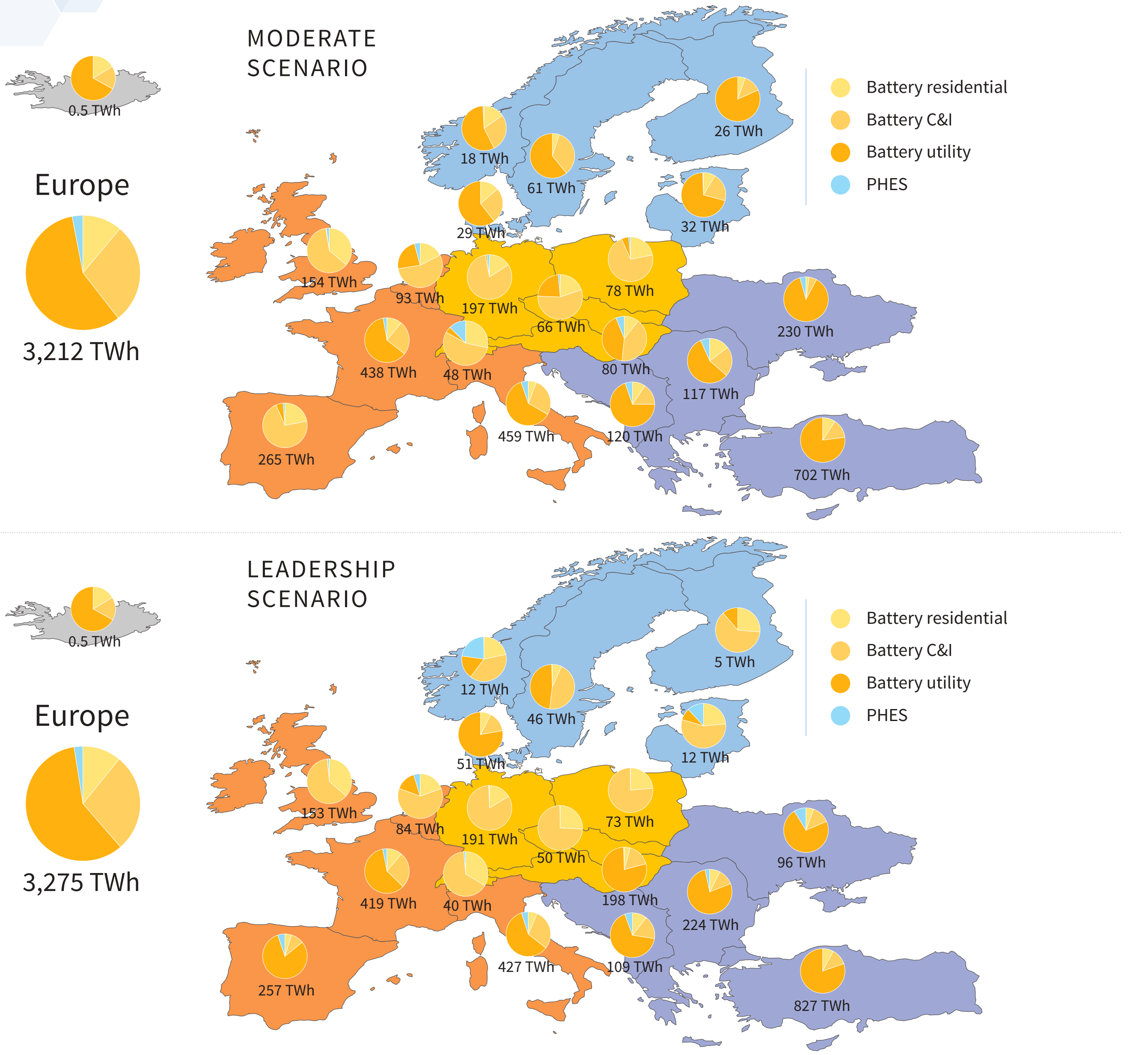


Source: SolarPower Europe.

of both the scenarios. Prosumer batteries deliver relatively larger shares in Europe's central and northern regions for both scenarios, although at much lower absolute numbers. This distribution pattern is due to two reasons: first, most solar capacities, which require short-term storage, are located in southern Europe; second, these are primarily large-scale power plants. On the other hand, smaller prosumer rooftop installations usually own higher shares in central European countries.

A concern frequently raised when it comes to 100% renewable scenarios for Europe is the amount of space needed to generate that energy domestically. The renewable capacities required for the Moderate scenario, for example, need around 1% of the total area for utility-scale PV and less than 2.5% for wind power plants. This area can also be used for other purposes, such as agriculture or livestock farming if designed appropriately (note that the fairly new PV application of floating solar is not included in this model).

FIGURE 4.3 REGIONAL ELECTRICITY STORAGE OUTPUT IN 2050 ACROSS EUROPE

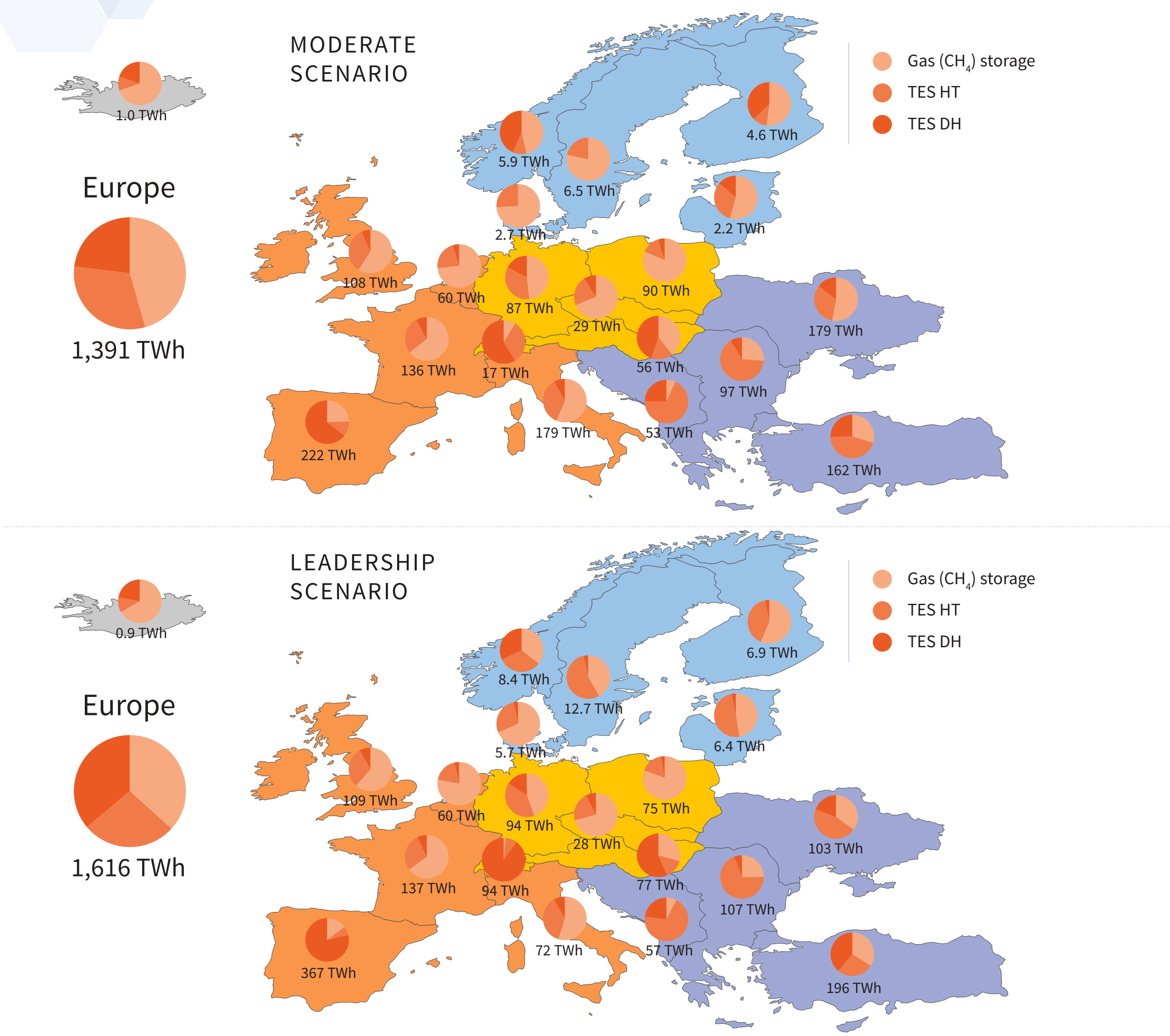


Source: SolarPower Europe.

When it comes to seasonal storage, **heat storage** plays a vital role in ensuring stable energy supply across Europe, predominantly in the winter, when there is huge demand for heating in the northern regions. This is taken care of by synthetic gas and thermal energy storage (district and individual levels), which supply heat across Europe in the two 100% renewable scenarios in 2050. Thermal energy storage has higher output shares in the southern regions, where the strong irradiation is used for solar heating, while the gas infrastructure is the base for synthetic gas storage output, which dominates the northern regions in both scenarios in 2050 (see Fig. 4.4).

Electrolysers are a key technology for a 100% renewable energy system, which not only have a vital role in the production of synthetic fuels, but also in enhancing the flexibility and integration of the energy system. In 2050, installed capacities of electrolysers

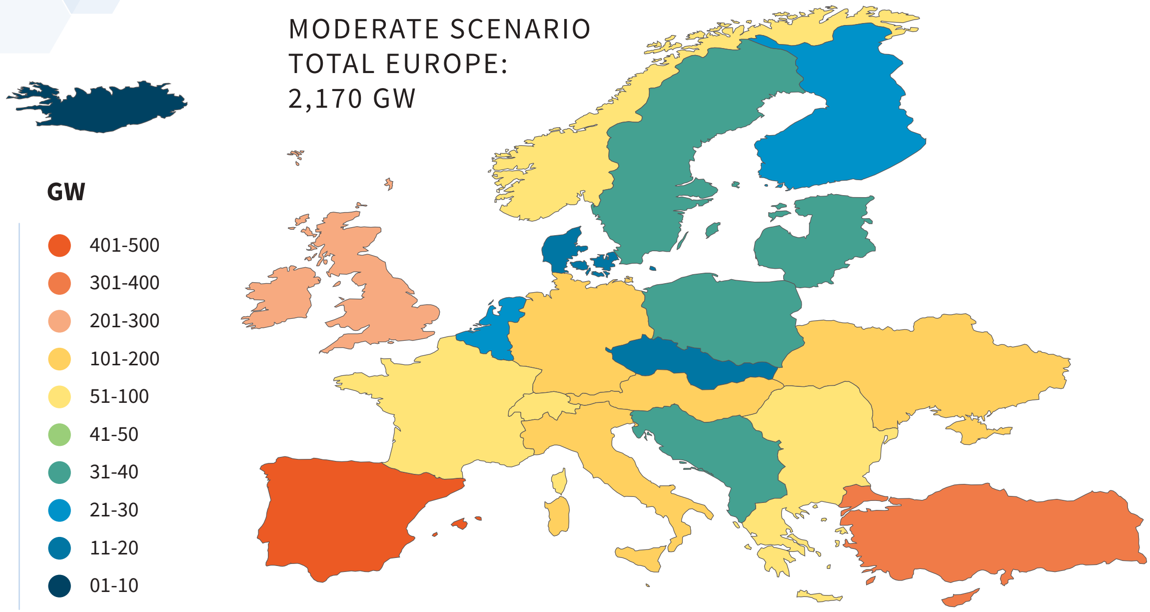
FIGURE 4.4 REGIONAL HEAT STORAGE OUTPUT IN 2050 ACROSS EUROPE

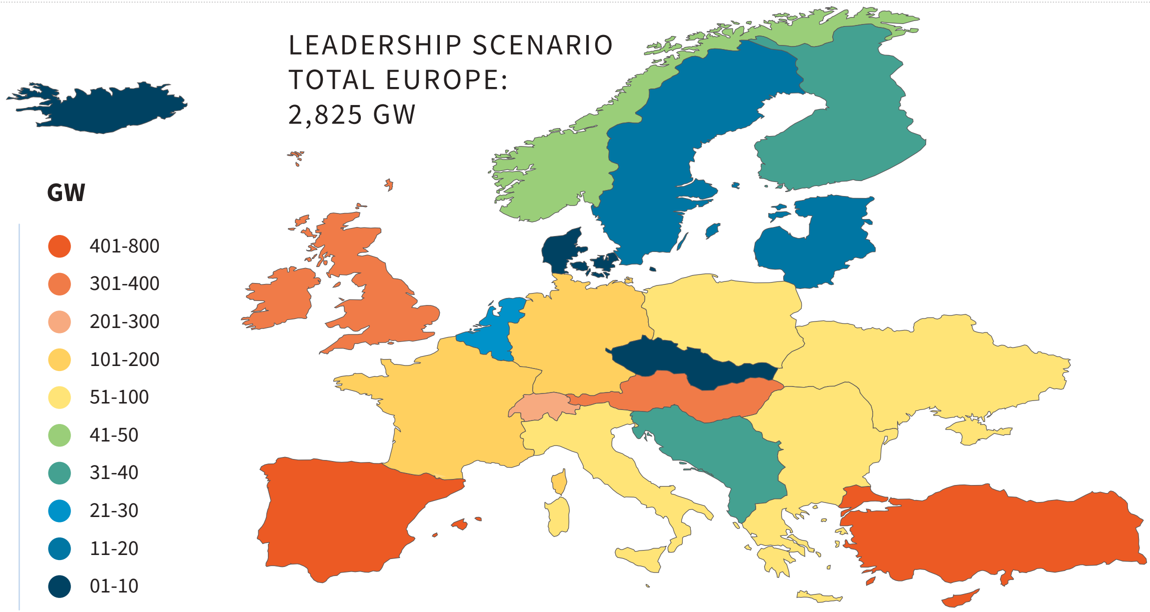


Source: SolarPower Europe.

will be well distributed across Europe in both the Leadership and Moderate scenarios, with the higher capacities operating in Spain and Turkey (see Fig. 4.5). Overall, the Leadership scenario sees 2,825 GW of electrolysers installed in 2050, that's 30% more than for the Moderate scenario with around 2,170 GW, as they will be needed from 2040 onwards for the production of synthetic fuel exports volumes. This is contrary to assumptions that synthetic fuels must be imported even for 100% renewable energy supply. While imports in an open market will very likely occur, **a detailed cost comparison has shown that synthetic fuel production in southern Europe in 2030 will not be more expensive than in North Africa, and that obviously there is a gain in energy security since the energy will be produced in Europe.**[27]

FIGURE 4.5 REGIONAL ELECTROLYSER CAPACITY IN 2050 ACROSS EUROPE

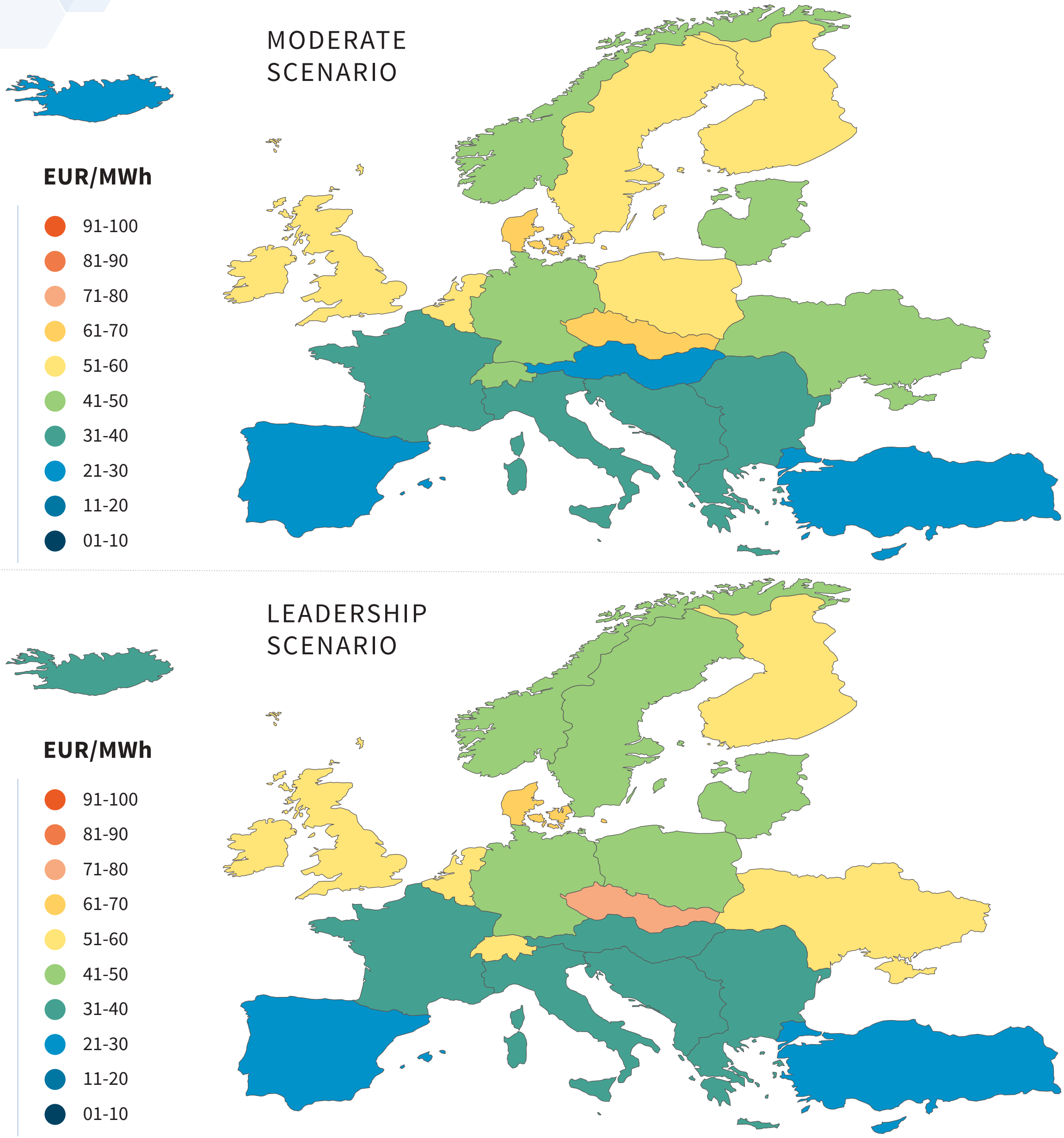




Source: SolarPower Europe.

The average **LCOE generation** in the 20 modelled sub-regions more or less follow the distribution pattern of utility-scale solar systems, which are capable of generating power at the lowest costs under the right conditions. That is primarily a question of available sun hours, which are highest in southern Europe, where in 2050 most of the utility-scale systems will be installed, and mostly with single-axis trackers to improve the yield even more. **The average LCOEs for both 100% renewable scenarios are basically at the same level in 2050: €39.3/MWh for the Leadership, and €39.2/MWh for the Moderate scenario**. However, there are slight regional differences in the two scenarios, with southern regions in the Leadership scenario showing slightly higher LCOEs due to a higher share of older and thus more expensive solar PV capacity installed prior to full decarbonisation by 2040, while the highest average LCOE in the Czech Republic / Slovakia region of the model stems from the significant stranded investments in nuclear power plants, which still add to costs without electricity supply, and a high reliance on imports.

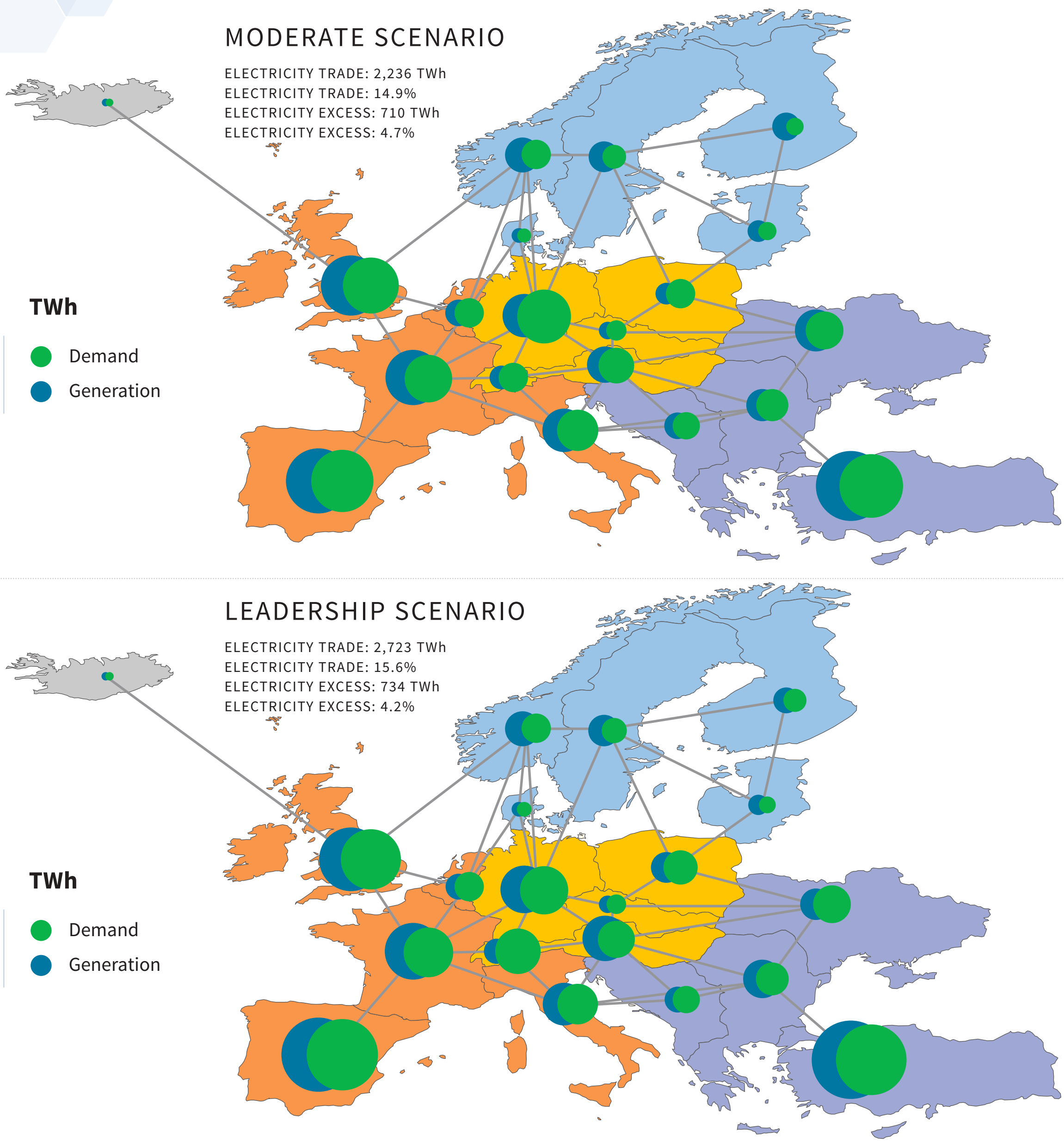
FIGURE 4.6 LEVELISED COST OF ELECTRICITY IN 2050 ACROSS EUROPE



Source: SolarPower Europe.

Adequate transmission interconnections across Europe (modelled for 20 regions in this project) are critical for optimal usage of local resources and low-cost generation using renewable energy. Integration of the energy system with high levels of electrification, sector coupling, and storage technologies result in optimised electricity trade across the 20 modelled regions in 2050, at around 2,200 TWh and 2,700 TWh in the Moderate and Leadership scenarios, respectively (see Fig. 4.7). Demand and generation are well synchronised in both the scenarios, indicating high utilisation of local resources to meet annual energy demand, realised with the support of medium and low-voltage electricity network. About 15% of the generated electricity is traded across the interconnected regions, which means that the bulk of electricity (85%) is generated within the regions where demand originates. This enables a highly decentralised energy system design, coupled with an interconnected and cost-optimised European energy system. As a result, curtailed electricity is less than 5% for both sustainable scenarios with 100% renewable energy.

FIGURE 4.7 ELECTRICITY DEMAND, GENERATION AND TRADE IN 2050 ACROSS EUROPE



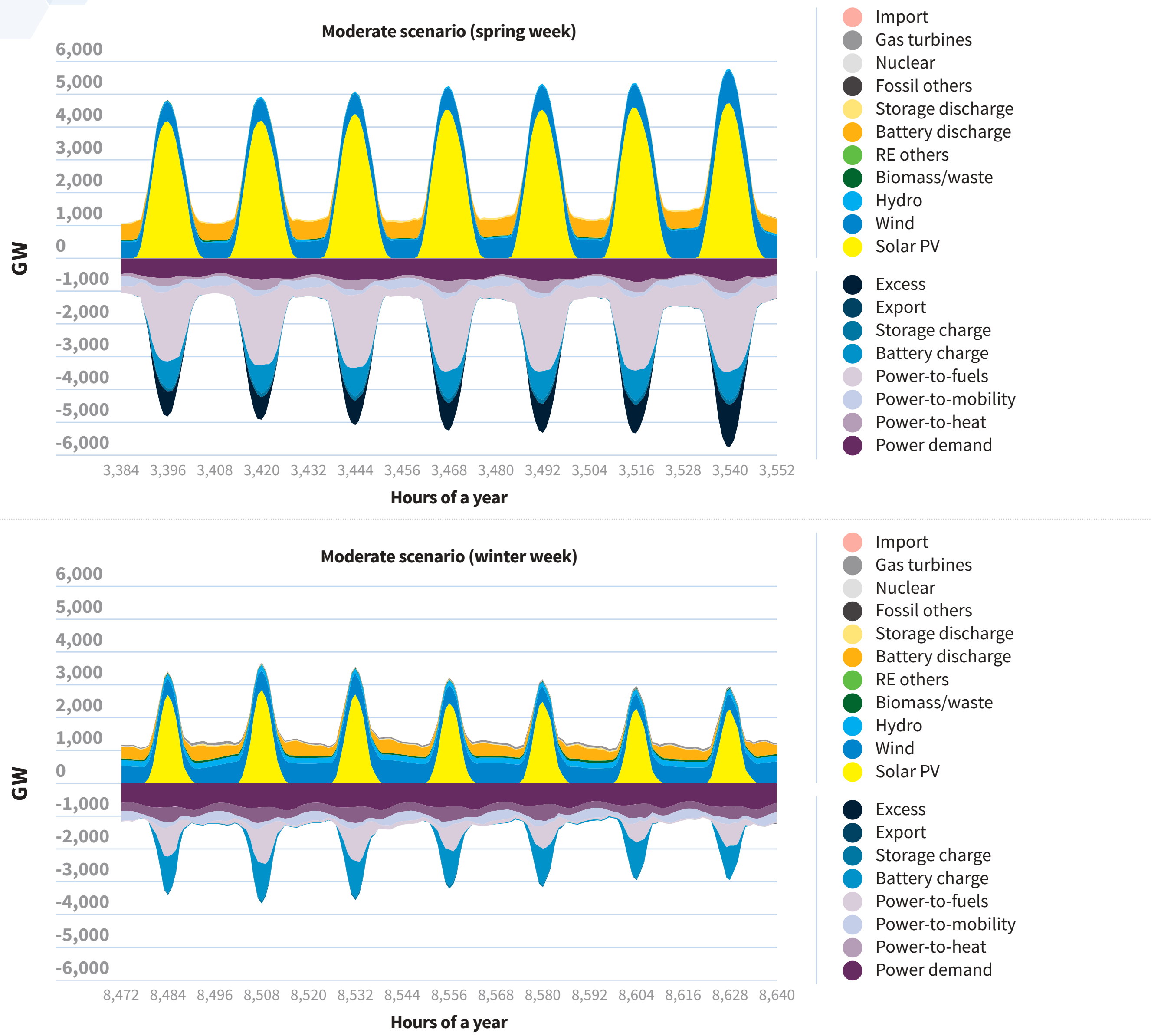
Source: SolarPower Europe.

Seasonal variation

The most frequently raised doubt on a 100% renewable-based energy system is the topic of seasonality. While critiques usually accept that batteries are an appropriate solution to overcome the night, it is more demanding to explain how an energy system running on solar and wind can survive throughout the winter. The hourly resolution of this model allows the supply and demand to be calculated for every day until 2050 in each of the 20 regions. In this regard, the hourly results (all 8,760 hours of a year) were selected for visualisation from the modelling of the Moderate scenario for the most resource-rich week (spring) and the week of least variable renewable energy generation (winter) in France, Germany, and Europe as a whole.

The hourly operation of the integrated European energy system for the Moderate scenario in 2050, during the week of highest generation in spring and the week of lowest generation in winter, is depicted in Fig. 4.8. During spring, there is substantially more electricity generation in the range of 4,750 GW to 6,000 GW in comparison to the winter week, which has electricity generation between 3,000 GW and 3,500 GW.

FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM

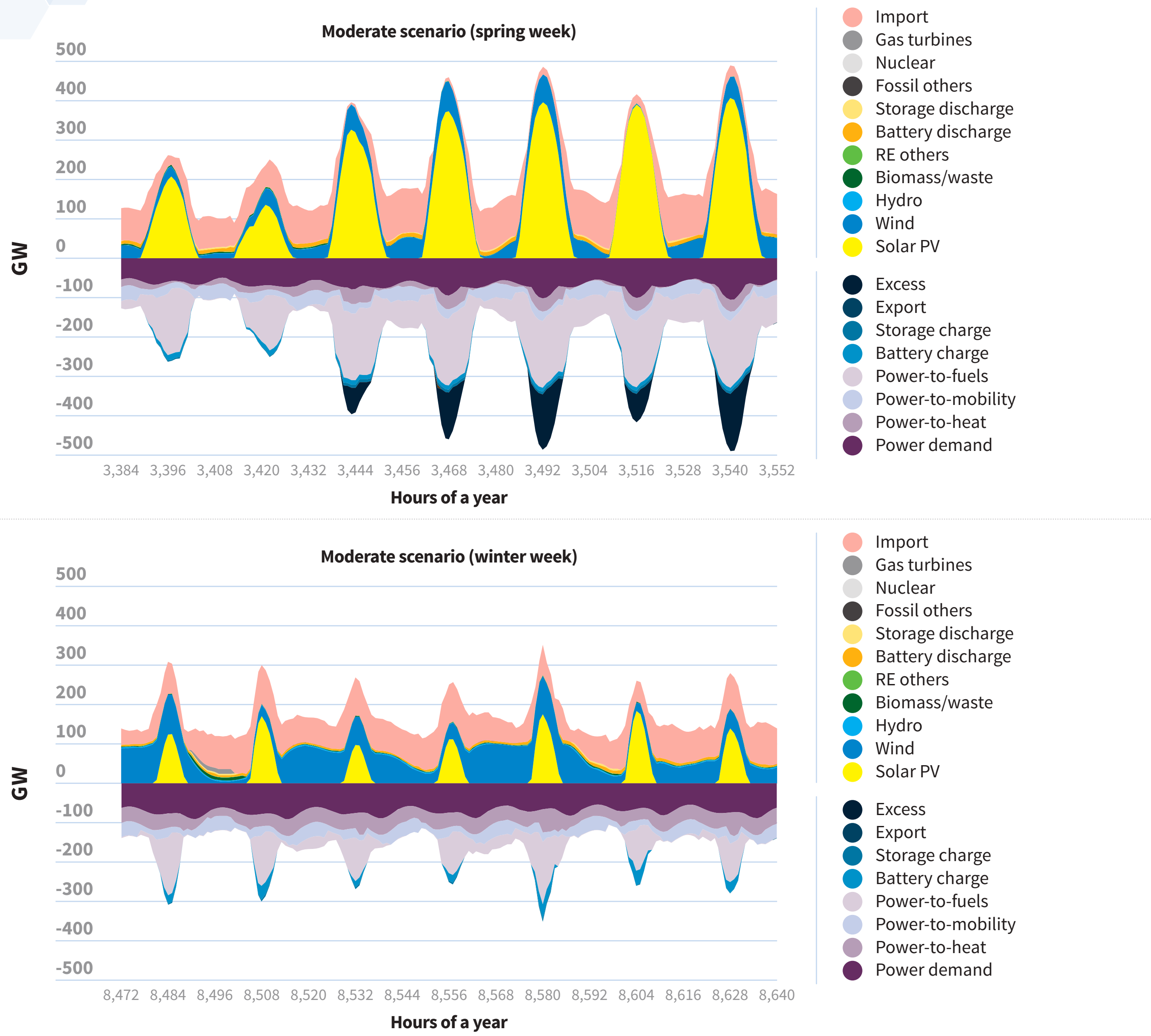


Source: SolarPower Europe.

While solar PV is the dominant energy generation source in the spring week, wind and hydropower generation supply the energy needs in the winter week. Much more Power-to-Fuels can be seen in the spring week, whereas more Power-to-Heat is needed in the winter week. Battery charging and discharging is prominent in both weeks. There is some excess electricity available in the spring week.

In order to better understand the operation of an integrated and interconnected European energy system in 2050 on a regional level, the Moderate scenario was modelled for a week in spring and winter in Germany (see Fig. 4.9). At this regional level, energy generation is higher in spring (up to 470 GW) than in winter (up to 275 GW). In the spring week, solar PV is the dominant energy source, while lower amounts of wind generation can be observed. During the winter week, wind is the dominant source of electricity. However, the installed solar capacity of 605 GW is able to produce around 16% of daily demand, despite there being less than 8 hours of sun per day. The value of interconnections is noticed in both weeks, as imports cover a substantial amount of electricity,

FIGURE 4.9 HOURLY OPERATION OF THE ENERGY SYSTEM IN GERMANY



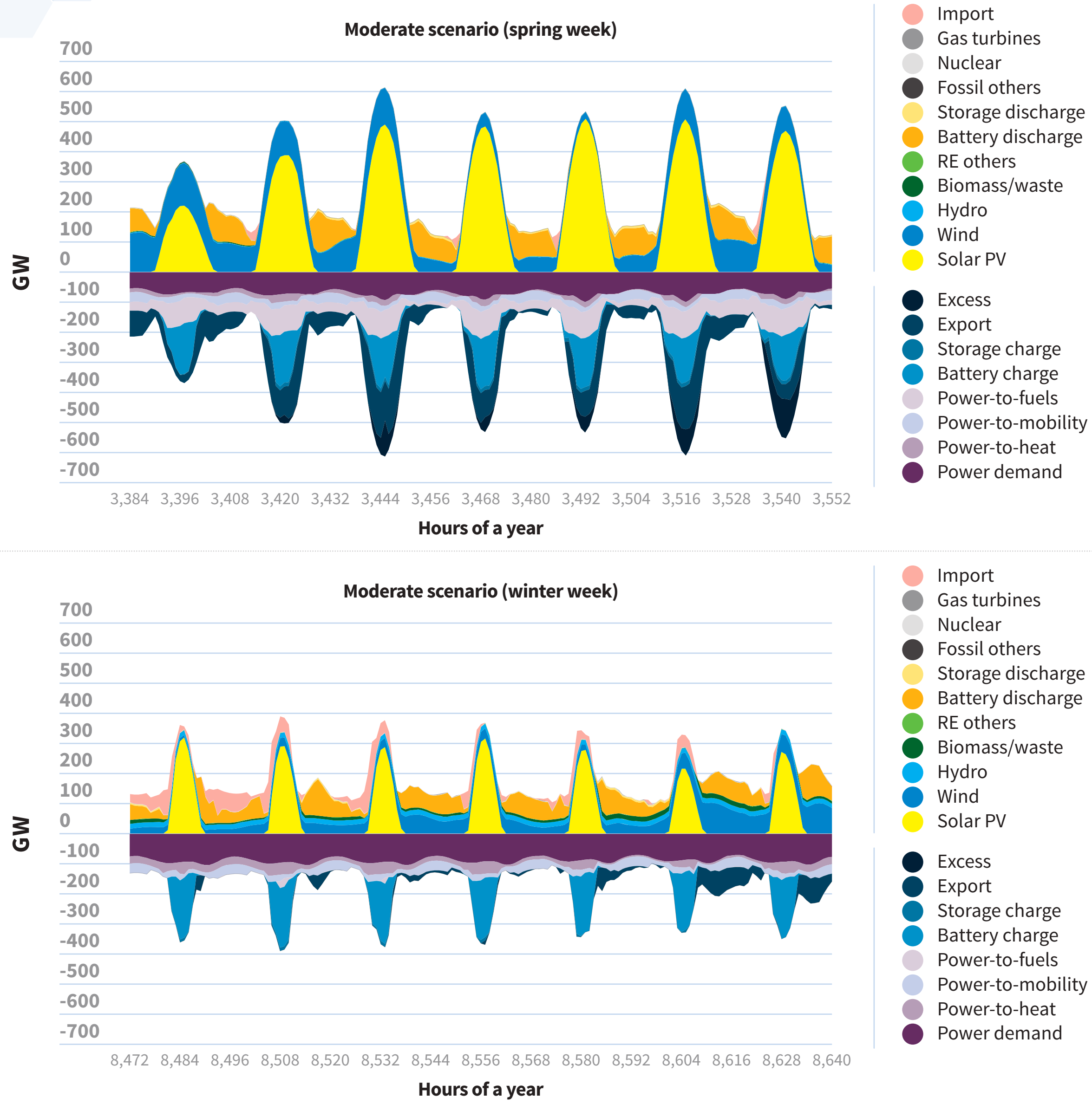
Source: SolarPower Europe.

therefore reducing the need for higher capacities of batteries. Power-to-Fuels, mainly electrolysers, are more operational in the spring week compared to the winter week, which sees a higher operation of Power-to-Heat, mainly heat pumps and direct electric heating, to meet the heat demand in winter.

Overall, in a cost optimal situation in 2050, imports are a vital source of electricity in Germany. On the contrary, France exports higher shares of power in both the spring and winter weeks (see Fig. 4.10). Imports are also observed in the winter week, whereas batteries have a vital role with charge and discharge cycles in both weeks.

In summary, the 100% renewable-based and fully integrated European energy system in 2050 will function without fail every day of the year. This is true during the dark winter days, when the continent's largest economies, Germany and France, both easily cope with energy demand. While different storage technologies and synthetic fuels are key, the possibility of importing power from neighbouring countries in the flexible and highly integrated system is also important.

FIGURE 4.10 HOURLY OPERATION OF THE ENERGY SYSTEM IN FRANCE



Source: SolarPower Europe.

ABBREVIATIONS

A-CAES	Adiabatic Compressed Air Energy Storage
BECCS	Bioenergy Carbon Capture and Storage
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
CCS	Carbon Capture And Storage
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat And Power
CSP	Concentrated Solar Thermal Power
DAC	CO_2 Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DH	District Heating
DME	Dimethyl Ether
FCEV	Fuel Cell Electric Vehicle
FLH	Full Load Hours
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GT	Gas Turbine
GW	Gigawatt
HDV	Heavy Duty Vehicle
HHB	Hot Heat Burner
HT	High Temperature
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IH	Individual Heating
LCOC	Levelised Cost of Curtailment
LCOE	Levelised Cost of Electricity
LCOEnergy	Levelised Cost of Energy
LCOH	Levelised Cost of Heat
LCOS	Levelised Cost of Storage
LCOT	Levelised Cost of Transmission
LCOW	Levelised Cost of Water
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
LT	Low Temperature
MDV	Medium Duty Vehicle
MED	Multiple-Effect Distillation
MSF	Multi-Stage Flash
MT	Medium Temperature
MW	Megawatt
OCGT	Open Cycle Gas Turbine
OPEX	Operational Expenditures
PHEV	Plug-in Hybrid Electric Vehicle
PHES	Pumped Hydro Energy Storage
PP	Power Plant
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
R/O	Reverse Osmosis (seawater)
SNG	Synthetic Natural Gas
ST	Steam Turbine
TES	Thermal Energy Storage
TPED	Total Primary Energy Demand
TW	Terawatt
TTW	Tank-to-Wheels

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Utility-scale PV. © SolarCentury

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