A SYSTEMIC APPROACH TO THE ENERGY TRANSITION IN EUROPE

Science Advice for Policy by European Academies

Evidence Review Report No. 9

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Science Advice for Policy by European Academies

A systemic approach to the energy transition in Europe

Informs the Scientific Opinion
of the European Commission Group of Chief Scientific Advisors

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About SAPEA

SAPEA brings together outstanding expertise from natural, applied, and social sciences and humanities, from over a hundred academies, young academies and learned societies in more than 40 countries across Europe.

SAPEA is part of the European Commission's Scientific Advice Mechanism. Together with the Group of Chief Scientific Advisors, we provide independent scientific advice to European Commissioners to support their decision-making.

We also work to strengthen connections between Europe's academies and Academy Networks, and to stimulate debate in Europe about the role of evidence in policymaking.

Europe's academies draw on the best scientific expertise to provide independent, balanced and authoritative scientific advice. This approach makes SAPEA a critical source of evidence for policymakers and the wider public.

Our five Academy Networks collectively represent over a hundred academies, young academies and learned societies across Europe. SAPEA works to strengthen these academies and provides a means for close collaboration in a unique and interdisciplinary way.

For further information about SAPEA, visit www.sapea.info.

Foreword

Climate change is affecting every country on every continent. It is affecting lives and disrupting national economies. Weather patterns are changing, sea levels are rising, and weather events are becoming more extreme.

The Paris Agreement, adopted in 2015, aims to strengthen the global response to the threat of climate change by keeping a global temperature rise well below 2°C above pre-industrial levels. The Agreement also aims to strengthen the ability of countries to deal with the impacts of climate change, through appropriate financial flows and a new technology framework. The European Commission's climate change strategy, the European Green Deal, launched in 2020, focuses on the promise to make Europe a net zero emitter of greenhouse gases by 2050 and to demonstrate that economies will develop without increasing resource use.

However, while the goal is clear, the pathway to reach net zero emissions is not. It will require a major transition of the European energy system away from the current reliance on fossil fuels towards low carbon or renewable sources of energy. The implications of the energy transition will impact all parts of our societies, including a range of technical, economic, and social aspects, which can be described as systemic effects of the transition. Euro-CASE member academies brought this scientific concept of a systemic approach to the energy transition in Europe to the attention of the European Commission, which as a result asked the following question to its Group of Chief Scientific Advisors: How can the European Commission contribute to the preparation for, acceleration and facilitation of the energy transition in Europe, given the present state of knowledge on the possible transition pathways?

This SAPEA Evidence Review Report informs the Scientific Opinion of the Advisors. Both reports inform the European Commission and other policymakers, at a time when independent and evidence-based science advice for policy is needed more than ever.

With Euro-CASE as the Lead Academy Network, SAPEA assembled an outstanding multidisciplinary Working Group of twenty European scientists from sixteen different European countries, covering the technical, socio-economic and regulatory aspects of the energy transition in Europe. The complexity of such questions can only be addressed by drawing on a broad range of expertise and an extensive literature review, characteristics that are at the heart of SAPEA.

This Evidence Review Report presents the state-of-the-art knowledge on the systemic approach to the energy transition in Europe and concludes with a set of evidence-based policy options that can help Europe implement the Green Deal and reach the Paris Agreement targets.

We warmly thank all Working Group members for their voluntary contributions and dedication, as well as everyone involved in pulling this report together, and especially the chairs of the SAPEA working group, Professors Peter Lund and Christoph Schmidt (who was co-chair until 11 May 2021).

Finally, we would also like to express our sincere gratitude to the science academies across Europe, through whose work SAPEA could bring together the outstanding experts to form the working group.

Professor Tuula Teeri
Chair of the Euro-CASE Board

Professor Antonio Loprieno
Chair of the SAPEA board

Executive summary

The transition of the energy system to tackle climate change is a key challenge and priority for the EU. The most recent policy framework for measures needed to make the necessary emission reductions have been defined in the European Green Deal in line with the recommendations of the Paris Agreement. This implies that the whole European energy system must be transformed to achieve net zero emissions by mid-century. The implications of the energy transition will impact on all parts of our societies, including a range of technical, economic, and social aspects, which can be described as systemic effects of the transition.

This SAPEA report is part of a project being carried out by the European Commission's Scientific Advice Mechanism on a systemic approach to the energy transition in Europe. The main question addressed here is:

> How can the European Commission contribute to the preparation for, acceleration and facilitation of the energy transition in Europe, given the present state of knowledge on the possible transition pathways?

The report takes a multidisciplinary and systemic approach to address this challenge, addressing economic, regulatory, social and technical perspectives in particular. The report provides evidence-based observations for achieving the EU's emission targets by 2050 from an energy system transition perspective, relying on the best scientific evidence.

There are many possible pathways towards carbon neutrality, but the transition already needs to accelerate to reach the necessary intermediate targets to stay on track. This needs to take place in a strategic direction that enables the long-term infrastructure related investments required to avoid technology lock-in risks and facilitate the highly challenging deeper decarbonisation required in the near future. This will also need decisive regulatory actions that combine with other European objectives and social principles. Consequently, the energy transition ahead requires solving a huge systemic problem, since it involves coordinating an almost countless number of individual voluntary decisions on investment, consumption, and behaviour in the EU. Therefore, this report does not recommend an unequivocal policy package for Europe, but rather a set of policy options addressing various facets of the overall challenge. However, as a central conclusion, any successful policy must involve a carbon pricing mechanism, in both the EU Emissions Trading System and Effort Sharing Regulation sectors, that delivers a sufficiently high carbon price while putting the pricing in a socially just frame.

The policy options of this report have been evaluated in terms of their potential to deliver an effective transition and reach the emission targets, their economic efficiency at the societal level, and their ability to maintain a social balance and social acceptability of the transition. Against this background, the SAPEA Working Group developed six policy options as follows:

- Shaping an effective and efficient regulatory strategy
- Supporting technical innovation
- Geopolitical perspective remains important
- Strong system integration is key for expanding electrification
- Technology diversity should be maintained
- Policy must stimulate behaviour alongside technology

The main content of these policy options is described below.

Shaping an effective and efficient regulatory strategy

There are a range of possible governance options the EU and its member states can employ to drive the energy transition. However, irrespective of the concrete policy package to be chosen eventually by European policymakers, a strong case is emerging for employing an all-encompassing carbon pricing mechanism as an important element of the resulting policy mix. A socially equitable energy transition needs to be stressed in this context that could include compensation mechanisms or reductions in direct or indirect taxes for low-income households. The EU should therefore continue to strive for a strong climate policy with sufficiently high carbon pricing, but in the form of a balanced policy portfolio that facilitates a Just Transition Mechanism, so that a majority of the public perceives it as being fair and equitable, and so that no one is left behind. Acceptance will require public engagement and participation across the diversity of publics, covering a spectrum of attitudes from nimby ('not in my backyard') to prosumer. To support this, policymakers should consider engageing in policies that highlight the need for experimentation and include more diverse publics and otherwise marginalised actors.

The EU should also intensify its efforts towards comparable total carbon costs at the international level and work towards an effective carbon club with at least important partners. Only where this is not possible, suitable regulatory mechanisms are required to bring international carbon costs into line, prevent leakage of carbon emissions outside the EU and thus ensure the economic viability of investments within Europe.

Huge investments in energy sectors are necessary during the transition until 2050. It is likely these will need to reach 2.5–3% of GDP each year above business-as-usual investment trends, with the majority going to energy consumers for building rehabilitation, improved industrial processes, efficient equipment and new transport technologies, and the remainder to energy suppliers for renewable generation facilities and infrastructure. Investment plans with clear priorities should be prioritised by the EU, especially as a failure to invest in technology and infrastructure now will result in higher costs and emissions in the future.

Supporting technical innovation

Technologies will play a key role in the successful transition of the energy system in reaching carbon neutrality by 2050 and beyond. Huge global investments in existing and new energy and end-user technologies will be needed in the coming decades.

The dependency of Europe on imported fuel will decrease through the introduction of efficient and clean energy solutions, leading to increased energy security. However, new dependencies will emerge instead. Many of the new technologies rely intensively on materials that could increase the dependency of Europe on some key materials, despite the technologies themselves being manufactured locally in Europe. Securing European industrial competitiveness is of major concern when comparing the EU globally against key research and innovation indicators. This may reflect adversely on new energy technologies, which employ both new and traditional know-how. Attention is needed to strengthening the European innovation ecosystem and supporting public-private partnerships to accelerate commercialisation of energy innovations. Securing access to critical materials which are needed for new technologies made in Europe will require strategies to expand and diversify the European material base, while also nourishing international relations because of the evident global interdependencies that will take new forms in the coming decades.

Promoting technological innovation and diversity involves not only maintaining and perhaps phasing out typical ageing and often inefficient equipment, but it also involves promoting currently commercialised best practices as well as investing in state-of-the-art options and steering investment in future frontier or breakthrough technologies.

To support technological development beyond providing this foundation for a potent European innovation system, policymakers can, on the one hand, opt for a strong involvement of the state in directing the process of searching for innovations by direct funding of research projects and the direct support of research in public research facilities. On the other hand, they can set the framework for companies to excel through the force of competition. A combination of both approaches seems natural, but its specific design requires a sound evaluation of overlaps and interactions to prevent countervailing effects.

Geopolitical perspective remains important

The EU is well placed to take a global lead in reducing emissions, but in a way that is economically efficient, socially equitable and maintains competitiveness. In doing so, the EU must argue strongly in international forums for global efforts to accelerate. If the world is to move in line with the Paris Agreement, there would be a strong shift in the geopolitics relating to fossil fuel reserves. This will be both in reduced power of the economies possessing the fossil fuel endowments, and in increased security of supply in regions relying on renewable energy. Such developments would be beneficial for the EU as a whole, but a challenge for the few EU regions still relying on domestic fossil fuel resources for electricity generation.

However, the energy transition will have a significant impact on Europe's raw material requirements. Although there will be a decreased dependency on fuels as the reliance on renewable energy increases, there will be a steeply increasing demand for certain materials: metals such as copper, cobalt and lithium, the platinum group elements, and rare earth elements. Stronger measures to manage this demand are needed, such as a focus on recycling, reusing, diversifying supply and substituting materials. In addition, research and development on alternative materials will be of high importance. The principle of circularity will be important for the energy transition to minimise the extraction of new materials and reduce the amount of waste our society generates.

Europe should also strengthen its diplomatic efforts to ensure that key countries and economies commit themselves to the Paris Agreement goals. Striving for uniform rules globally, such as global carbon pricing, enables different pathways to be followed and would most likely provide the best economic efficiency to Europe and globally. Such a scheme should also be subject to compensation for social imbalances. To prevent carbon leakage and to preserve the competitiveness of European industry, a carbon border adjustment mechanism can be employed. But, since Europe strongly benefits from international trade, such trade barriers should be avoided wherever possible, and they should comply with the World Trade Organisation's rules.

Strong system integration is key for expanding electrification

There is a general assumption, evidenced from EU reports and others, that the energy transition will be based on large amounts of variable renewable energy (wind and solar), backed up by alternative low-carbon generation, to decarbonise the electricity system. At the same time, large-scale electrification of all sectors (heating and cooling, transport, industry) is expected as a main mitigation measure, coupled with alternative approaches in hard-to-decarbonise sectors (agriculture, aviation, etc.). Demand reduction and management, supported by increased digitalisation, will also play a crucial role. Considering the large amount of electricity needed in this context in Europe, not only massive new investments in infrastructure will be necessary, but also the balancing of the power and energy system needs special consideration. During the transition period new market designs and structures will be required, which could include different elements such as capacity markets, but also stronger market signals to incorporate sector integration strategies.

Both energy efficiency and energy savings are important for the energy transition in order to reduce or limit the growth of the overall demand for energy. These include no-regret options that increase the possible pathways to carbon neutrality, improve security of supply and have high levels of social acceptance. Energy efficiency has been an important driver of reduced energy demand and is economically profitable in many cases, but it can suffer from the rebound effect and a lack of understanding that leads to the energy efficiency gap. Energy savings require changes in behaviour from the public that require time and engagement to realise. Digitalisation of the energy system will affect the whole value chain from supply to demand, opening up opportunities for smarter and more efficient use of energy. Increased data flows accompanied by the Internet of Things (IoT), advanced data processing, artificial intelligence, and other innovations offer major possibilities to improve efficiency and manage complexity in energy systems.

It will be a huge challenge to develop an energy system based mainly on variable renewable electricity. This will be further challenged by the increasing demand on electricity when other sectors start to electrify, such as transport, heating and cooling, and heavy industry. A successful transition of the electricity system will urgently require efficient integration of both supply and demand systems by means of different system integration approaches and sector coupling. Sector coupling, or smart energy systems, exploits synergies between sectors that can lower the cost of transition and introduce energy storage options. For example, power-to-heat combines the power system with district heating, combined heat and power, heat pumps or thermal storage while smart charging and vehicles-to-grid connects the power system to an increasing fleet of battery electric vehicles. Such complex systems integration and energy system flexibility is promising and can increase the European security of supply and improve system stability.

Pathways toward climate neutrality will depend on the extent to which the transport system can be decarbonised, either directly through batteries and electric road systems, or indirectly through sustainable synthetic fuels, particularly for hard-to-electrify modes of transport such as shipping, aviation, long-haul freight and some industrial applications.

Heating and cooling is a critical and challenging sector. Policies should always be evaluated and designed in connection with strategies on improving the energy efficiency of the building stock, and in most cases, it is important to follow an energy-efficiency-first principle. In addition, European buildings have the potential to be economically converted into net zero energy buildings through retrofits, which would substantially reduce demand in that sector.

This would leave low-carbon energy resources available for the sectors where it is much more difficult to reduce energy demand or carbon emissions. For industry, the range of energy uses is broad, but for the industries with large point sources of emissions, mitigation technologies are generally available: mainly combinations of carbon capture and storage, fuel shift, and direct and indirect electrification. The challenge in the industrial sector will be to ensure that the main policy measure regulating emissions from these industries, namely the EU Emissions Trading System, will deliver a long-term price signal sufficiently strong to foster the transition without jeopardising the competitiveness of the industry.

Technology diversity should be maintained

Although the present trend indicates that variable renewable electricity (solar, wind) and electrification will play a key role in the European decarbonisation pathway, maintaining a broad emission-free technology and policy base would be well justified for several reasons, such as each member state having its own particularities, energy structure and lock-ins. Also, as policies are seldom able to pick the winning technologies of the future or to predict future technology disruptions, it should be a priority to nourish research, development, and innovation capabilities in Europe in general rather than focusing on a single technology. The cost of emission reductions, but also the severity of systemic issues in the energy system, will increase when approaching carbon neutrality. As a result, the role of carbon sinks, both technical and biogenic, will increase as indicated by European scenarios.

The energy transition will rely on many technologies that face major challenges, requiring EU-level policy consideration:

- **Bioenergy** is the main source of renewable energy in the EU gross final energy consumption, albeit with a substantial heterogeneity across the EU, and it can replace fossil fuels in all energy markets (heat, electricity and fuels). However, there is significant debate on how much biomass could be harvested in an environmentally and socioeconomically sustainable way. Agricultural and forestry, renewable energy, environmental policies and research, development and innovation policies need to be better aligned to release the full potential of bioenergy for climate change mitigation while simultaneously supporting rural development and a diversified energy market, but also considering the carbon payback period of bioenergy.

- There will be an increasing need for carbon sinks when approaching carbon neutrality, which could increase the strategic role of both biogenic and technical CO_2 sinks in the EU. **Carbon capture and storage** could be an important option for carbon-intensive industries, most notably the cement and ceramic industries but the steel and petrochemical industries could also benefit from it. As for **carbon capture and utilisation**, this should only be used in cyclic mode and using carbon from renewable energy sources.
- **Nuclear energy** is viewed as one of the pillars for decarbonisation scenarios in many countries, although it is the subject of controversial societal discussions around the world and the largely ageing nuclear power plant fleet is not being replaced with new reactors in some EU member states mainly for economic reasons, but also for political reasons. Its proponents emphasise its potential for a flexible supply of dispatchable carbon-free energy as an asset to support the rapid growth of intermittent renewable energies. However, to do so, nuclear energy has to meet key challenges, including an efficient control of the time and cost of new builds, the safe management of radioactive waste, and demonstrations of efficient decommissioning of ageing nuclear plants.
- **Batteries** will be a strategically important technology in the future energy system, in particular for the electrification and decarbonisation of the transport sector. New value-chains could mean that batteries also find new uses in the power systems in the longer term. The EU lacks a sizable manufacturing capacity of batteries as well as domestic raw material supplies, which could adversely affect the opportunities ahead and the goals of the energy transition. Stronger measures on a broad basis are needed, including increasing research and innovation efforts, supporting advanced manufacturing, scaling up manufacturing capacity, diversifying the critical material base, and updating the EU electricity market regulatory framework to better integrate distributed energy storage.
- While direct electrification is always the most efficient route for electricity use, **hydrogen and synthetic fuels** will mainly have applications in hard-to-abate sectors such as industry and aviation. As a first step, using carbon capture and storage can contribute to major carbon reduction in present applications of hydrogen. In the longer run, carbon-neutral hydrogen based on green electricity or pyrolysis will be needed. Combining green hydrogen with CO_2 yields e-fuels (methanol, methane, e-kerosene, etc.) which could be used in aviation and industry, while combining it with nitrogen opens the ammonia route. Hydrogen will be an important element in the future energy system, although its direct final use will probably be limited to industrial feedstocks. Given the costs and the significant amounts of green electricity needed, import of sustainable fuels from outside the EU may also be needed.
- Policies also need to focus on **energy infrastructure**, including investment in grid networks such as the power system or district heating to enable full integration and

exploitation of the different technologies needed to reach carbon neutrality. This would also support technology diversity.

Policy must stimulate behaviour alongside technology

Most greenhouse gas emissions can be ascribed to household consumption. This makes decarbonation as much about household decision-making, demand and behaviour as technology. Demand-side options are often linked with lifestyles and required behavioural change to decarbonise lifestyles. Unfortunately, policies and behaviour are often misaligned, but the potential emissions reductions to be achieved by targeting behaviour can be very large. Policies should not view households as passive recipients loosely connected to climate change, but as active participants whose lifestyles play a central (and disruptive) role in contributing to energy and climate problems. Therefore, behaviour can be just as important as new technologies.

COVID-19 has had a significant impact on energy demand caused by lockdowns of society with significant reductions seen across the EU, although recent data suggests that demand is returning to pre-pandemic levels as social restrictions are removed. The lessons learned over this period will provide valuable insights, particularly in terms of social behaviour around working practices and mobility. Along with this, the very significant spending on economic recovery, as well as the induced changes in energy markets and digitalisation, provide a unique opportunity for accelerating the energy transition.

Chapter 1. The energy transition

The European Union has set ambitious climate targets and decarbonising the economy is a primary political objective. The European Commission has proposed a target of net zero greenhouse gases (GHG) emissions in the EU by 2050 (European Commission, 2018).

The goal is clear but the pathway to reach net zero emissions is not. It will require a major transition of the European energy system away from the current reliance on unabated fossil fuels towards low-carbon or renewable sources of energy. An impartial, independent and systemic approach, with insights from experts with a multidisciplinary background, will be needed to fully understand the interdependencies and developments in order to provide a robust information-based anticipation of future requirements for the energy transition.

In this context, the European Commission's Group of Chief Scientific Advisors was asked to provide a Scientific Opinion on a systemic approach to the energy transition in Europe.[1] The main question to the Advisors is:

> How can the European Commission contribute to the preparation for, acceleration and facilitation of the energy transition in Europe, given the present state of knowledge on the possible transition pathways?

Considerations should include constraints from technologies, services, primary energy sources, economics, raw materials availability, preferred pathways, social considerations and environmental boundaries.

In support of the Scientific Opinion by the Group of Chief Scientific Advisors, SAPEA established a working group to produce this Evidence Review Report. The aim of the report is to provide a clear assessment of the realities, uncertainties and risks, identification of critical barriers or opportunities, as well as system-related aspects of the critical issues that need to be resolved. It does not provide answers to specific questions or policy recommendations, but considers evidence to help understand the critical issues and how they are all connected, with a focus on the importance of the systemic approach for the energy transition in Europe.

1 Scoping paper: A systemic approach to the energy transition Europe, European Commission, March 2020.

Particular consideration is given to the following three questions:

- **What is possible and what could be possible?** In order to meet the climate targets, there will need to be a clear understanding of what is known, what is only partially known and what is currently unknown with respect to the evidence base and underlying assumptions about the European energy system.
- **What is needed for success?** In setting a strategy for the energy transition, a coherent set of policies will need to be put in place. This will require a systemic understanding of the social, economic and geopolitical issues.
- **How do we understand social impacts and build support?** Support for and participation in the energy transition among politicians, citizens and business will be critical to success. What advice, incentives and broader instruments can be utilised to make transitions acceptable and manageable for industry, society and business?

1.1. The basis of the report

The energy transition required to meet the Paris Agreement target will require substantial changes to all aspects of the EU's energy system. Analysis of current evidence leads to the following, generally accepted view that forms the basis of this report.

The energy transition

All scenarios in line with the Paris Agreement will require a massive transformation of both the demand and supply sides of the EU's energy system. This will rely on significant amounts of clean energy production, such as variable renewable electricity generation in the form of wind power and solar PV, with their individual contributions depending on local geographical characteristics.

Other low-carbon-emission technologies will play a role, including carbon capture and storage, nuclear power, bioenergy, waste heat, hydropower and hydrogen, although there is more uncertainty concerning their respective levels of deployment.

At the same time, the industrial and transport sectors envision a high degree of electrification as a means of decarbonisation, including indirect electrification via synthetic fuels. Decarbonisation of heating and cooling will also increasingly make use of electrification (e.g. heat pumps in buildings and as part of district heating networks), but also rely on other low-carbon technologies, such as renewable energy and energy-efficient end-use technologies.

Energy demand reduction is expected to play a critical role in all sectors, along with demand flexibility and sector integration, including links between electricity, transport and heating systems.

Multiple possible pathways exist that could meet the Paris Agreement target. The choice will depend on a range of technical, economic, political and social factors.

1.2. EU decarbonisation strategies

In November 2018, the European Commission published *A clean planet for all* (European Commission, 2018) which set out a long-term vision for an energy system with net zero GHG emissions by 2050, with the aim of offering a pathway consistent with the Paris Agreement. In 2019 the EU completed an update of its energy policy framework, including the European Green Deal (European Commission, 2019), to facilitate the transition away from fossil fuels towards cleaner energy and to meet the commitments in the Paris Agreement. There is a new 'energy rulebook' called the *Clean energy for all Europeans* package (European Commission, 2021) which consists of eight legislative acts.[2] There is a political agreement by the Council and the European Parliament, meaning the different EU rules came into force in 2019, giving EU member states 1–2 years to transpose the new directives into national law. The aim of coordinating the changes at EU level is to underline EU leadership in tackling global warming and to contribute to the EU's long-term strategy of achieving carbon neutrality by 2050.

Important directives are:

- the Energy Performance of Buildings Directive (Directive (EU) 2018/844)
- the recast Renewable Energy Directive (Directive (EU) 2018/2001)
- the amending Directive on Energy Efficiency (Directive (EU) 2018/2002)
- the Regulation on the Governance of the Energy Union and Climate Action (Regulation (EU) 2018/1999)

In addition, part of the *Clean energy for all Europeans* package has the aim of establishing a modern design for the EU electricity market that will promote a more flexible and market-oriented system and facilitate integration of variable renewable electricity. The electricity market design elements include new electricity regulations, amending

2 The package is considered a significant step towards the implementation of the energy union strategy, published in 2015 (COM(2015) 080), which builds on five dimensions: security, solidarity and trust; a fully integrated internal energy market; energy efficiency; climate action, decarbonising the economy; research, innovation and competitiveness.

electricity directives, risk preparedness, and a regulation outlining a stronger role for the Agency for the Cooperation of Energy Regulators.

On the way to reaching the EU's long-term goal of carbon neutrality by 2050, the European Commission (2020h) proposed to raise the 2030 greenhouse gas emission reduction target to at least 55% (relative to 1990). In April 2021, the European Parliament and Council reached a provisional agreement supporting both the long-term and intermediate targets[3] with the legislative programme for meeting the 2030 target set out in the *Fit for 55* package.[4]

The European Commission highlights cooperation between sectors as a key enabler of the required energy transition. All scenarios for the energy transition in Europe imply significant electrification of all sectors, with an increase in electricity demand in the range of 35%–150%, depending on the degree of electrification versus high end-use energy efficiency and circularity of the economy.

An electrification strategy entails an increased supply of low-carbon electricity sources. According to the European Commission (2018), by the middle of the century the European electricity system will mainly be supplied by wind and solar power, accompanied by hydro, bioenergy and nuclear power. Furthermore, *A new industrial strategy for Europe* acknowledges the need for "a more strategic approach to renewable energy industries, such as offshore energy, and the supply chain underpinning them" (European Commission, 2020a). This is in line with recent scenarios developed by the International Energy Agency for a cleaner global energy transition to meet the global climate targets (IEA, 2017). If the cost of solar power continues to decrease as expected (IEA, 2017), solar power could reach grid parity[5] and thus become an attractive option for distributed generation not only in the south of Europe but also in northern Europe. On the other hand, the electricity generation and distribution systems are a mix of deregulated (generation) and regulated (distribution) markets. At present, there are limitations in the electricity grid at the Transmission System Operator, Distribution System Operators and local levels, and lead times for increasing transmission capacity have historically been long. Thus, the electricity transmission and distribution system may limit efficient integration of electric vehicles with smart charging strategies and the electrification of industry.

Due to the variability of wind and solar power generation, their value to the electricity system is reduced as their share in the system increases (Hirth, 2013; Zipp, 2017) unless demand-side flexibility, sector integration and smart energy systems are applied (Rai &

3 European Council, European climate law: Council and Parliament reach provisional agreement: https://www.consilium.europa.eu/en/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement/

4 Legislative train schedule, Fit for 55 package under the European Green Deal: https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/package-fit-for-55

5 The point when the cost of an alternative energy becomes equal to or less than electricity from conventional energy sources.

Nunn, 2020; Mathiesen et al., 2015; Mathiesen & Lund, 2009; Connolly, Lund & Mathiesen, 2016). This requires flexibility which can be provided by dedicated storage systems such as stationary batteries, hydro power reservoirs and hydrogen storage, as well as through linkages to other sectors such as heating and cooling, transport and industry (Kiviluoma, Rinne & Helistö, 2017; Pilpola & Lund, 2019). Thus, sector integration is crucial for the efficient deployment of wind and solar power, as emphasised by the European Commission (2020b) in their communication *Powering a climate-neutral economy: An EU strategy for energy system integration*. Sector integration can, for example, include smart charging solutions for electric vehicles, flexible operation of heat pumps in district heating systems with thermal storages, flexible production of hydrogen with storage of the end synthetic fuels for selected industries and heavy-duty transport, and flexible operation of combined heat and power plants combined with thermal storage units. The role of these technologies will be system-dependent (see Chapter 5, p.78).

Thus, while electrification is expected to increase the pressure on the exploitation of renewable resources, it can also increase the ability of the electricity system to accommodate varying renewable electricity generation if implemented strategically (Joskow, 2019). While such a strategy makes the system more complex and difficult to control, it could offer substantial benefits that would increase the competitiveness of the European energy system. If combined with energy efficiency measures in each sector, the supply chain effects can reduce the costs of decarbonisation and ease the strain on renewable energy sources. There is much to gain from optimising the organisation and multi-level governance of these different sectors and systems (Bistline, 2019). Increased transmission capacity between regions would also facilitate integration of variable renewable electricity.

Linked to flexibility, the EU has proposed *A hydrogen strategy for a climate-neutral Europe* (European Commission, 2020c) with the target of hydrogen being on an open competitive market from 2030 and onwards, reaching all the 'hard-to-decarbonise' sectors for which the alternatives are unfeasible or entail a higher cost. The strategy concludes that "renewable electricity production needs to massively increase as about a quarter of renewable electricity might be used for renewable hydrogen production by 2050". This fits well with increasing the use of hydrogen in some industries, as in the Swedish HYBRIT project[6] for developing hydrogen-based steelmaking. Hydrogen may also be required to decarbonise some parts of the transport sector as a complement to direct electrification using battery electric vehicles and electric road systems.

6 HYBRIT – short for Hydrogen Breakthrough Ironmaking Technology – is a joint venture between SSAB, LKAB and Vattenfall, aiming to replace coal with hydrogen in the steelmaking process.

1.3. The role of energy demand in reaching the EU's climate goals

When considering the general issue of energy demand, it is important to distinguish between the terms 'energy efficiency' and 'energy saving'. 'Energy efficiency' means using less energy to perform the same function, whereas 'energy saving' (or conservation) is any behaviour that results in the use of less energy. Energy efficiency measures are typically achieved by improved technology, whereas energy savings will involve changes in the behaviour of consumers or other actors (e.g. in industry or in building maintenance). Both efficiency and savings are important for the energy transition in order to reduce the overall demand for energy, or to limit its increase in cases where a growth in energy services can be expected.

The importance of absolute energy demand reductions has been a priority since the adoption of the Paris Agreement in 2015. An effective focus on demand reductions will put less pressure on the supply side and require less deployment of negative-emission technologies or approaches. The International Institute for Applied Systems Analysis Low Energy Demand (LED) scenario (Grubler et al., 2018) showed that, by placing a major emphasis on reducing final energy demand, it is possible to reach 1.5°C-compatible climate goals without major deployment of bioenergy with carbon capture and storage, and without compromising development or service demands.

To strive for reduction in energy demand in an absolute sense therefore seems pivotal. Correspondingly, the EU has been introducing a wide range of strategies, regulations and action plans towards improving energy efficiency and reducing energy demand. In addition, the EU has also set an 'energy efficiency first' principle[7] in its legislature intended to ensure a secure, sustainable, competitive and affordable energy supply in the EU. Today it is an established concept embedded in a broad range of legislative actions, including:

- the *Clean energy for all* package (Energy, 2021)
- the Internal Market for Electricity Directive (Directive (EU) 2019/944) and Regulation (Regulation (EU) 2019/943
- the Governance of Electricity Regulation (Regulation (EU) 2018/1999)
- one of the five pillars of the Energy Union[8]

However, at present, the LED scenario has not been downscaled to the EU level, and there are few, if any, energy scenarios that are similarly ambitious and comprehensive on the demand side as the LED while being rooted in robust science.

7 Energy Efficiency, Fact Sheets on the European Union.
8 Energy Union, European Commission.

There is a need to further quantify, operationalise and implement the potentials for energy efficiency in buildings, transport and industry. Reduced end demand in one energy sector can contribute to impacts in other sectors and, in particular, in the supply chain. There are synergies between sectors including the energy supply chain effects and additional societal, economic and environmental impacts. A concrete example is the synergy between end demand savings in buildings and a redesign of the energy system towards a more decentralised system with more energy carriers using district heating. Such systems can reduce primary energy demand while reducing transition costs, using known technologies, and increasing the overall security of supply in a decarbonisation Europe. In industry, electrification can increase efficiency by replacing inefficient fuel conversion processes, but this will of course require carbon-neutral electricity.

1.4. Summary

In summary, the above documents show that there is a clear commitment in the EU to transform the energy system towards climate neutrality and present detailed targets for a wide range of facets of the energy system. In addition, *A clean planet for all* (European Commission, 2018) presents a comprehensive overview and analysis of the technologies available for the energy transition as expressed by PRIMES modelling results, including estimated wider economic effects of the transition.

It should also be stressed that it is not visions, targets or technologies that are lacking to tackle the energy transition. The challenge will be to scale-up delivery of the necessary technologies across all sectors of the economy — power, transport, buildings and industry — in a way that maintains a secure, cost-effective and socially acceptable supply of energy services. And this implies that there should be a clear and strong climate policy as well as a frame of action for the myriad of individual private actors, companies and households, which provides the appropriate incentives for their investment decisions and consumption choices to shift in the direction of a carbon neutral economy. In this respect, it is important to draw on lessons learned by EU member states regarding policies in each area.

Chapter 2. General context of the energy transition

The aim of this report is to consider the systemic issues that pertain to the challenge of meeting the EU's target of reaching net zero GHG emissions by 2050 and the resulting transition in the energy system that will be required. The primary focus of the report is therefore the EU, but as climate change is a global problem and the EU's targets form part of the Paris Agreement, it is clear that international considerations are important.

This chapter establishes the global context of the challenge and the general political and economic conditions that will influence the energy transition. In addition, it recognises that the EU is not a homogenous whole and considers how differences between member states could have an impact.

2.1. Global energy and economic comparisons

The European Union is one of the largest economies and trading blocs in the world (behind the USA, ahead of China), based largely on the trade of manufactured goods and services, and of inbound and outbound international investments. In terms of energy and emissions, China, EU, and USA account for roughly half of global energy consumption and greenhouse gas (GHG) emissions, and close to 60% of global GDP (Eurostat, 2020). The EU has a lower carbon intensity (emissions per unit of GDP) than China (which is 75% higher) and the USA (42% higher). To some extent, this puts Europe in a more favourable starting position for decarbonising its economy than its main competitors, since some of the obstacles on the path to such an all-encompassing transition have already been overcome.

On the other hand, as reaping the low-hanging fruits typically entails lower marginal costs, being further ahead in the transition also implies that the economic costs of progressing further are higher than avoiding GHG emissions elsewhere, making the challenge of managing the mitigation process in an economically efficient way all the more important. In any case, the EU's limited share of global emissions (see section 2.4, p.34) implies that Europe needs to pursue a climate policy which encourages others to join in with global efforts to reduce emissions, especially those with relatively large shares of global emissions. Moreover, as Europe also commands a smaller domestic market for domestic industries than China (whcih is 250% higher) and the USA (54% higher), free trade is of utmost importance for the competitiveness of the EU's economy, not least its clean energy industries. Actually, the USA and China are EU's largest trade partners, accounting for (15.2%) and 13.8% of international trade respectively (Eurostat, 2020). The prevailing trend suggests that the EU's share of world energy, emissions, and economy will decrease in the future.

Carbon emissions in the EU and the USA are declining (though based on different drivers and policies, and not enough to meet even a share of the global targets which reflect their weight in the global economy), whereas China's emissions have increased more than threefold since 2000 (Figure 1). In terms of the Paris Agreement that calls for carbon neutrality in the period 2050–2060, China and the USA would need to have a much steeper decarbonisation gradient than the EU to reach such a target. Yet how the burden should be shared is not obvious and the EU should also act as a forerunner in the transition. As argued in section 2.6, p.37, the EU could combine deep emission cuts with carbon border adjustments and aid newly industrialised economies in the transition. As for China, the attribution of emissions is not always clear, since there are large imports of products from China, meaning the EU has exported part of its carbon emissions to China. Thus, there can be a large difference between consumption-based and production-based emissions. In fact, several member states of the EU have higher emissions from consumption than production (Friedlingstein et al., 2020). Better tracking of the origin of energy and emissions embedded in the imported products and collecting related data is important to increase the awareness of consumers and policymakers in this context. When approaching the carbon neutrality target of 2050, the consumption-based emissions will start to play a major role in the total carbon balance of the countries.

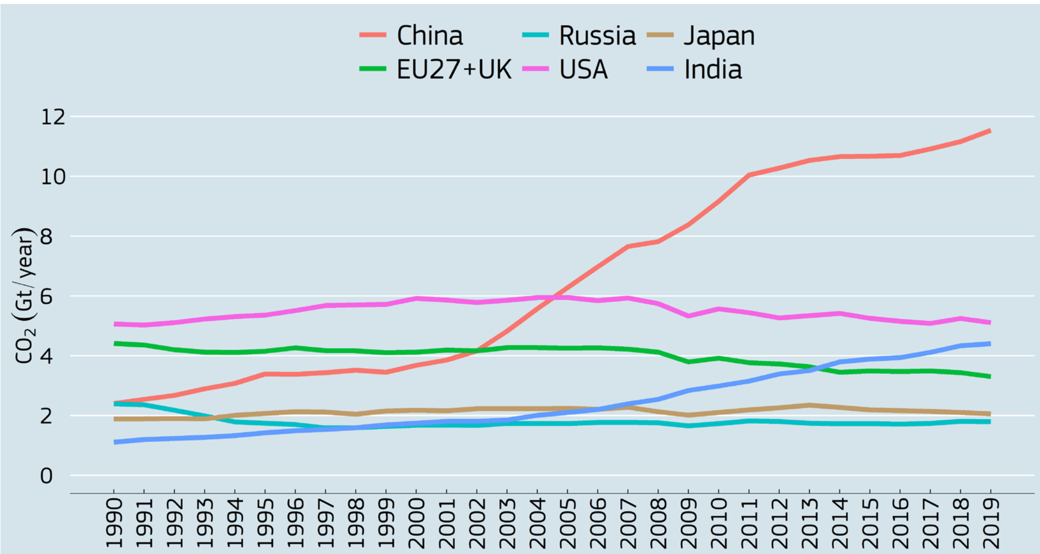

Figure 1. CO_2 emissions of the major emitting economies (Crippa et al., 2020)

The EU is highly dependent on energy imports in the form of primary fuels. All EU member states are net energy importers, with the EU as whole importing 58% of its energy. The production of fossil fuels has steadily dropped in the EU, whereas the production of renewable energy has increased, accounting now for more than a third of all primary energy (Figure 2). Imports of oil (95% of all oil) and coal (45%) have been relatively stable, whereas natural gas imports have grown over the last five years and now account for 80% of all gas used. Russia is the principal supplier of crude oil (40.4%, 2018), coal (42.4%), and natural gas (40.4%). In comparison, China's primary fuel imports corresponded to 27% of its total energy consumption in 2018 (65% of oil imported, 41% of gas, 8% of coal).[9,10] In the US, 4% of energy was imported in 2018, but it is now a net total energy exporter (natural gas and coal are exported, while oil is still imported).[11]

Thus, the present energy base of the EU compared to China and the USA is more vulnerable. The security of the EU's primary energy supplies may be threatened if the high proportion of imports continues to be concentrated among relatively few partners. This could be a major energy security issue, for example if natural gas was extensively used in connection with the energy transition as a bridging fuel or to provide flexibility in the energy supply. Energy transition strategies based on carbon capture and storage, for example, could extend the EU's imported energy dependency, whereas renewable energies would have an opposite effect. Therefore, decarbonisation and energy security will be more strongly coupled in the EU case. On the other hand, if the world complies with the Paris Agreement, it could be argued that fossil-fuel-dependent economies are the ones that will be vulnerable to the risk of stranded assets.

9 IEA (2020). Key world energy statistics. August 2020. (Accessed 3 November 2020, www.iea.org/statistics).

10 U.S. Energy Information Administration (2020). Country Analysis Executive Summary: China (30 September 2020) (Accessed 3 November 2020, https://www.eia.gov/international/analysis/country/CHN)

11 U.S. Energy Information Administration (2020). Imports fill the gap between U.S. energy use and U.S. energy production. (Accessed 3 November 2020, https://www.eia.gov/energyexplained/us-energy-facts/imports-and-exports.php)

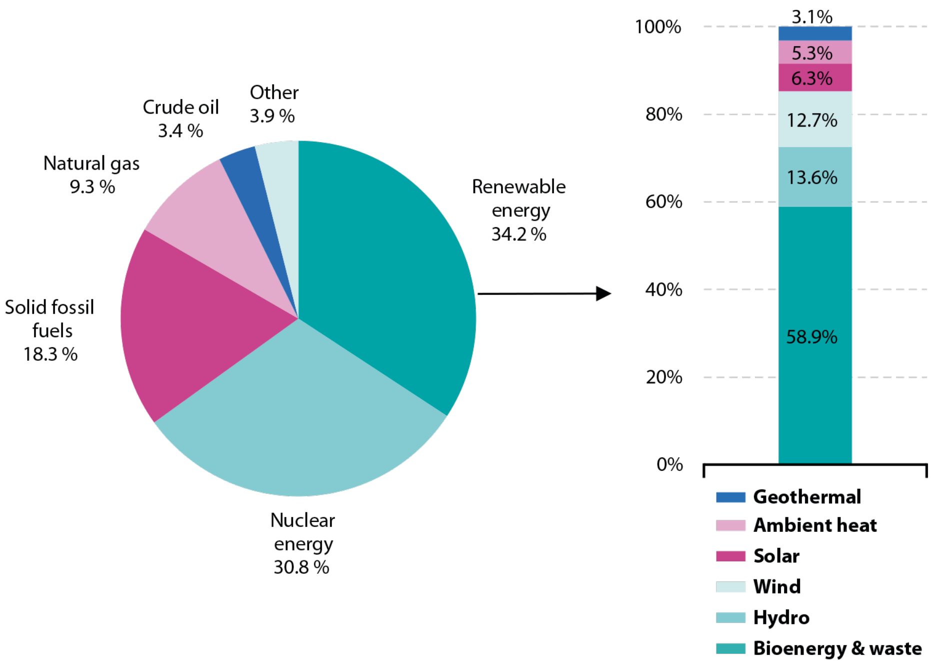

Figure 2. Primary energy sources, EU-27, 2018 (% of total) (Eurostat, 2020)[12]

2.2. Improved energy efficiency as an important 'fuel' in the EU energy system

Balanced against the primary energy needs of the EU is the level of energy demand required by society and, as noted in section 1.4, p.27, the importance of reducing this in absolute terms through energy efficiency or energy savings. Analysis shows that since 1990 energy efficiency is equivalent to the single largest 'source' of energy in the EU (Figure 3) with 30% of primary energy demand 'saved' by 2016 through improved energy intensity (units of energy per unit of GDP). However, since this trend in intensity improvements includes low-hanging-fruit measures, it will be more challenging to continue this trend (and the reduced demand from the COVID-19 crisis is likely to be temporary to a large extent).

12 Eurostat (2020), Energy production and imports of EU-27, 2008-2018. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports#Production_of_primary_energy_decreased_between_2008_and_2018

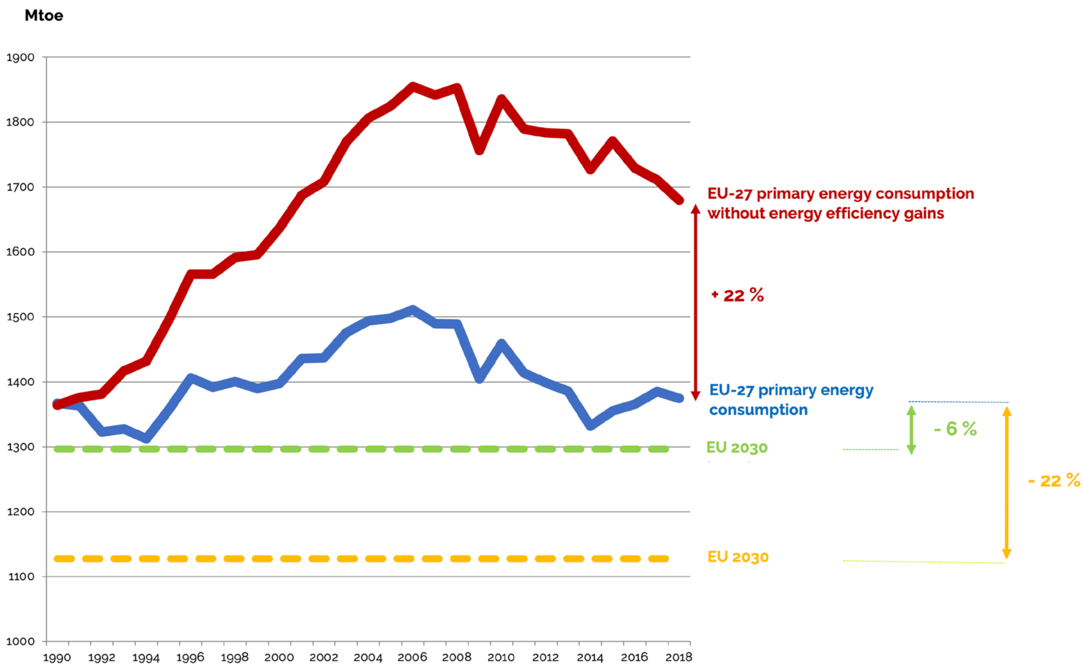

Figure 3. EU-27 primary energy consumption trends (Eurostat; European Environment Agency; aK & Company)

Although the rate of primary energy intensity change has recently been improving slightly, increased GDP growth has outpaced intensity gains, resulting in a slight overall primary energy increase since 2014 (blue line in Figure 3).

Analysis (Odyssee[13]) points out that most of the primary energy intensity gains are due to shifts in the power mix towards less primary-energy-intensive fuels such as renewables as well as a switch from coal to gas. In terms of sectors, transport and services have been most responsible for driving EU energy demand upwards over the past few decades, while industry and households are largely either stagnating or have been declining due to the post-2007 economic crisis. The difference between the red and the blue lines in Figure 3 shows the total energy reductions from these efficiency improvements. The highest contributors to the EU energy reductions from the energy efficiency gains (i.e. the red line minus the blue line in Figure 3) have been households. According to the analysis, 46% of the energy reductions since 2000 can be attributed to this sector, while transport and industry contributed roughly 25% each, with services only 4%. The Odyssee decomposition analysis attributes these results to "the importance of policy measures implemented in that sector, in particular … the many EU regulations affecting buildings and appliances". It concludes, however, that the 2030 efficiency target will not be met with the present trends and policies.

13 An internet database, part of the The Odyssee-Mure project: https://www.odyssee-mure.eu/project.html

2.3. General conditions for the energy transition

As the EU moves towards full decarbonisation, it is especially important that it remains economically competitive in relation to other regions of the world. Due to the openness of its economy, the EU is more dependent on world markets than some other economic regions. Europe therefore faces particularly tough challenges in progressing further in combining a successful energy transition with retaining economic viability.

Overall, the EU could play an important role in setting an example of how to organise a highly ambitious energy transition while simultaneously retaining high economic competitiveness and social balance. In principle, this is in line with the proposed European Green Deal (European Commission, 2019) that aims for climate neutrality by 2050, but whether Europe will succeed will depend on the specific Green Deal policies becoming implemented. So, the question of what can and cannot be done not only poses technical questions, but also economic and social questions.

The energy transition in Europe and elsewhere will be based on the introduction of different clean energy technologies at a massive scale. EU industries are generally well positioned for this transition in technologies related to the electrification of the energy system, clean fuels and sector coupling (REN21, 2020; European Commission, 2020e), meaning that domestic industries could play a central role in building the new energy infrastructure needed in Europe. However, in the energy storage and solar energy fields, Europe lacks manufacturing and scaling-up capabilities, relying heavily on technology imports. Europe is relatively competitive in applying digitalisation to energy systems, but it is behind China and USA in artificial intelligence (AI) applications in energy, which could grow into a major weakness over time if not given adequate attention, as AI will play an important role going forward.

Maintaining and improving the competitiveness of European industries in the clean energy field will be important for the goals of the European Green Deal. Classically, market-pull and technology-push efforts would be useful in this context. The domestic market could be of help for many emerging technologies, but for maturing technologies, Europe's market size may be too small to provide sufficient help from economies of scale. Securing competitiveness on a global scale will therefore be important. Improving the technology base and making more effective technologies is well within the scope of the EU's capabilities. However, China and the USA have clearly overtaken Europe in research, development and innovation (RDI). Europe should aim to reverse this trend to better secure the competitiveness of its clean energy industries. The public sector in the EU plays a much stronger role in RDI compared to our main competitors, both in terms of funding and RDI personnel. Therefore, providing more incentives to the private sector to invest in RDI will be important.

2.4. The strategic nature of European climate policy

To mitigate global warming, GHG emissions must be reduced drastically and, most importantly, at the global scale. The contribution that the EU can make on its own behalf is limited, as its share of global carbon emissions is in the order of 10%. Solving the global warming problem is a 'collective action problem', meaning the costs of contributing are concentrated while the benefits are shared. As indicated above, the role of the EU should be to set an example for others to follow. This is consistent with the commitment by developed countries, especially the EU, to pursue stricter targets than less developed countries as set out in the Paris Agreement. It would not be consistent, however, with overachieving these targets unilaterally without insisting on reciprocal commitments by other countries.

In this spirit, Europe should also be active in climate diplomacy aimed at reaching the Paris Agreement targets on global scale, as focusing only on European efforts would have less global impact. Thus, it is of great importance that the EU (and hopefully the US) will be able to set positive examples and convince other countries, in particular large emitters such as China and India, to follow in their actual policy choices, not only their pronouncements. The prospects for this should be good, considering previous experiences with the global diffusion of new technologies such as electric vehicles and solar PV panels.

Therefore, if EU climate policy is to contribute effectively to mitigating global climate change, its own mitigation efforts need to be combined with a strategy aimed at binding agreements for internationally coordinated mitigation efforts. The sensible focal point of such a strategy should be the eventual introduction of a uniform carbon price at the global scale, encompassing all regions, sectors, technologies and emitters. To reach this ultimate aim, Europe must make progress on two levels.

It must act as a role model in actually reducing emissions. Setting highly ambitious reduction targets is not sufficient. Rather, they need to be reached (GCEE, 2019):

- in an economically efficient manner
- without social distortions
- without doing serious harm to the competitiveness of the domestic economy

Setting an example in this way would be a promising overarching strategy because, by contrast to the previous European record of partially failed, albeit less ambitious targets, it would clearly underline the seriousness of the now even more ambitious European climate targets. After all, fulfilling these three decisive quality criteria will be difficult enough. Moreover, the prospect of even an economically highly developed economy, which has so far been using fossil fuels intensively, succeeding in achieving ambitious climate targets in an economically efficient manner and without major social disruptions, should have a positive and encouraging effect, and strengthen Europe's negotiation position in international climate conferences.

Additionally, European climate policy must seriously consider this strengthened negotiation position to drive globally coordinated action to meet the goals of the Paris Agreement, which could include stronger efforts to request other countries for reciprocal action. The carbon border adjustment mechanism (CBAM), endorsed by the European Parliament, may be one possibility in this context, but would need careful implementation as the EU is strongly dependent on free world trade. It will be important that the CBAM is World Trade Organisation-compatible, and designed specifically to meet climate objectives and not for enhancing protectionism. It should also include special conditions to support developing countries. The revenues generated from the CBAM could be used to further enhance the effects of the European Green Deal and to compensate for possible social imbalances.

2.5. Particularities of EU member states in the energy transition

Though the EU has common climate goals, there is no single European energy solution. EU member states have very diverse energy systems that reflect their local conditions, capabilities, limitations and past decisions (Euro-CASE, 2019). Therefore, the future paths towards carbon neutrality may be quite diverse in Europe. Figure 4 illustrates the mix of final energy sources used in the EU-27 as a whole and in its different member states, clearly showing the large diversity. Some countries, such as Finland, France, Latvia and Sweden, have a major share of energy coming from non-fossil resources, whereas most of the EU countries are heavily dependent on fossil fuels. A common feature is the high share of oil, mainly for transport. As for the electricity system, which is regarded a key element for decarbonisation, countries with hydro-based systems (such as in Austria, Finland and Sweden, as well as Norway and Switzerland which have electricity systems that are closely linked to the EU) will be in a better position to provide the energy system flexibility necessary for large-scale integration of variable renewable electricity, whereas the thermal generation systems typical in central and eastern Europe will face larger challenges in decarbonising their power systems. Actually, electricity in the Nordic countries is already more than 90% carbon-free and expected to be fully decarbonised by the end of the 2020s.

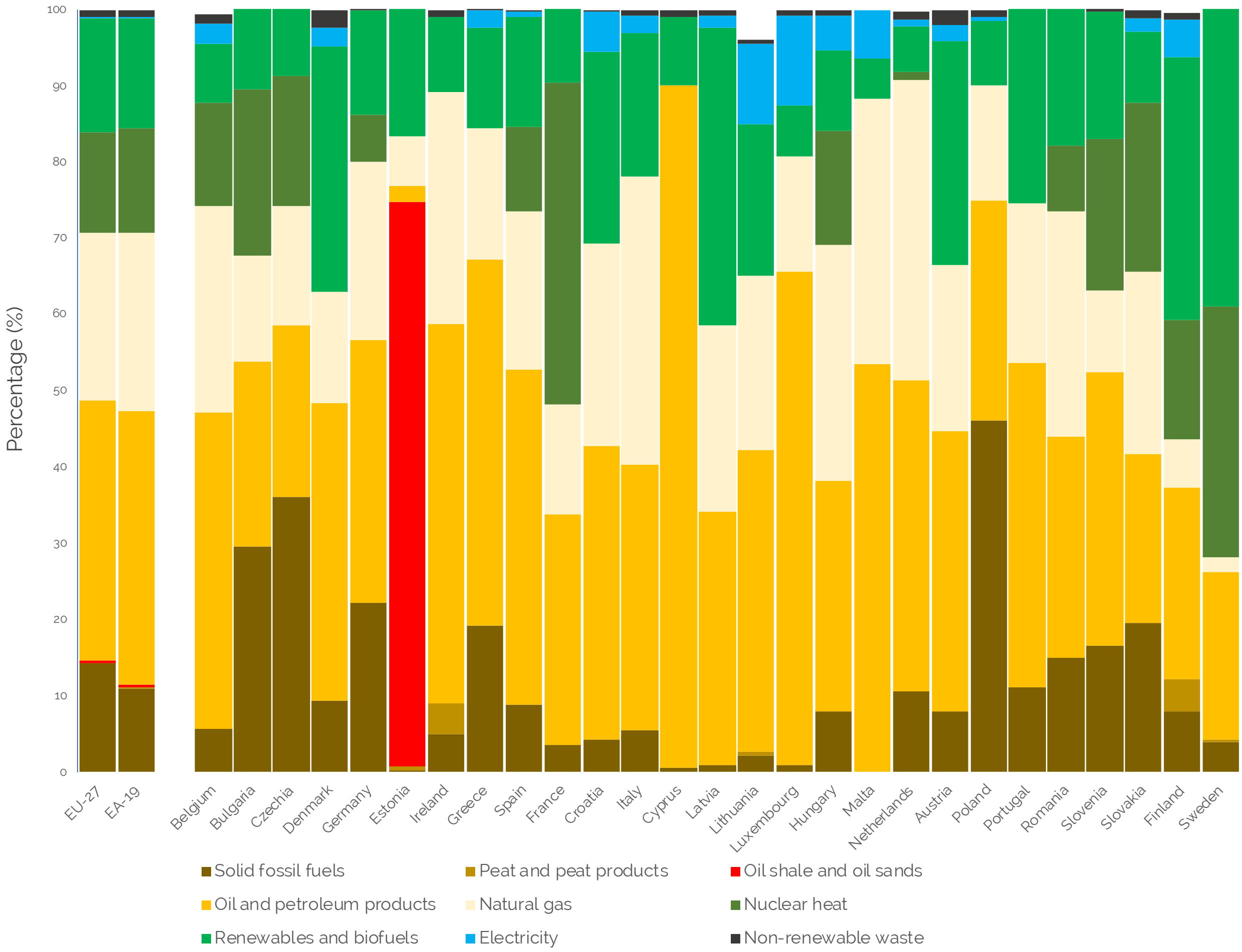

Figure 4. Gross inland energy consumption by fuel, 2018 (Eurostat, 2020)

Though the energy system differences in Europe are large, several factors are improving 'unification' and European scale solutions, such as the common European electricity market, which will necessitate Europe-wide investments in infrastructure, but also serve European countries more widely with low-carbon power. The strong electrification trend in mobility will also support unification in this respect. However, despite these trends, significant regional features may remain in the future, such as the use of nuclear power in Finland and France, or bioenergy in countries with large forestry industries.

The particularities of the EU member states are also strongly influenced by their economic capabilities. Figure 5 shows the carbon intensity and economic standing of EU countries, clearly indicating that the wealthier member states typically have a less carbon-intensive economy, whereas east and central Europe can be characterised by lower GDP per capita and a higher carbon dependency in their economy, making the energy transition more challenging. The division of the EU into two blocs is quite evident in this respect.

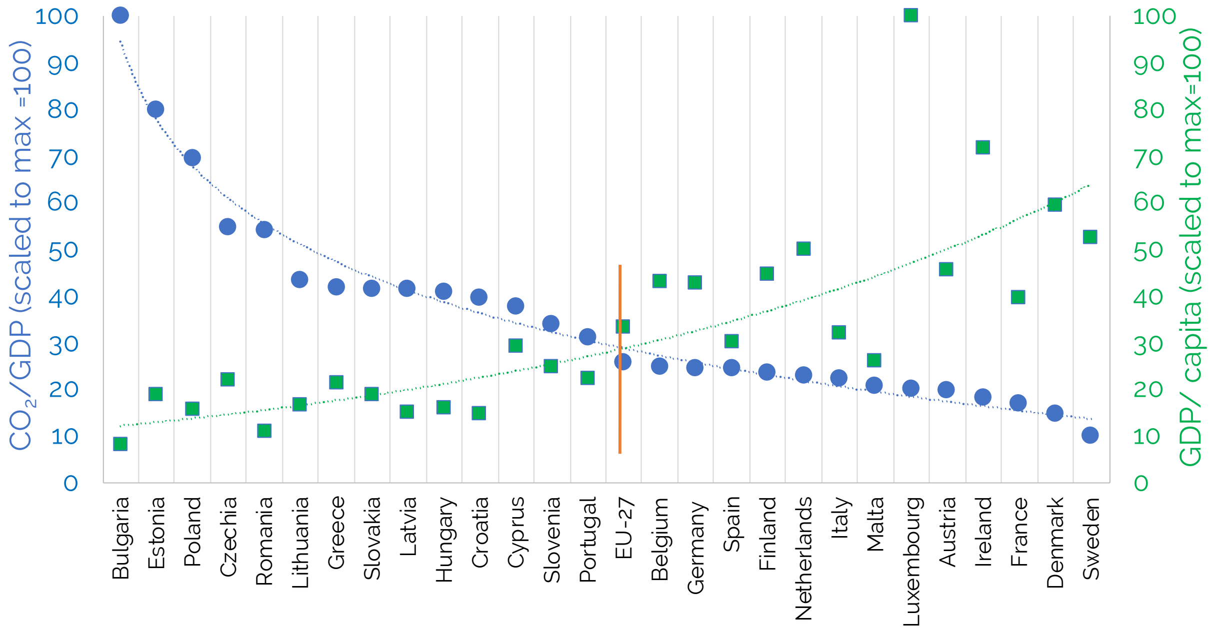

Figure 5. Carbon intensity and wealth in the EU
Blue dots indicate carbon intensity, expressed as CO_2 per GDP. Green squares indicate wealth, expressed as GDP per capita. Dashed lines show trendlines. (Eurostat, 2020)

2.6. Implications from the geopolitics of fossil fuel resource distribution

It is worth remembering that the primary reason for anthropogenic climate change is the global, but unevenly distributed, abundance of fossil fuels being burned, which has significant geopolitical implications.

Only a part of the available reserves of fossil fuels can be extracted and burnt if the world is to limit warming to well below 2˚C (McCollum, Bauer, Calvin, Kitous & Riahi, 2013; Steckel, Edenhofer & Jakob, 2015). The emission potential of the aggregated global fossil fuel reserves is around 2900 Gt of CO_2 (BGR, 2016; IEA, 2017), corresponding to around three times an estimated average remaining carbon budget of approximately 900 Gt of CO_2 to have even a two-thirds chance of avoiding a 2˚C rise in temperature.[14] It should also be noted that total fossil fuel resources, coal in particular, are much greater than the economically available reserves, although a large part of the resource base is associated

14 Climate Analytics, *ZERO IN on the remaining carbon budget and decadal warming rates*: https://climateanalytics.org/publications/2019/zero-in-on-the-remaining-carbon-budget-and-decadal-warming-rates/#:~:text=From%20the%20start%20of%202020,CO2%20for%20a%2066%25%20probability

with high extraction costs. The total emission potential (reserves plus resources) is around 47 000 Gt of CO_2 (BGR 2016; IEA 2017).

There is a fundamental difference between today's fossil-fuel-based energy system and a future renewable energy dominated system, in that the present energy system is largely based on geographically concentrated resources — fossil fuels — whereas this will not be the case for a renewable system mainly based on wind and solar energy. The present system therefore comes with geopolitical power around the distribution of fuel resources with economic advantages for the regions possessing these resources. Globally, this has an obvious effect when it comes to climate negotiations where countries with large domestic fossil fuel reserves tend to use these and resist strict emission reduction targets (Johnsson, Kjärstad & Rootzén, 2018).

The challenge is that fossil fuels still account for more than 80% of the global primary energy demand and the large expansion of renewable energy has, so far, not resulted in any noticeable reduction in the fossil fuel share of primary energy demand, as can be seen from Figure 6. The fact that the fossil fuel share in global energy demand has remained largely constant (80%) for the last 15 years, in spite of rapid expansion of renewables, obviously imposes a great threat to climate change mitigation, including its geopolitical impacts. There is also a worrying tendency that global investments in renewable technologies have levelled off during the last years. As shown by Johnsson, Kjärstad & Rootzén (2018), only countries with limited domestic resources of fossil fuels have significantly reduced their share of fossil fuels in primary energy supply. The EU corresponds to such a region which, as a whole, does not have large fossil fuel resources (except in a few member states, most notably Poland). This has already had an impact: the EU is already changing course towards a renewable system, in that these technologies have not only added to the fossil-fuel-based technologies but to some extent replaced them.

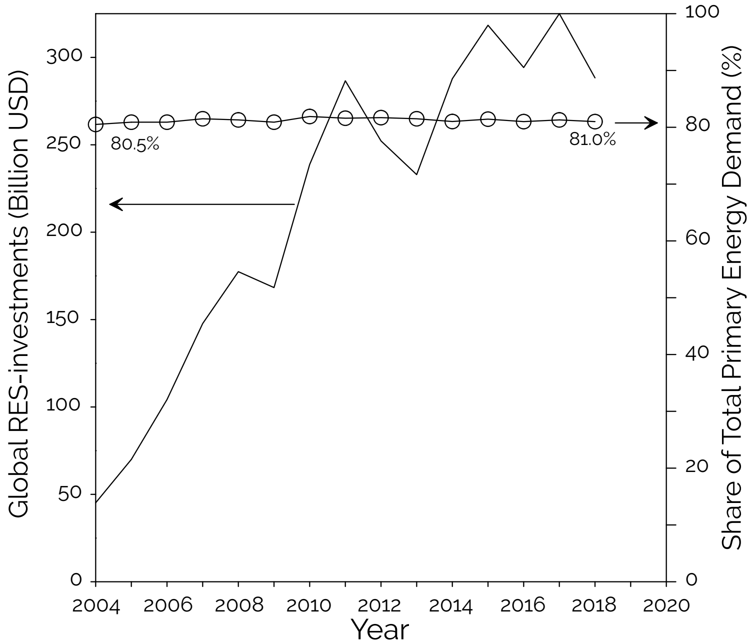

Figure 6. Comparison of the global trends in investments in Renewable Energy Supply (RES) with fossil fuel share in total primary energy demand
(Updated figure from Johnsson, Kjärstad & Rootzén, 2018)

If the world is to move in line with the Paris Agreement, there would be a strong shift in geopolitics relating to fossil fuel reserves, with reduced power of the economies possessing the fossil fuel endowments, and in terms of security of supply. The latter will be strengthened with an increased reliance on renewables in the form of wind and solar (and other non-fuel-based renewables). Equally, there could then be a risk for fossil-fuel-rich countries that their reserves become stranded assets, unless their use can be combined with carbon capture and storage, where the cost then corresponds to the additional marginal cost of using fossil fuels in a climate-constrained world. As should be clear from Figure 6, it is not obvious that countries rich in domestic fossil fuel reserves will leave these in the ground. More generally, Figure 6 indicates the failure of not making carbon pricing the main driving force for the energy transition. Rather, renewable energy has generally been supported through subsidies and any carbon pricing has been too low (Johnsson, Kjärstad & Rootzén, 2018).

It is therefore important for the EU to ensure that carbon pricing increases. Adding a carbon price to imports of certain goods from outside the EU by means of the above mentioned carbon border adjustment mechanism[15] might be required to counter the ensuing effects of carbon leakage. Such a strategy should be well aligned with the official strategy of most industries in the EU, but also in many other regions, which typically

15 With respect to the global ambitions to reduce greenhouse gas emissions, the European Green Deal (COM(2019) 640) emphasises that "should differences in levels of ambition worldwide persist, as the EU increases its climate ambition, the Commission will propose a carbon border adjustment mechanism, for selected sectors, to reduce the risk of carbon leakage".

have targets in line with the Paris Agreement — not least spurred by a growing customer demand for low-carbon products. Yet the initiative is still under discussion, and a form must be found that is legally and technically feasible and that is compatible with trade agreements, the World Trade Organisation (WTO), and other international commitments, but also keeping in mind Europe's global trade relations and dependency on these. A challenge is that developing economies lack the resources and technology to transition in a sufficiently short timeframe. It should also be stressed that part of the reason advanced economies such as the EU have been able to mitigate their carbon emissions is that much of the manufacturing has been reallocated to emerging markets who have invested in carbon-intensive energy systems for this reason. It is therefore likely that, for a cross border adjustment to be successful, it must be combined with aid to help developing economies to meet climate targets.

If the EU has the ambition to be a forerunner in meeting climate targets, it should be of paramount importance for the EU, as a large economy, to develop carbon pricing systems in a way that can avoid carbon leakage and to put pressure on other regions with a weaker climate policy, but at the same time find ways to support developing regions in their climate mitigation work. The latter will be of importance to gain acceptance within world trade agreements for carbon border adjustments or other instruments that put an additional price on imported carbon-intensive goods.

2.7. Implications for competitiveness

There are countries outside the EU with few domestic fossil fuel reserves that have strategies for expanding renewable energy for environmental and security of supply reasons. This has potentially important geopolitical implications. For example, northern Africa may change course towards the increased use of renewables (especially solar power) and increase their competitiveness. Morocco has a target to reduce energy imports from 90% to a target of 52% renewable energy in the electricity mix by 2030. If this is fulfilled, Morocco may be a highly competitive location for carbon-free industry. For example, a recent IEA report (2019a) shows that northern Africa (and southern Europe) will be competitive when it comes to hydrogen production from renewable energy. In turn, this may have important implications for the competitiveness of carbon neutral industry based on hydrogen. For example, it could result in less competitive conditions for production of hydrogen-based steel in northern Europe.

Therefore, if there is a decreased demand for fossil fuels for export, there will be an obvious challenge for economic development in countries that are highly dependent on fossil fuel exports. It therefore seems logical that some countries in the Middle East have initiated diversification strategies to reduce their reliance on these exports. There are also great challenges for countries rich in fossil fuels for which exports are an important part of their economy, which relates to the concept of “natural resource curse” (Venables, 2016).

Chapter 3. Economic and regulatory aspects of the energy transition

3.1. European Commission energy transition scenarios[16]

As part of the European Green Deal (European Commission, 2019), the European Commission (2020h) proposed to raise the 2030 greenhouse gas emission reduction target to at least 55% relative to 1990 and to achieve climate neutrality by 2050 (European Commission, 2020i). In April 2021, the European Parliament and Council reached a provisional agreement supporting both targets.[17] This increase in ambition is substantial and implies the need to incentivise low-carbon investments and innovations at an unprecedented scale. It also requires a review of most of the EU's climate- and energy-related legal acts, among those the Renewable Energy Directive (RED II)[18] and the Energy Efficiency Directive (EED).[19] Extraordinary political efforts are required to achieve these goals within a very limited timeframe. Especially for the 2030 target, only a few years remain, and the longer the decision-making process lasts on the principal strategic route to be taken by the EU, the less time will be left for its implementation.

While there is a wide range of options in principle for this principal strategic route, in September 2020 the European Commission provided a valuable anchor for this discussion by subjecting its proposed intensified climate targets to an impact assessment (European Commission, 2020d). This analysed six scenarios based on different policy architectures. Here we disregard the two scenarios which do not achieve the 55% target and the single scenario overachieving the target, since it seems sensible to concentrate on discussing the principal architecture of the three scenarios that achieve the 55% target:

16 Please see Annex 2, p.148 for a dissenting view from two Working Group members on sections 3.1 to 3.9 inclusive.

17 European Council, European climate law: Council and Parliament reach provisional agreement: https://www.consilium.europa.eu/en/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement/

18 Directive (EU) 2018/2001

19 Directive 2012/27/EU as amended by Directive (EU) 2018/2002

the REG, MIX and CPRICE scenarios. The scenarios differ regarding the relevance of carbon pricing, of the EU's Effort-Sharing Regulation (ESR) and of measures taken in the areas of energy efficiency, renewable energy, buildings and transport.

- In the **REG scenario**, the focus is on the entirety of 'regulative' measures that build on the existing instruments; it basically relegates carbon pricing to a supporting role.
- By contrast, the **CPRICE scenario** focuses on 'price-based' measures by extending the scope of the EU ETS (especially to buildings and transport), thus giving the carbon price a starring role. Elements of the respective other extreme are retained in each scenario.
- The **MIX scenario** strengthens various elements of the existing regulatory framework. Most importantly, it specifies the intention to integrate the buildings and transport sectors into the EU ETS, while leaving the buildings and transport sectors within the scope of the ESR. In this setup, the carbon price would take a supporting role "as an additional EU mechanism to achieve national emission reduction targets under the ESR" (European Commission, 2020d, p. 28).

The impact assessment does not provide any information on the exact design of the policy instruments; it merely stipulates that all scenarios represent "coherent combinations of policy options that have been translated into policy scenarios" (European Commission, 2020d, p. 42). It also does not suggest specific legal reforms or analyse impacts on specific member states. Thus, while it is arguably a valuable first stab at the issue, in this report we assess the pros and cons embodied in these distinct regulatory philosophies, rather than their yet-to-be-specified concrete translation into fully delineated policy packages. To distinguish between the concrete impact assessment scenarios and the regulatory philosophies analysed here, in the following discussion we will use the names of the implied regulatory philosophies (**Regulation**, **Mixed**, **Prices**).

Nevertheless, it is clearly extremely difficult to design a consistent set of policies that address the same objective from different perspectives and with overlapping interventions into the decision set of the myriad of relevant private actors. After all, the decisions, choices, and actions of millions of households and enterprises need to be combined into an overall energy transition, and it will be difficult to design policies which do not interfere with one another, even though they all aim at the same overall objective. This insight will be particularly relevant for the assessment of the **Mixed** approach. Thus, we follow the inspiration offered by another recent study on the implications of the impact assessment scenarios (Knodt, Pahle et al., 2020), and distinguish within the **Mixed** approach between two possible scenarios not having been the subject of assessment, one that satisfies a high standard of internal consistency and another one that fails to do so.

Specifically, we define the coherent 'best of all worlds' variant of the **Mixed** approach as one that requires the design and coordination of concrete instruments within the package to correspond to a **clear regulatory principle**, and to avoid interference between them. This might be achieved by defining one instrument as the core instrument and designing all other instruments as complements which merely address any remaining market or policy failures. Furthermore, we presume the ensuing policy mix to be continuously monitored and adapted. Table 1 summarises the basic elements of each scenario.

	Regulation	Mixed	Prices
Implications for concrete facets of the regulatory framework			
EU ETS	Extension to intra-EU maritime navigation	Extension to intra-EU maritime navigation, buildings and transport	
Policies & measures	High intensification	Medium/low intensification	EE and RES: no intensification Transport: low intensification
ESR	Same sectoral scope	Same sectoral scope	ESR does not apply to buildings & transport
Overarching characteristics and implications			
Regulatory mindset	Focus on regulation	Searching for the 'best of both worlds'	Focus on carbon pricing
Legal competences	Energy policy competence	Environmental competence	Environmental and energy policy competence
Main requirement for successful implementation	Tightening climate targets in ESR and/or strengthening the enforcement mechanism of the Governance Regulation	unclear	Political willingness to accept high carbon prices

Table 1. Key elements of the regulatory philosophies implied by the European Commission's impact assessment
This table incorporates elements of tables in Knodt, Pahle et al. (2020)

3.2. Assessment criteria

In our assessment of the different strategic routes which could be taken by the EU, we use as a starting point a previous analysis by the ARIADNE project (Knodt, Pahle et al., 2020). While we are in agreement with many aspects of its appraisal of the strengths and weaknesses of each scenario, we feel that is necessary to widen the scope of the employed assessment criteria for the purposes of this report. More specifically, the increased level of ambition stipulated in the new 2030 climate targets necessitates close scrutiny on how different strategic routes would be able to ascertain economic efficiency. A summary of our assessment is provided by Table 2. As many of the details of the policy design of each scenario have been left open in the IA, this assessment mainly concerns the implied regulatory philosophies embodied in each scenario.

Our assessment of the scenarios is based on five sets of criteria, each comprising two facets:

- **Effectiveness.** It will be important to pursue a strategic route that ensures the new, more ambitious climate targets are reached effectively. Two requirements appear to be crucial to do so with a high level of credibility. First, it will be necessary to ensure the consistency of the policy mix, in the sense that the various policy instruments are not interfering with one another, and that they are indeed likely to have the intended effects. Second, different policy strategies provide the European Commission with different instruments to control the implementation of EU law by member states. There exist soft monitoring measures in the EU Governance Regulation ((EU) 2018/1999), while the most important 'hard' instrument is the right to initiate infringement proceedings laid down in Art. 258 TFEU.[20]
- **Transformative potential.** The extent to which a regulatory regime will be able to initiate a system-wide transformation of the European energy system and its utilisation will be of considerable importance. Firstly, on the level of individual action, this pertains to the incentives to adhere to the spirit of the regulation: whether the instruments constituting the policy package are backed up by an effective **enforcement mechanism** which applies with a high level of credibility, even if enforcement were to imply high economic or political cost. Secondly, this pertains to the question of whether the package can effectively alter the **mindset** of individual actors to support long-term behaviour change.
- **Economic efficiency.** The large number of individual choices, decisions, and actions of private and public actors constituting the energy transition need to be **coordinated** in an efficient way. In this regard, two highly distinct regulatory philosophies can be contrasted: **detailed planning** by state and regulators ('command and control') and decentralised coordination by **markets** with price signals serving as coordination devices. While, in principle, detailed planning can be designed in a way which is entirely equivalent to a market mechanism, tremendous obstacles tend to prevent the achievement of this objective in the real world. Most importantly, a key requirement would be that policymakers and planning agencies do not suffer from any **information deficiencies**. This is especially unlikely in the case of the European energy transition, since in many respects the intensified climate ambitions require policymakers, enterprises and households to enter uncharted behavioural territory.

20 Article 258 of the Treaty on the Functioning of the European Union (TFEU): https://ec.europa.eu/home-affairs/sites/default/files/news/docs/infringements/article_258.pdf

Installing a market mechanism will typically help to reveal information on important behavioural aspects, such as willingness to pay or abatement cost, that would otherwise remain obscure to all actors or hidden as private information. Thus, prices would not only serve as coordination devices, but could also serve as a **discovery mechanism**.

- **System compatibility.** While the criterion of economic efficiency receives its importance from the highly intensified level of ambition reflected in the new 2030 climate targets, it is not the only qualification which needs to be satisfied by any potential EU policy strategy. There are two facets of compatibility with the economic and social European system. Next to effectiveness and efficiency, the EU should pursue a policy strategy which ascertains economic **competitiveness** and avoids massive carbon leakage (which is the flip side of the same coin from an environmental perspective). Another key requirement is the capability of any principal regulatory approach to maintain an adequate **social balance** despite the massive changes implied by the energy transition.
- **Political feasibility.** Selecting a principal strategy for the energy transition is not an exercise in theoretical rigour. It also needs to be feasible in the short term. That is, it would be a large disadvantage if **procedural hurdles** were to prevent the transition from accelerating, as it must not be delayed. It would also be a disadvantage for any strategic choice if it were to face severe obstacles created by **path dependencies** implied by the previous course of national or European energy and climate policies.

3.3. Effectiveness: achieving the climate targets

The first indispensable requirement for any strategic policy choice in the context of the EU's energy transition is confidence in its effectiveness. Climate targets will only be reached if the concrete policy package derived from any regulatory philosophy is internally **consistent**. Interactions between the various policy instruments employed should be set up in a way that avoids interferences or even contradictions between them. This is not a hypothetical consideration, but a matter of considerable relevance in political practice. It is evidenced, for example, by the interference between national policies to subsidise the discretionary phase-out of coal power plants on the one hand (a policy which is exemplary for the **Regulation** philosophy), and the carbon pricing regime adopted by the EU ETS for the energy sector on the other (a policy which is exemplary for the priced-based philosophy in **Prices**).

Such examples abound, as the EU and its member states have so far pursued a plethora of targets and entertained a wide range of instruments whose design was developed independently of one another, each following its own motivation and not a systemic perspective. Nevertheless, there might also be many instances in which various policy instruments complement each other fruitfully. A carbon price might, for example, fail to reach its full potential for incentivising investments into low-carbon equipment or into energy saving refurbishments if the adequate public infrastructure is lacking. In that case, public investments into the appropriate infrastructure might serve as a facilitator. Other examples include public support for fundamental and applied research, and programmes supporting the quest for technical or social innovations and their wider dissemination.

Our assessment of how the different regulatory philosophies perform according to this criterion is reported in Table 3, p.60. The direct regulative strategy **Regulation**, which obviously resembles most closely the strategic policy route taken so far by the EU, predominantly relies on state planning. Among its core instruments are regulatory measures regarding renewable energies, energy efficiency, and transport. For buildings and transport, this approach generally manages to avoid the interference potentially created by any parallel mechanism relying on economic incentives. For the energy and industry sectors, this interference is already strongly visible in current energy policies, since the EU ETS partly overlaps with these regulatory measures. In sum, while it is likely that this strategic approach will be translated into an internally consistent concrete policy package in some sectors, this ship has already sailed in the EU ETS sectors, leading to an overall assessment of **intermediate** adequacy.

The same **intermediate** assessment would apply to the 'best of all worlds' variant of the **Mixed** approach. While it will not be possible to avoid the interference between carbon pricing by the EU ETS in the energy and industry sectors, the **Mixed** strategy could be designed in a fairly consistent way in the other relevant sectors. This would require policymakers to carefully plan the policy package as a whole instead of just adding more and more individual measures. Most specifically, in such a coherent mix, each possible market failure would be addressed by exactly one policy instrument (Knodt, Pahle et al., 2020, p. 18).

Illustrating this general point, the negative effects of transport are manifold, extending far beyond GHG emissions (pollutants, noise, traffic congestion, accidents, etc.). Specific policy measures like regionally and temporally differentiated road pricing for the entire transport infrastructure may address these specific problems and may contribute to climate protection. However, it is important to specify the precise objective of any complementary policy intervention and to carefully calibrate these additional policies. Moreover, to fulfil the requirement of internal consistency, such an intricate policy mix requires very careful monitoring, and a prespecified process facilitating speedy adaptation if this becomes necessary.

There is a high risk, however, of the **Mixed** philosophy being implemented inconsistently. Without a core instrument that can be used as a reference point for other instruments, the risk of inconsistencies tends to rise in comparison to the other scenarios (Knodt, Pahle et al., 2020, p. 15). The number of instruments addressing energy and climate matters at the EU level is already large, and they lack a coherent structure. Thus, it is already difficult to understand the complex interactions between all instruments. This holds, for example, for the coexistence of carbon emission standards for cars or buildings on the one hand and a carbon price on the other. As the impact assessment indicates that the **Mixed** approach will entail a parallel regulation by keeping the buildings and transport sectors in the EU's Effort-Sharing Regulation (ESR) and extending the EU ETS to these sectors, this is likely to exacerbate the situation, leading to a **low** assessment for the alternative **Mixed** approach which does not satisfy the 'best of all worlds' standard.

By contrast, the **Prices** strategy benefits from the same advantage as the **Regulation** approach, as it is being guided by a clear core instrument, the carbon price. While this core instrument cannot be left to operate on its own (it needs to be augmented by complementary policies in all remaining instances of market or coordination failures), on the aspect of internal consistency this strategy scores an unequivocal **high** assessment.

Regarding the **control of implementation** of EU law by the member states, the assessment for the **Regulation** strategy is only **low,** because the EU Governance Regulation (Regulation (EU) 2018/1999) merely contains a soft monitoring mechanism to control the national energy and climate plans. It would only be **high** if the soft monitoring instruments in the governance regulation could be changed into hard monitoring instruments. In the transport, buildings and other industry sectors, for instance, the ESR and its binding national targets could be tightened directly. Similarly, more ambitious detailed targets could also be implemented via an adapted Governance Regulation regarding energy efficiency and renewable energy, which is the EU's framework for establishing the member states' National Energy and Climate Plans[21] and creates a monitoring mechanism for the EU's climate and energy related targets (Schlacke & Lammers, 2018; Schlacke & Knodt, 2019). Member states' adherence to its obligations could be connected to funding, for example to the European Structural and Investment Funds,[22] in order to incentivise member states to work towards the overarching energy efficiency and renewable energy targets (Leopoldina et al., 2018, pp. 41–42).

By contrast, the **Prices** strategy scores a **high** assessment, since, in order to control the member states compliance with the Emissions Trading Directive (Directive 2003/87/EC) the Commission has the right to initiate an infringement proceeding according to Art. 258

21 European Commission, National Energy and Climate Plans: https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

22 European Commission, European structural and investment funds: https://ec.europa.eu/info/funding-tenders/funding-opportunities/funding-programmes/overview-funding-programmes/european-structural-and-investment-funds_en

TFEU[23] if implementation is eventually insufficient. The **Mixed** approach correspondingly scores an **intermediate** assessment.

3.4. Transformative potential: enabling a system-wide transformation

To reach a high transformative potential, the chosen policy strategy needs to comprise instruments which set the right incentives for individual compliance, by including an effective **enforcement mechanism** designed to back up the implementation of each instrument. That is, individual actors should expect strict and consistent enforcement of regulations and policy instruments. Under the regime of the EU ETS, for example, the ceiling set for carbon emissions needs to be understood as binding, even if prices for emissions certificates were to increase steeply. A different aspect pertains to the ability of the chosen policy package to permanently alter the **mindset** of individual actors with respect to energy-related decisions and behavioural choices. This potential is likely to be **high** for those strategies which follow the guidance of a clear core instrument or set of instruments (the **Prices** and the **Regulation** strategies respectively). The assessment on this account is rather **intermediate** for any strategy of a **Mixed** approach, though.

The main enforcement mechanism of the price-based strategy **Prices** is the high fines penalising the failure to present sufficient EU ETS emission certificates. It is highly likely that an enhanced EU ETS that would also cover the emissions from buildings and transport would display higher carbon prices. While evidence is necessarily scarce, due to the fact that carbon pricing has not been implemented in these sectors so far, one might expect the common carbon price in the EU ETS to increase steeply upon its adoption by the buildings and transport sectors, reflecting low price elasticities by households regarding their mobility and heating demand. This scenario will be credible only if policymakers credibly commit to accept these high prices, i.e. to leave the ceiling on overall emissions untouched in the face of high carbon prices instead of increasing the number of certificates in a discretionary fashion. As the decision to opt for the **Prices** approach would already entail this commitment, this leads to a **high** assessment.

23 Article 258 of the Treaty on the Functioning of the European Union (TFEU): https://ec.europa.eu/home-affairs/sites/default/files/news/docs/infringements/article_258.pdf

3.5. Economic efficiency: coordination and beyond

Since the energy transition is a process which involves myriad decentralised consumption and investment decisions, any climate policy that ignores economic considerations would ultimately be doomed to failure. Effective protection against climate change requires a drastic reduction of global greenhouse gas emissions and, consequently, a comprehensive transformation of energy supply systems away from the fossil fuels currently dominating them. As targets for emission reduction consistent with the Paris Agreement can only be achieved by deploying considerable economic resources, which are therefore not available any longer for competing purposes, cost-effectiveness is an essential requirement for climate policy. In addition, the political strategy chosen should fulfil further requirements related to the ability to achieve economic competitiveness and social balance despite the massive alteration to the European energy system implied by ambitious European climate targets.

The least costly transition would be a combination of the many individual consumption and investment decisions making up the overall transition in a way that would satisfy or at least approximate the economic principle of the division of labour. That is, individual actors should engage in specific mitigation efforts, and invest in corresponding machinery and equipment, for whom the contrast of benefits and costs is the most favourable. In its most simple form, this principle would suggest that the lowest-hanging fruit — according to the technical possibilities available at the time — should be harvested first. Technological advances then enable further necessary savings to be achieved more cost-effectively over time.

However, it is important to understand that, in the current context, this principle applies to the overall path of transition to climate neutrality, not to the short-term. An inexpensive mitigation measure, which might look attractive now, might actually not be preferable to a more expensive yet more encompassing measure, if taking the inexpensive route first prevents further mitigation measures from being picked up later due to lock-in effects. A prominent example is the renovation of buildings where further renovation measures might be precluded for some decades. It is dynamic efficiency over the complete horizon of the transition that policymakers should aim at, not a sequence of statically efficient mitigation choices.

This makes it all the more important to devise a climate policy strategy which convincingly signals long-term commitment to the climate targets. Consumers and investors form expectations regarding future circumstances. If they know that carbon prices will increase steeply or surrogate measures will be tightened eventually, it will be completely rational for them to opt for mitigation measures which are more costly today but deliver low cost over the complete planning horizon. But this possible divergence of statically and dynamically efficient solutions should not be confused with a refutation of the principle of division of labour. The burden of proof is clear. Opting for statically inefficient solutions is only acceptable if this serves dynamic efficiency. By contrast, the mere possibility of this divergence is hardly a sufficient justification for this.

In the practical implementation of the transition, myriad individual actors, most importantly households and businesses, will shape the actual transformation by making decisions about their energy consumption and their investments, partly based on private information not available to outsiders. A coordination strategy guided by market-based principles thus plays a key role in achieving the goal of a cost-effective transformation. A uniform price on CO_2 emission equivalents would ensure that GHGs would never be emitted if avoiding them was cheaper than paying for them. Mimicking this combined role of coordination device and detection mechanism would be almost impossible to achieve by any detailed planning mechanism.

Due to its enormous informational demands, this requirement is extremely difficult to fulfil in the direct **Regulation** approach, leading to a **low** assessment. By contrast, choosing as its leading instrument a uniform price on carbon encompassing, basically, all relevant sectors, the price-based philosophy **Prices** scores an unequivocal **high** assessment. This assessment is easy to motivate, since the market mechanism delegates the coordination of individual actions to an anonymous and well-proven mechanism, obviating the need to gather highly detailed and accurate information on all relevant actors as a basis for planning the whole set of decisions and choices. For a subset of sectors — those already covered by the EU ETS — this market mechanism has been shown to function.

What is more, carbon pricing not only sets incentives for investment into low-carbon equipment and machinery and for the consumption of low-carbon goods and services, it also serves as an incentive to invest in **innovation** by researchers and companies. In addition, while the strategic route of the **Regulation** approach would require ample **information** as its input, the strategic route of the **Prices** approach would yield information as its output which would otherwise remain obscure. Learning about citizens' willingness to pay instead of guessing its magnitude would provide highly useful support for policy design. Thus, on this aspect, the **Regulation** approach again receives a **low** assessment and the **Prices** strategy again receives a **high** assessment.

On both accounts, providing for an efficient coordination of individual actions and for a powerful mechanism of information gathering, the assessment of the **Mixed** approach depends on the quality of implementation. In its 'best of all worlds' variant it scores an **intermediate** assessment on both accounts, since it will be relying to a considerable extent on a pricing mechanism. If implemented poorly, it shares the **low** assessment on both accounts with the **Regulation** approach, for the reasons outlined above.

3.6. Social compatibility: effect on households and industry

The political strategy chosen by the EU needs to pay attention to the international repercussions it might imply. There is general agreement that the EU should attempt to reach its ambitious climate targets effectively, because only then there could be hope that an effective global alliance for the protection of the climate could be forged. This present report emphasises that effectiveness will not be enough, and economic efficiency will also be important. Avoiding waste of economic resources retains these scarce resources for other purposes; and if the EU is able to engage into a complete overhaul of its energy system at manageable cost, this promises to set an inspiring example for other economies.

But as the EU proceeds to lower emissions either through command and control measures or through carbon pricing, it needs to ensure that carbon emissions are not simply exported to other economies which do not employ the same standards, and then imported later embodied in the goods imported from these economies. This **carbon leakage** would not only be detrimental to the global climate, but also negatively impact European economic prosperity. European companies which compete on world markets need this competition to be fair. Otherwise, they may be forced to leave the market altogether or to set up their business elsewhere, leading to lower jobs and less economic prosperity in Europe.

Thus, the EU should pursue a policy strategy which maintains economic competitiveness and avoids massive carbon leakage. As we document in section 3.7, p.53, this is far from an easy task. But one requirement for implementing a compensation mechanism such as a border adjustment tax is the ability to quantify the degree of unfairness in the competition, in monetary terms. This will tend to be almost prohibitively difficult if the principal strategy predominantly relies on non-price mechanisms. Therefore, the **Regulation** philosophy scores a **low** assessment on this criterion, the **Mixed** philosophy scores an **intermediate** assessment only for its 'best of all worlds' variant, and the **Prices** philosophy scores a clear **high** assessment.

Similarly, yet another key requirement for a sensible strategic policy route will be its capability to achieve an adequate social balance despite the massive changes implied by the energy transition. Without an adequate **compensation** mechanism, any climate policy, whether based on a price mechanism or not, will tend to exert a regressive effect. That is, due to their high expenditure share on energy services, low-income households will find the transition to a low-carbon economy more burdensome relative to their disposable income than moderate- and high-income households. Carbon prices will make this relatively high burden highly transparent, but non-price measures such as a ban on old diesel cars, for example, might even exert a more regressive effect. One simply cannot escape the fact that virtually all policy measures entail distributional consequences.

While combining the principal strategic route with a policy of income redistribution will be possible to some extent in any case, only carbon pricing will entail a direct way to collect public revenue for this purpose. Making the connection between stipulating a carbon price and providing compensatory payments is likely to enhance acceptance for climate policy. And, due to the revenue being collected, carbon pricing also obviates the need to reduce public expenditure in other areas. However, as the evaluation of carbon pricing depends on the design of the compensation mechanism, all regulative approaches score an **intermediate** assessment.

3.7. Political feasibility: overcoming short-term obstacles

The choice of the strategic route taken on climate policy is not a theoretical exercise; it needs to be feasible in the real world.

Many possible routes will be feasible politically if there is sufficient political willingness to take them. This was evidenced by the remarkable display of European solidarity during the coronavirus pandemic, when sizable funds were provided to alleviate acute emergencies. Moreover, this report is meant to assess the pros and cons of different strategic routes based on their conceptual quality, not on the pain or ease their negotiation implies for policymakers. Nevertheless, the short-term political feasibility of any scenario will influence its quality as an option. Two criteria are entertained here to assess this aspect: the height of the potential procedural barriers any strategy would need to clear in the political process, and the path dependencies implied by previous policy choices and structural developments.

Procedural barriers

From a legal perspective, there are two main barriers to an extensive reform of EU energy and climate law to be considered in each scenario (Knodt, Pahle et al., 2020, pp. 7–8; Schlacke et al. 2021): whether the EU has the legislative competence to reform the legal framework as envisaged, and which decision-making procedure in the European Council (unanimity or majority) apply. The choice of the specific instrument also has temporal implications.

The **Regulation** approach implies increasing the energy efficiency and renewable energy targets, while the EU ETS would not be extended significantly. Art. 194 (1) of the Treaty on the Functioning of the European Union determines the EU's energy competence and is the legal basis currently chosen for the Energy Efficiency Directive and Renewable Energy Directive II. An increase of the energy efficiency and renewable energy targets would probably also be based on the EU's energy competence. But there is a risk that such a tightening of targets could affect the conditions for the use of energy resources, the choice between different energy sources and the general structure of a member state's energy supply (Art. 194 (2) TFEU). If this is the case, the EU does not have the competence to ratchet up these targets or put the necessary measures into force (Knodt, Pahle al., 2020, p. 10). Overall, this leads us to award a **low** score for the **Regulation** approach.

The **Mixed** approach entails strengthening the energy efficiency and renewable energy targets and measures, although this is not as ambitious as in the **Regulation** approach. At the same time, this scenario describes an extension of the EU ETS to the buildings and transport sectors. As far as can be evaluated without specific legislative proposals, Art. 194 (1) TFEU (energy competence) and Art. 192 Abs. 1 TFEU (environmental competence) would provide a sufficient legal basis for this reform and the Council could decide with a majority, if the member states were not (significantly) impaired in determining the conditions for the use of their energy resources, leaving it their choice between different energy sources and the general structure of their energy supply (Knodt, Pahle et al., 2020, pp. 14–15). Thus, irrespective of the possible inconsistencies arising from the fact that in this scenario the ESR would be maintained, subjecting the buildings and transport sectors to the EU ETS and to an absolute reduction target via the ESR at the same time, the **Mixed** approach scores an **intermediate** assessment on the question whether it will be legally and politically feasible.

In the **Prices** strategy, the buildings and transport sectors would be included into the EU ETS and simultaneously excluded from the ESR. Art. 192 (1) TFEU would generally provide a sufficient legal basis for this extension of the EU ETS. Nonetheless, the requirement of a unanimous decision of the Council after consulting the European Parliament enshrined in Art. 192 (2) TFEU could become relevant in two respects. Only extending the EU ETS to buildings and transport while excluding them from the ESR would limit the member states' leeway to put further national measures in place. This could fuel an argument for the need to come to a unanimous decision within the Council because of an infringement of the member states' sovereign right to choose their mix of energy sources. Furthermore, if not only emissions trading but also fiscal instruments were used, such as a revised Energy Tax Directive, the affirmation of the requirement of unanimity pursuant to Art. 192 (2) a) TFEU or Art. 113 TFEU would not be unrealistic (Knodt, Pahle et al., 2020, p. 12).

Moreover, the respective choice of the specific legal instrument, whether Directive or Regulation (Art. 288 TFEU), also has temporal implications. Choosing a Directive, as would probably be the case for an extension of the EU ETS, could cause a considerable time delay due to the necessary implementation at the member state level. Considering the limited time to achieve a strengthened 2030 target, the appropriateness of such a delay is doubtful and would have to be overcome.

In addition, the European Commission is planning to submit a proposal for a CO_2-related levy that would be included in the EU's own resources system. According to Art. 311 TFEU, the introduction of a new own resource (levy or duty) will be implemented by a so-called 'own resource decision' in a special procedure. After consulting the European Parliament, the Council unanimously adopts such a decision, which then requires the consent of all member states according to their respective constitutional requirements (Knodt, Pahle et al., 2020, p. 12). In sum, the **Prices** approach scores a **low** assessment regarding political and legal risks.

Path dependencies

The likelihood of a scenario crossing the procedural hurdles described above depends on the status quo at which the member states have arrived on the basis of previous choices of energy sources, their energy mix, and the instruments of climate and energy policy employed. Moreover, the reaction of national constituencies to various policy measures might play an important role. While there are good reasons to prefer carbon pricing, such as its cost-efficiency, its transparency might also bring distributional concerns to the fore. And while regulatory measures are often seen as an effective approach to achieving climate targets, their low cost-effectiveness endangers their acceptance. Which of these tendencies prevails will likely vary from member state to member state.

Since both the **Regulation** strategy and the **Prices** strategy are extreme strategies, this might diminish their feasibility compared to **Mixed** strategy which takes a middle ground as a compromise solution. All candidate scenarios entail the implementation of a climate policy whose degree of ambitions is intensified. Thus, we assess the short-term political feasibility of all scenarios as **intermediate** at best, with the **Regulation** approach and the **Prices** approach both scoring a **low** assessment.

3.8. Summary of assessment

Overall, our assessment leads to the following results.

- Regarding **effectiveness**, a mixed assessment emerges. While pursuing the price-based strategy **Prices** implies a high level of consistency, leaving all other principal strategies behind, placing all emphasis on regulatory measures such as in the direct regulative **Regulation** strategy will allow the highest reach-through for the European Commission, by contrast to concentrating on carbon pricing.

- Regarding **transformative potential**, all strategic routes have at least an intermediate chance of initiating a systemic change of energy-related behaviour. Only the highly consequential strategies **Regulation** and **Prices** have a high chance of permanently altering the mindset of individuals, though, and only the **Prices** strategy tends to provide highly effective individual incentives.
- On both aspects regarding **economic efficiency**, the strategic route implied by the **Prices** approach dominates the other candidate scenarios, with a well-designed strategy according to the **Mixed** approach coming close to the quality of the **Prices** strategy to some extent.
- When it comes to assessing the potential of the chosen strategy to satisfy **system compatibility** in the sense of preserving economic competitiveness and ascertaining social balance, the **Prices** strategy again excels, due to its practical implications for revenue collection and providing objectified gauges required for compensatory arrangements.
- Finally, a strategy following the **Mixed** approach scores slightly better in terms of **political feasibility**, although all strategic routes will tend to face considerable obstacles.

Most importantly, since the cost of climate policy increases with its increasing ambition, cost efficiency becomes more and more important to ensure public support for climate policy. A good policy mix is therefore not static, but will need to be continuously improved, and the relative importance of the various policy instruments will need to change over time. This might pave the way for a **compromise strategy** which starts out within the 'best of all worlds' variant of the **Mixed** approach and mutates into the **Prices** approach as quickly as possible. In the near future, regulatory measures might still be highly important in sectors where the EU ETS has yet to be implemented and prove its effectiveness. Later in the process, when more hurdles for a successful carbon price have been overcome and more green technologies are available, the EU ETS would be strengthened and the role of complementary instruments would be decreased. Ultimately, the carbon price will be allowed to reflect the social costs of climate damages and act as a cost-efficient core instrument.

	Regulation	Inconsistent Mixed	Consistent Mixed	Prices
Effectiveness				
Consistency	intermediate	low	intermediate	high
Control of implementation	low	intermediate	intermediate	high
Transformative potential				
Enforcement mechanism	intermediate	intermediate	intermediate	high
Mindset	high	intermediate	intermediate	high
Economic efficiency				
Coordination	low	low	intermediate	high
Information-gathering	low	low	intermediate	high
System compatibility				
Competitiveness	low	low	intermediate	high
Social balance	intermediate	intermediate	intermediate	intermediate
Political feasibility				
Procedural barriers	low	intermediate	intermediate	low
Path dependencies	low	intermediate	intermediate	low

Table 2. Assessment of the regulatory philosophies implied by the European Commission's impact assessment
The table assesses the three principal regulatory philosophies being reflected in the impact assessment's scenarios REG, MIX, and CPRICE, according to the set of criteria discussed in the text of the present report. It incorporates elements of the corresponding table in Knodt, Pahle et al. (2020, p. 9), but also partially deviates from it.

3.9. Measures to rectify induced economic imbalances (regressivity)

Regarding its distributional effects, climate policy tends to be regressive. Low-income households typically spend more of their income on energy services than high-income households. This becomes particularly transparent when an economy-wide carbon price is implemented, since this requires the integration of further sectors into the EU ETS, specifically buildings and transport. Including these sectors promises lower emissions in private households through two channels. First, and unequivocally desirably, the 'substitution effect': relative change in prices incentivises households to shift their consumption portfolio to relatively cheaper (i.e. less carbon-intensive) goods and services. Second, the 'income effect': as prices for carbon-intensive goods and services rise, the available income for other purchases decreases, reflecting the costs of climate policy at household level. What is more, the higher the carbon price, the larger the imbalance tends to be, to the detriment of low-income households by reducing their disposable incomes (Frondel, Sommer & Vance, 2015; GCEE, 2019).

These regressive distributional effects are not exclusive to carbon pricing, though. Aggravating or even prohibiting specific energy services or subsidy schemes might even imply a stronger regressivity. This is strikingly visible, for instance, with Germany's subsidy scheme for building up capacities for renewable electricity generation since it benefits landowners and houseowners and distributes the financial costs of the scheme more widely. Consequently, the income effect, and in particular its distributional imbalance, need special attention as it tends to reduce acceptance of climate policy. While the less transparent regressivity induced by non-price measures might deflect attention away from this problem in the short run, this is likely to become even more detrimental for acceptance once their genuine distributional effects are uncovered by thorough empirical analyses (Andor & Fels, 2018; Frondel, Sommer & Vance, 2015).

Carbon pricing not only induces these regressive effects on disposable incomes but, in contrast to non-price measures, it also leads to the collection of additional public revenues. Since the generation of additional public revenue is not the inherent aim of carbon pricing, the resulting revenues can be redistributed completely to increase social acceptance and mitigate regressive effects. What is more, this revenue will in all likelihood be collected at the national level which, according to the governance of the EU, is the appropriate level for conducting social policy and alleviating income imbalances. Thus, as a wide spectrum of redistributive measures is available, in principle, it is particularly helpful that the specific setup for redistributing this revenue could be tailored to the preferences and social policy system of each member state (Tagliapietra et al., 2019).

In its special report of 2019, the German Council of Economic Experts scrutinised four major options for implementing redistribution and suggested a set of criteria for gauging their attractiveness. Accordingly, an appropriate redistribution scheme should fulfil six purposes (GCEE, 2019):

- mitigating or even reversing regressive distributional effects
- incentivising pro-environmental behaviour
- setting positive incentives for labour supply
- guaranteeing transparency to support public acceptance
- assuring administrative feasibility
- maintaining dynamic revenue neutrality

A first redistribution option is a per capita lump sum transfer as it is currently implemented in Switzerland. Such a 'climate dividend' especially relieves households in the lower half of the income distribution and is particularly beneficial because it is highly transparent and salient for all households. However, its implementation imposes high administrative challenges. Switzerland, for example, draws upon a full register of citizens from their universal public health insurance system; other states, like Germany, do not have such a list and would need to seek alternative solutions.

An easier option from an administrative point of view would be to use the additional revenue to fund a reduction of indirect taxes, especially on electricity. In member states with very high taxes and charges on electricity, such as Denmark, Germany and Portugal, these reductions could lower electricity prices and thus promote sector coupling. Making fossil fuels more expensive while reducing the price of electricity could create strong incentives to switch to electric equipment.

Another popular and readily implementable redistribution option is the increase of existing social transfers. However, while this reverses regressive effects on transfer recipients, it has no effect on other disproportionally highly affected households, such as single-person and low-wage households. Furthermore, an earmarked transfer for energy expenditures would entirely offset the price signal and thus fail completely on the second major criterion.

A fourth option with low administrative hurdles is a reduction of direct taxes or social security contributions. This alternative even provides the opportunity for creating a 'double dividend': the carbon price would not only ensure that the externalities of carbon emissions were internalised by the price and carbon emissions were reduced, but by financing tax cuts in other areas it could also reduce inefficiencies in the tax system. Nevertheless, this option only affects taxpayers and employees, and hence cannot completely mitigate regressive effects.

	per-capita lump sum transfer	reduction of indirect taxes	increase of social transfers	reduction of direct taxes or social security contributions
Mitigating regressive distributional effects	possible	possible	distributional effects limited to transfer recipients	distributional effects limited to taxpayers or employees
Incentivising pro-environmental behaviour	income effect partly offsets carbon price signal	lower charges on electricity remove ecological disincentives	carbon price signal is (partly) offset for transfer recipients	income effect partly offsets carbon price signal
Incentives for labour supply	depends on transfer volume and elasticities	depends on transfer volume and elasticities	rather negative; depends on transfer volume and elasticities	removes market disturbances, 'double dividend'
Public transparency	high, direct information on transfer volume	low	low and limited to specific groups	information on the volume of reductions is possible
Administrative feasibility	difficult, complete register required	assured, change of existing tax rates	assured, change of existing transfers	assured, change of existing tax or contribution rates
Dynamic revenue neutrality	time-variable lump sum	automatic mechanism possible but complex	not given	automatic mechanism possible but complex

Table 3. Evaluation of different redistribution schemes
This table uses the following colour scheme:

Option satisfies criterion	Neutral	Option does not satisfy criterion

For long-term acceptance of ambitious climate policy, the communication accompanying the implementation of any measure, especially of a highly transparent encompassing carbon price, is of utmost importance. While the public discourse should document concerns about the distributional effects of carbon pricing, it should also be emphasised that economic actors can largely influence their monetary burden by adjusting their behaviour accordingly. They are especially able to do so if consistent carbon pricing is not introduced too abruptly and, at the same time, it is clearly flagged up as a long-term climate policy strategy. Additionally, policymakers should simultaneously remove any obstacles preventing households from switching to low-emission economic activity. This includes providing information and necessary infrastructure, for example by expanding local public transport (GCEE, 2019).

Furthermore, the cost of modifying current behaviours and adapting existing equipment for heating or mobility purposes is likely to be unevenly distributed. A possible extension of any redistribution scheme is to provide additional support for adjustments carried out by actors who incur particularly high costs, for instance by granting modernisation funds.

However, it would be hard to justify compensating them to the full extent because these households' environmentally harmful behaviour has been indirectly subsidised by society in the past. After all, carbon pricing merely makes externalities and their social costs transparent; it does not cause them.

In addition to distributional challenges among households within a single country, there are also distributional challenges between member states. A similar level of ambition across all member states in the buildings and transport sectors implies a particularly high burden on lower income households in eastern member states. This implies that a transfer scheme is necessary to ensure a fair burden (distributional equity) between member states in order to get the political consensus for increased ambition.

As with national distribution issues, the international distributional challenges can in principle be dealt with through a suitable allocation of auction revenues. The auction revenues are highest in the CPRICE scenario at €75 billion in 2015 prices. The financial leeway for reducing distributional impacts is more limited in the MIX and REG scenario due to their lower EU ETS revenues (€55 billion and €16 billion respectively in 2015 prices). Correspondingly, allowances could be used to create a transfer mechanism, for example, in the spirit of the 'energy solidarity fund' recently proposed by Poland. But there is a trade-off with the following other needs:

- financing climate measures in member states
- EU ETS Innovation Funds
- creation of own resources
- set-asides for negative emissions

In the face of that, it is crucial that these trade-offs must not hinder the successful extension of the EU ETS by implementing fair transfer schemes. However, it is unclear which particular allocation of allowances to the different uses would achieve the best outcome.

3.10. Competitiveness and carbon leakage

An effective transformation of the energy system also needs to be affordable, without major social upheaval or an unsustainable loss of competitiveness. However, increasing ambition for climate policy will result in higher cost. It is crucial that higher ambitions in climate protection at the European level are matched by efforts in other countries. The EU should intensify its efforts towards comparable total carbon costs at the international level and work towards an effective carbon club at least with important partners.
Only where this is not possible, suitable regulatory mechanisms are required to bring

international carbon costs into line, prevent leakage of carbon emissions outside the EU, and thus ensure the economic viability of investments within Europe.

These observations apply irrespective of the concrete regulatory strategy pursued. A heavy reliance on carbon pricing has the advantages of making the cost of transition transparent and, at the same time, providing an objective basis for the quantitative assessment of the individual financial burden caused by the pursuit of ambitious climate targets. Specifically, a carbon price which European companies have to pay, while their direct competitors on world markets do not, would provide a direct gauge of the financial burden imposed by European climate policy. If climate targets are pursued by non-price measures, instead, the ensuing financial burden could not be revealed directly from the regulations. Instead, it would have to be derived from an econometric comparison of production cost. This adds another element of uncertainty to these considerations, but it does not alter the principal train of thought: pursuing ambitious climate targets is costly.

In the following, we condense the financial burden put on European actors by a relatively ambitious climate policy with respect to the rest of the world by the term 'carbon price'. All considerations apply to non-price measures, apart from the fact that without a monetary basis to directly assess any regulation-induced competitive burden, it will be very difficult to arrange for compensation, let alone to do so in a manner which is not viewed as a protectionist trade measure. A highly ambitious climate policy will be associated with high carbon prices and will endanger the competitiveness of those European companies which compete on world markets against their non-European competitors. This might induce them to relocate their production to sites outside Europe. This carbon leakage would counteract EU ambitions to hamper global climate change, and it would also damage the prospect for maintaining economic prosperity.

This problem has so far been addressed quite successfully under the auspices of the EU ETS, by the cost-free allocation of emission certificates to European companies facing international competition, based on a benchmarking system. This current system of free allowances for sectors at the highest risk of relocating their production outside of the EU will soon be no longer feasible, as the number of available free allowances is reduced quickly with increased efforts. To address this problem, carbon border adjustments have been suggested as a promising alternative (Kasturi, van Asselt, Droege & Mehling, 2018). By levying a charge on imported goods, carbon border adjustment mechanisms increase costs of products manufactured abroad based on their carbon content, reducing the risk of relocation of their production. In addition, there is hope that it might become relatively more attractive for trading partners outside the carbon club to join, as carbon prices are increased over time and carbon emissions in production are reduced.

In an ideal world, the carbon content of all goods would be measured accurately, allowing carbon border adjustments to eliminate any climate-policy-related distortion of international competition. However, although in principle carbon border adjustments are very similar to charging value-added taxes, precisely determining the carbon border adjustment for each individual good tends to be much more difficult due to the manifold differences between highly complex production chains for the same product, and the requirement that the adjustment has to reflect the product's carbon content. As for the free allocation of certificates in the current EU ETS, carbon border adjustments will have to be based on benchmarks instead, based on assumptions on the technology employed for the good's production. This effort only seems worthwhile for highly energy-intensive and easily tradable goods facing a high risk of carbon leakage, such as steel and chemical products.

Moreover, as EU trading partners might interpret carbon border adjustments as a protectionist measure, it will be crucial to design the mechanism in a way that avoids intensified trade conflicts. The most important aspect, next to the derivation of these adjustments according to a set of clear and well-motivated standards, would be the attempt to include as many trading partners in the carbon club as possible. A possible lever to forge such an alliance will be provided by the revenue collected via this adjustment. Instead of using this revenue as a source for enhancing the EU budget or disbursing it to the member states, it could also be used as a reservoir for transfers to less developed and emerging economies in exchange for their participation in the carbon club.

The same qualifications — that compliance with World Trade Organization and EU law has to be ensured, and that carbon border measures have to be used in a very targeted and prudent manner, and only successively in a few sectors — also apply to the idea of a carbon-added tax (i.e. a consumption tax for carbon, which can be considered as an economically comparable approach). It could be structured analogously to the value-added tax principle in that the added carbon content of products would be taxed at each stage of production. Alternatively, the tax would only be levied on the final consumer. In any case, the final consumers pay the tax on the entire production process. A carbon added tax puts an explicit burden on citizens that makes it rather unattractive from a political-economy perspective.

3.11. Investment challenges in the energy transition

Decarbonisation is a colossal endeavour. Replacing fossil fuels will require investments in renewable plants, grids and pipelines, storage facilities and carbon-free fuel alternatives, as well as the rehabilitation of buildings, efficient industrial processes and appliances, new transport technologies and smart systems. The envisioned transition also provides an opportunity for new, technology-driven new economic growth, as long as Europe is in a position to produce this equipment domestically and implement investment in a cost-effective manner. Financing conditions, stable conditions for future markets, and policy coordination (including effective regulation) are all necessary to implement new technologies and move along their steep learning curves.

Market coordination failure might be an important problem when restructuring markets, and technological innovations depend on many actors. The role of policymaking is to enable the coordination of investment decisions by infrastructure developers, technology developers, manufacturers, financing institutions and, most importantly, final consumers in the uptake of new technologies. In this way, market coordination can bring positive benefits such as cost reductions and improved performance. The quantitative assessment of the European Commission's decarbonisation strategy, performed using the PRIMES energy system model (Capros et al., 2019), indicates that investment might increase substantially in all energy sectors. Expenditures in infrastructures increase faster than spending in energy production units, while also lagging behind money for energy efficiency improvement.

Investment in energy sectors during the transition until 2050 needs to reach 2.5–3% of GDP each year above business-as-usual investment trends. The most considerable portion of total investment, 60–65%, would need to go to energy consumers for building rehabilitation, improved industrial processes, efficient equipment and new transport technologies. About 35–40% would need to go to energy suppliers to develop and reinforce energy infrastructure, to build plants using renewable sources and modern facilities for storing energy, and to factories for producing carbon-free hydrogen and synthetic fuels.

The majority of energy sector projects have extended lead times and operation lifetimes. The projects are typically irreversible economic decisions and present high risks of locking in particular technologies or approaches if not well planned. The learning process behind technology development and the achievement of economies of scale in the industry are also long-term processes. Therefore, investment plans, cautiously designed with clear priorities in mind, should be moved to the top of the EU's agenda as early as possible. Besides, economic analysis has shown that failure to invest in technology and infrastructure in the 2020s will result in higher costs and emissions in the future, rendering the next decade as a 'lost decade'.

The emergence of synthetic gaseous fuels (see 6.5, p.118), whose carbon footprint is very low or even zero, would make it possible to continue using the extensive European gas transmission and distribution network. However, gas infrastructure could be adapted to accommodate a paradigm shift in which a larger share of the gas is no longer imported into Europe via pipeline or liquefied natural gas terminals, but is instead from domestic sources. The new gas infrastructure will have to accommodate multiple energy generation points at its core rather than its periphery, and be able to transport gases towards regions that cannot produce this type of energy.

Furthermore, the grid infrastructure for electricity transmission will have to extend considerably. The aim will be to access renewable energy produced in remote areas, supply electricity to centralised facilities producing hydrogen and synthetic fuels, and fully integrate the markets to balance resources effectively. At the same time, the electricity distribution system will have to expand significantly to integrate battery recharging networks, be able to respond to demand and highly dispersed generation, and reap the full benefits of digitalisation.

It is worth noticing that the largest part of the investment will have to be undertaken by final energy consumers — individuals and businesses. Investment decisions of individuals tend to be highly risk-averse, depending upon subjective considerations regarding cash flow capability, technical uncertainties and lack of information. Low-income households often confront lack of access to cash flow and funding, and might invest less in building insulation and the purchasing of advanced appliances and vehicles compared to high-income households. These severe distributional consequences might lead to 'technology poverty' that will potentially also imply energy poverty in the future.

The standard practices of financial institutions with regard to the financing of energy-related investment have to be revisited. Examples for reconsideration are:

- the way of assessing infrastructure projects
- the funding conditions required for the rapid industrialisation of proven but not yet fully mature alternative fuels and technologies
- the promotion of platform business models to enable large-scale integration of renewable production
- most importantly, effective ways to facilitate fundraising by individuals

The model-based macroeconomic assessment of the European Commission's long-term strategy has shown that the financing conditions are of utmost importance for the impacts on the EU's GDP. Under certain conditions, adequate financing may even enable positive new growth and jobs stemming from the replacement of imported fossil fuels by domestically produced goods and services.

Chapter 4. Embedding the energy transition into society

All energy technology — indeed, all technology — exists within society. For any technology to be embraced, a "seamless web" of technical, political, economic, and social conditions must simultaneously and synergistically exist (Hughes, 1983).

One recent review identified three core groupings of relevant work for how to think about embedding transitions in society: socio-technical systems, policy, and expertise and publics (Sovacool et al., 2020). These were further divided into fifteen distinct topics, as shown in Figure 7. The figure gives a broad overview of how different aspects that are crucial for embedding transitions in society relate to three distinct but overlapping core groupings of relevant approaches that should be taken into account when discussing how to embed technologies and related transitions in society. This demonstrates the plurality of perspective, topics, concepts or tools that is needed to understand how to embed transitions in society. It also highlights the importance of taking on a sociotechnical perspective, an approach that has proved both analytically robust and impactful. Lastly, the figure implies that these elements exist as part of an interconnected system (hence the Venn diagram), meaning approaches that focus on only one aspect of the system will miss the attributes nested in other dimensions of the system, which highlights the necessity of systems level thinking.

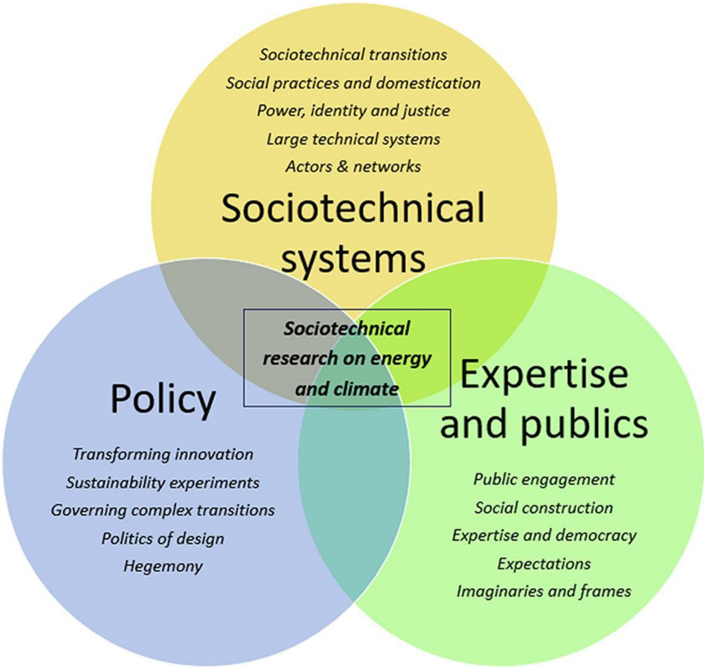

Figure 7. Overview of sociotechnical perspectives and aspects relevant to embedding transitions in society (Sovacool et al, 2020)

Embracing a technology comprises a range of facets, including producing, installing and using it to a noticeable extent. It also blends together the intensity of diffusion of a technology at various levels, from the individual or household level, the community level, to the regional and country level, making it multi-scalar (Essletzbichler, 2012). An accelerated diffusion requires acceptance, which in the socio-technical literature is considered to encompass the entirety of technical, social, political, and economic factors driving the diffusion of a particular technology (Schot & Kanger, 2018; Kern & Rogge, 2016; Geels, Sareen, Hook & Sovacool, 2021). These factors comprise aspects pertaining to this technology as well as those pertaining to its alternatives. So it is always situational and comparative (Devine-Wright et al., 2017).

The reliable estimation of the net benefits of decarbonisation is difficult, and the literature supports a wide range of estimates (Smith & Haigler, 2008; Ürge-Vorsatz, Herrero, Dubash & Lecocq, 2014). Even more difficult is the attribution of costs and benefits to different groups of actors or to different regions and economies. This fact not only provides a huge, albeit not completely insurmountable, obstacle to finding international agreements on climate policy; in the context of the European energy transition, it also complicates the quest for sufficient political support for measures of climate policy.

To receive persistent electoral support for participating in a joint European climate policy, the burden placed on each member state and on different groups of actors within each member state needs to be perceived by a majority of voters as being in accordance with principal notions of equity and fairness. Getting broad consensus for transformational change requires leaving no one behind.

Efforts to ensure a (sufficiently) equitable transition for the relevant affected individuals, communities and societies require as core elements:

- investments in establishing low-emission and labour-intensive technologies and sectors
- research and early assessment of the social and employment impacts of climate policies
- social dialogue and democratic consultation of social partners and stakeholders (Smith, 2017; Swilling & Annecke, 2012)
- training and skills development for exposed workers
- social protection alongside active labour markets policies
- local economic diversification plans (Healy & Barry, 2017; Newell & Mulvaney, 2013)

4.1. The EU Just Transition Mechanism

The Just Transition Mechanism (JTM)[24] is an important part of the European Green Deal effort to create a climate-neutral economy by 2050. The JTM aims to overcome the economic and social costs of the climate transition in the most vulnerable coal- and carbon-intensive regions. It consists of three pillars of financing:

- the Just Transition Fund, strengthened by the Recovery Package
- a dedicated just transition scheme under InvestEU
- a public sector loan facility

The three pillars are expected to mobilise more than €150 billion of investments in the EU regions most vulnerable to the climate transition over the period 2021–2027.

Territorial just transition plans define the territories in which the JTM will be used. However, it seems that the focus is put on coal regions, while carbon-intensive regions are neglected. Meanwhile, countries with high potential fossil fuels resources use them more intensively in the energy sector, energy-intensive industries and households. The identification of these territories is carried out through a dialogue with the European Commission. While these plans are supposed to address the specific challenges in each

24 European Commission, *Financing the green transition: The European Green Deal Investment Plan and Just Transition Mechanism*: https://ec.europa.eu/regional_policy/en/newsroom/news/2020/01/14-01-2020-financing-the-green-transition-the-european-green-deal-investment-plan-and-just-transition-mechanism

territory, as well as the development needs and objectives to be met by 2030, it remains an open question:

- whether and to what extent this mechanism will really lead to developments which would not have happened otherwise (there are problems of free-riding and substitution)
- whether and to what extent it will really lead to net benefits for some actors or regions that are not (over)compensated by losses incurred by other actors or regions
- to what extent these difficult-to-identify effects address issues of transition-induced social imbalance

It therefore seems advisable to accompany the JTM from the outset with thorough monitoring and evaluation processes, conducted by independent parties using appropriate country-specific indicators. Particular attention should be given to social issues related to the transformation of both coal regions and other regions, since the transition will be in constant danger of suffering from antagonisation between social groups.

4.2. Social acceptance

Social acceptance is a large and growing area of research. Of particular relevance to this report are three types of studies:

- those looking at national styles of regulation
- those analysing the barriers to renewable energy
- those looking at the factors that drive local acceptance and opposition to renewable energy, often through surveys of public attitudes and beliefs

For example, acceptance and rejection at the scale of local communities tends to revolve around issues related to local environmental quality, procedural justice, distributional justice, and trust (Sovacool, Sidortsov & Jones, 2014; Greenberg, 2014), yet at larger scales involve broader socio-political and market dimensions related to public approval, electricity prices, profitability for investors, and the ability to improve energy security. Some forms of opposition or nimbyism can cut across community, socio-political and market dimensions simultaneously (van der Horst, 2007; Burningham, Barnett & Walker, 2014). Landowners may oppose a wind farm because they fear it will lower their property values and increase their electricity bills; environmentalists because they believe it could harm birds and require fossil-fuelled power stations to ‘backup’ intermittent wind generation; investors because they worry about delays in project implementation; politicians and regulators about job losses and public controversy. These forms of opposition fuse community, environmental, economic, and political concerns together (Sovacool, 2009).

Two prevailing factors that seem to influence the phenomenon of nimbyism, or the lack of it, are location and time. Research (Breukers & Wolsink, 2007) found differing attitudes towards wind energy in the Netherlands (where public opposition was more about the prospect of volatile electricity prices and an exclusionary method of approving wind projects), the United Kingdom (where opponents were critical of the 'neo-liberal' approach to wind development), and Germany (where the public was primarily concerned about protecting the environment). Research suggests that opposition to wind projects changes significantly before and after projects are completed, with projects contentious at the planning stage but generally accepted after they have been constructed. Put another way, local people become more favourable towards wind farms after their construction and the degree of acceptance tends to increase in proximity to the wind farm.

Devine-Wright (2005) performed a study on local acceptance of a wind project before, during and after construction of the wind turbine, and found that the acceptance generally decreases close to the commencement of the project, but then rebounds over time. The same result has been found in a case study from Nadaï & Labussière who discovered that local inhabitants found the need to complain about the wind turbine project just before the public enquiry round (Nadaï & Labussière, 2009).

A study in the UK showed that public attitudes towards wind turbines and landscape often cause a 'green or green' dilemma (Warren, Lumsden, O'Dowd & Birnie, 2005). This phenomenon is experienced when locals living nearby a proposed wind farm have to choose between a 'global good', the reduction of CO_2, and the 'local bad', the wind turbine's impact on the local landscape. This is especially the case with wind turbines as they are very visible in the landscape (Nadaï & van der Horst, 2010), due to their size which, furthermore, is increasing (Manwell, McGowan & Rogers, 2011).

Other studies have found that wind turbines were primarily accepted or rejected based on broader factors relating to public interest and the interests of others as well as notions of fairness and equity. Drawing from and synthesising this literature suggests the social opposition to onshore wind turbines will cut across environmental (including the impact on flora and fauna), aesthetic (including the visual impact, noise and flicker effects and placement), and socioeconomic (including the impact on local properties and businesses) dimensions (Enevoldsen & Sovacool, 2016). The inverse holds true: wind turbines with minimal environmental impact or environmental benefits, which are aesthetically pleasing, and contribute to local economies will, by and large, be socially accepted.

Indeed, other studies looking at the local acceptance (or opposition) to renewable energy projects have tended to confirm these findings (Wolsink, 2000; Warren, Lumsden, O'Dowd & Birnie, 2005; Breukers & Wolsink, 2007; Wolsink, 2007; Ansolabehere & Konisky, 2009). Providing incentives for local citizens to invest in or own part of a project, or inviting them to participate in planning and siting procedures, can strongly influence public acceptance. Greenberg, for instance, surveyed more than 2700 residents in the United States and found that familiarity with type of energy and proximity to a site were strong indicators of public acceptance, that greater concern about local environmental conditions showed a strong correlation with a preference for renewables and against fossil fuels, and that those participants that trusted authoritative institutions such as government and energy suppliers were usually supportive of coal and nuclear technologies (Greenberg, 2009).

Drawing on this work, we propose one possible conceptual framework consisting of nine factors to explain the acceptance of renewable electricity resources (Sovacool & Lakshmi Ratan, 2012). Depicted in Figure 8, we believe that acceptance hinges upon the prevalence of these nine criteria that each correspond to socio-political, community, and market factors.

Socio-political factors

- Strong institutional capacity
- Political commitment
- Favourable legal and regulatory frameworks

Market factors

- Competitive installation/production costs
- Mechanisms for information and feedback
- Access to financing

Community factors

- Prolific community/individual ownership and use
- Participatory project siting
- Recognition of externalities or positive public image

Figure 8. Conceptual framework for social acceptance of renewable energy (Sovacool & Lakshmi Ratan, 2012; Devine-Wright et al., 2017)

Any reliable technology is a precondition for all nine criteria and is therefore not included in any of our three dimensions (although it is partially subsumed by competitive costs, since a poorly designed or unreliable technology would ostensibly cost more). It also means that all, or most, of the nine criteria are needed for acceptance to occur.

Many of the criteria in the framework are interrelated, or at least have strong interactive effects between them. This is because the framework is both mutually exclusive (each criterion is distinct from the others) and collectively exhaustive (including a comprehensive list of metrics). In doing so, the framework blends together producing and installing, since use requires both to have happened. It also blends together individual and community, as these occur at a scale below the country or province.

The framework treats acceptance as relative and different from diffusion. Its conditions are not believed to facilitate absolute acceptance, which would imply total market saturation, but an accelerated level of diffusion compared to other countries and places. Diffusion is a neutral term, in this case having large numbers of renewable energy systems installed (and high installed capacity or production per capita). Acceptance is social, and refers to the diverse technical, social, political, and economic factors driving (or even constraining) diffusion. Acceptance of renewable energy need not imply that such technologies are favoured among producers and users; it could be that other energy options such as fossil fuels and nuclear power are disliked, whereas stakeholders are apathetic towards renewable energy (for instance, a person may not necessarily like or even accept wind energy, but hate the thought of another coal plant, meaning wind 'wins' by default). So the framework emphasises that social acceptance is always situational and comparative.

For the sake of simplicity, the framework treats each criterion as equal. It may be that some criteria are truly more meaningful and influential than others. Strong institutional frameworks and access to financing may be true 'knockout' criteria that are always needed for acceptance, whereas countries without political commitment and participatory project siting may still create frameworks generally conducive to acceptance. Further research ought to perhaps weigh the criteria through conjoint choice analysis, clustering, or other techniques to create a hierarchy of importance.

Devine-Wright et al. (2017) note the potential usefulness of this framework, and also posit that it is useful for distinguishing contrasting aspects of acceptance, each involving different actors. However, they also suggest that the framework is weakened by a lack of emphasis on how each dimension interrelates across different geographical scales (from macro to micro; international, national and local). Moreover, they argue that few empirical studies have encompassed more than one of the three aspects in their respective analytical frames.

Additionally, Geels & Johnson (2018) and Geels et al. (2021) distinguish four processes of societal embedding of innovations that also go beyond some of the factors in the social acceptance framework: cultural appropriation (including discursive and framing struggles); regulatory embedding (including political debate over regulations and standards); embedding in the business environment (including business strategies and strategic games); and embedding in user environments (which involves not just purchase, but also appropriation and domestication.

4.3. Public engagement, deliberation and ecologies of participation

Energy transitions will require substantial public support. This challenge is frequently conceptualised through the notion of 'public acceptance'. The potential agency of diverse publics, however, moves far beyond the accept/reject dichotomy. Even though publics have often been understood as a barrier to progress, either by failing to take up new technologies or by responding with selfish criticism of new developments (e.g. nimbyism), such explanations have been accused of being reductionist, of giving misleading simplifications of people's potential engagement with new energy technologies, and of being poorly anchored in empirical evidence (Aitken, 2010; Besley & Nisbet, 2011; Heidenreich, 2015; Devine-Wright, 2009; Wolsink, 2012; Ryghaug & Skjølsvold, 2021).

More recently the envisioned role of energy users has shifted from being passive consumers to being active energy citizens and participants in energy transitions (Ryghaug, Skjølsvold & Heidenreich, 2018). Including and involving diverse publics in decision-making is increasingly seen as important to the success of energy and climate transitions in the academic and policy sense and in the view of research funding agencies (Ingeborgrud et al., 2020). Newer approaches in this area also recognise that technologies offer potential opportunities for engagement (Marres, 2016).

Analysis of the ongoing introduction of new products has highlighted how these technologies can also be seen as material interventions catering for sustainable practices, and how artefacts such as the electric car, the smart meter and solar photovoltaics may become objects of engagement that foster energy citizenship (Ryghaug, Skjølsvold & Heidenreich, 2018). Similarly, demand side management technologies may have much broader impacts if they are not only understood as a means of managing energy demand and providing system flexibility in such a way that social agency is reduced to just levels of consumption (Wallsten & Galis, 2019). Relating to the discussion on energy justice above, they might feed into social processes of reducing energy poverty, traditional gender roles and other forms of inequalities (Suboticki et al., 2019; Powells & Fell, 2019).

Recent perspectives on participation highlight that participation in energy transitions is a rational, emergent and co-produced phenomenon where a wide ecology of actors and different kinds of collectives might produce different models of participation (Chilvers & Longhurst, 2016; Chilvers & Kearnes, 2016; Chilvers, Pallett & Hargreaves, 2018). Such a perspective also points to the fact that research (for example, pilot and demonstration projects) are not only sites where citizens, organisations, companies and researchers can opt-in or opt-out of participation in transition-oriented activities, they also constitute sites where participation is formatted, orchestrated and shaped (Ryghaug & Skjølsvold, 2021; Skjølsvold, Throndsen, Ryghaug, Fjellså & Koksvik, 2018). Such projects have tended to cater for participation in the form of acting as a consumer, attempting to instigate behaviour change, or producing acceptance for new technologies (Chilvers, Pallett & Hargreaves, 2018).

Research policies might have vast impacts on participation. Policymakers might consider engaging in transformative energy policies that highlight the need for experimentation and include more diverse publics and otherwise marginalised actors in innovation and research (Schot & Steinmueller, 2018; Steward, 2012; Schot et al., 2018). This approach emphasises the limits of incrementalism and the need for pervasive transformative innovation (Steward, 2012) that bring into the process not only dominant actors but also niche actors, as well as actors from various sectors including producers, civil society, consumers and policymakers.

4.4. Restorative and regenerative design

Moving to a sustainably oriented society, new concepts and design paradigms of sustainable construction are being developed. Several are focusing on including elements of nature in the built environment, like biophilic design, restorative environmental design (RED), regenerative design, and restorative environmental and ergonomic design (REED). The latter focuses not only on placing nature indoors but also on material choice. All the mentioned design principles are created in a direction towards a more sustainable environment and are pointing at many positive effects that nature in buildings has on human wellbeing, however more evidence proving these statements are needed, especially on how to use natural materials properly, and how to present and convince relevant stakeholders to start using them (Jones & Brischke, 2017).

The restorative environmental and ergonomic design (REED) is a design principle that was developed by InnoRenew CoE researchers in 2017. It was created with the goal to inspire designers, help manufacturers, and guide researchers when solving design and material issues. Certification schemes and all relevant stakeholders should be aware that incorporating natural materials indoors, where humans spend most of the time, is positively affecting human health, and has positive environmental and societal impacts (Jones and Brischke, 2017). It is an expansion of RED and regenerative design. REED integrates aspects of ergonomics and kinesiology (the science of body movements), material science, architecture, engineering, psychology, physiology and other disciplines in a scientific framework that seeks to improve building design for occupants. Research has shown that incorporating nature into the built environment by using natural materials like wood, for example, improves how people view nature and motivates them to care about the environment (Burnard, Kutnar & Schwarzkopf, 2016). We can sum up that REED aims to improve human health and wellbeing through building practices by employing principles of biophilic design to bring building occupants closer to nature and with this to improve their overall wellbeing and accelerate their restoration following stress. Moreover, it aims for application of ergonomic principles to align interior furniture and spaces with human needs and to encourage physical activity in buildings.

The social life cycle assessment (S-LCA) is a method for assessing social and sociological aspects along the value chain of products and services or organisations. S-LCA is a compilation and evaluation of social risk and opportunities associated with the flows (economical or physical) in the scope. The newest consensus-based guide on S-LCA is the new S-LCA Guidelines from UNEP/SETAC Life Cycle Initiative (UNEP, 2020) released in Dec 2020, but the research field is still in development.

S-LCA can look at different stakeholder categories: worker, society, local community, consumers and value chain actors. The method looks at indicators that often are linked to the UN Sustainable Development Goals.

An S-LCA may be motivated for the following analytical, managerial, or societal reasons:

- to provide structure, credibility, and consistency to supply chain materiality assessment
- to identify the risks and opportunities to reduce the negative (social footprint) and increase positive (social handprint) impacts
- to support in building a targeted strategy for future development of social policies
- to manage social risk thanks to the identification of social hotspots
- to initiate sustainability communication and reporting (like non-financial information) with stakeholders
- to support decision-making processes that involve a variety of stakeholders with different knowledge and background
- to demonstrate social awareness for marketing or legal requirements purposes

However, the objectives for S-LCA should be adapted to each study. The strength of the life cycle based methods is to prevent shifting of burden between different life cycle stages, but also between different stakeholder groups.

4.5. Transforming innovations and research policies

Research policies have significant impact on participation (and justice), and as noted above, there is a need for transformative energy policies that highlight the need for experimentation that includes more diverse publics and otherwise marginalised actors in innovation and research (Schot & Steinmueller, 2018; Steward, 2012; Schot et al., 2018). In order for socio-technical system change to happen, public policy and research should focus more on anticipation, experimentation, participation, and directionality. This framing of innovation involves a 'questioning of how to use science and technology policy for meeting social needs and addresses the issues of sustainable and inclusive societies at a more fundamental level than previous framings or their associated ideologies and practices' (Schot & Steinmueller, 2018).

In general:

- Investments in research and technology refurbishment or renewal are needed for making energy technologies better comply with stronger expectations of the public about sustainability, environment preservation, and overall life cycle impact.
- At the same time, research and tests of novel technologies are needed to demonstrate the capacity to contain the costs of energy products affordable for each European country.

4.6. Demand-side options for reducing carbon emissions

A final and critical area of focus is that of energy users, households and demand, which are socially shaped and mediated by both technologies and policies as well as social practices. For example, one study (Laitner, Ehrhardt-Martinez & McKinney, 2009) found that three types of simple, low- to no-cost actions could save significant amounts of energy (and the related greenhouse gas emissions):

- infrequent actions like installing LED lights, placing weather stripping on windows and doors, and inflating car tyres to correct pressures
- more frequent actions like slower highway driving, air-drying household laundry, and turning off unneeded lights and appliances
- making informed purchases and investment decisions for more efficient windows, appliances, and automobiles

The study found that these three sets of changes alone could reduce total energy use among individuals and homes by 23%.

Another investigation found that the majority of energy consumed by an average United States household was directed at two purposes: running a private motor vehicle and controlling the temperature within a home. Relatively little energy is used for lighting, cooking, running computers, and so on. The authors found that if individuals were to switch to more fuel-efficient automobiles, upgrade their heating systems, and turn their thermostats down during the winter (or up in summer), they could cut household energy use by more than 50% (Gardner & Stern, 2008). Although these studies were limited to the US, similar actions in high-income, northern European countries could also achieve significant emission reductions; for example, Dubois et al. (2019) found that households could conceivably cut about half of their emissions.

An interdisciplinary study of 16 action types concluded that implementing the most successful behavioural programmes could reduce US household carbon emissions by 20% by 2020, an amount equal to all greenhouse gas emissions from France (Dietz, Gardner, Gilligan, Stern & Vandenbergh, 2009). Similarly, Moran et al. (2018) project that changes in consumer practices and consumption patterns could reduce carbon footprints further beyond business-as-usual by roughly 25% (Moran et al., 2018). Levesque et al. (2019) even project that adopting new, energy-saving practices globally could reduce energy demand from buildings by up to 47% in 2050 and 61% in 2100 compared to a scenario following current trends (Levesque, Pietzcker & Luderer, 2019). Another recent study looking at four high-income European countries — France, Germany, Norway and Sweden — also found that voluntary behaviour change could cut household emissions by as much as 50%, through measures such as changing heating practices or travel modes (Dubois et al., 2019).

Chapter 5. Specific systems aspects of the transition pathways

This chapter considers the various technologies and technology related approaches that will be critical to the energy transition and how the system might evolve along different pathways, with particular consideration of the systemic issues. The purpose of this chapter is to consider how these various factors might affect the energy transition and to guide policymakers on how to design policies and regulation to meet climate goals in the most cost-effective and socially acceptable way.

5.1. Energy demand

Demand for energy and the role of energy efficiency

In many cases, increased energy efficiency will require a more diversified energy supply to adapt to different conditions. There is a broad range of possibilities for increased energy efficiency, such as improving the thermal insulation of badly insulated buildings or renovating industrial platforms with more efficient equipment and heat recovery between co-located industries. Although many energy efficiency measures are economically profitable over time (assuming typical interest rates), there is often a lack of knowledge with many actors involved in the decision to implement the measures, including split incentive problems, that result in the measures not being implemented. The difference between what is actually implemented and what would have been economically feasible to implement is referred to as the 'energy efficiency gap' (Ó Broin, Mata, Nässén & Johnsson, 2015, and references therein).

It is of great importance to develop good government support schemes that can accelerate energy efficiency improvements. Due to complexity and the many decision-makers involved, such schemes are not only about money but also about the education of different actors, setting standards, and changing values and norms. This is especially important in areas related to private consumers, such as in the buildings and transport sectors. There is also a need for research funding and investment support programmes for the timely deployment of energy-saving technologies that are core measures for cutting domestic and industrial carbon emissions in the short term.

When it comes to private consumers, energy savings are challenging to achieve since they depend on a change in values and norms which can only happen over time. So-called 'nudging' can help accelerate changes in values, but this is still a slow process when considering the entire population, albeit an important one. Thus the EU goal of increased consumer involvement is important, but how this will reach and influence the broader population is not clear. Unless clear and proven strategies are developed, it would be a risk to put too much faith in the effectiveness of energy savings and efficiency measures. There is also the issue of the rebound effect, in which increasing efficiency makes the energy bill smaller or the product cheaper, and thus can increase use (see "Rebound effect", p.83). Although most studies indicate that direct rebound effects are typically rather limited, what is more challenging to understand and analyse is the indirect rebound effect: making a process more efficient will create value that will give room for increased spending on other goods or services which can be carbon-intensive (e.g. increased flying). A recent meta-study suggests economy-wide rebound effects typically exceed 50% (Brockway, Sorrell, Semieniuk, Heun & Court, 2021). Thus, it is always important to strive for a carbon price; energy efficiency and energy saving measures should not be seen in opposition to other measures (and vice versa).

Both energy efficiency and energy savings are typically no-regret options. Security of supply will increase and provided that strategies such as economic support are fairly distributed it should gain social acceptance. The biggest threat to the successful adoption of both energy efficiency and energy saving measures is the many actors involved and the fact that energy for many is not seen as a major expense, although this is not the case for a significant proportion of the population. Its influence on job opportunities is not obvious, but assuming that increased energy efficiency includes renovation of existing building stocks, it should be favourable, since there is a large demand for renovation of the existing building stock, particularly of multifamily buildings built in the 1960s and 1970s. It is likely that successful implementation of both energy savings and energy efficiency will require new services to be developed that would have a positive effect on jobs.

With respect to the industry sector, energy efficiency measures can result in several co-benefits in addition to reduced carbon intensity, such as improved productivity, product quality and enhanced competitiveness (see, for example, Zuberi et al., 2020). A clear strategy on improved energy efficiency is also likely to lead to innovations.

Future outlook on EU energy demand

In 2016, the PRIMES model projected a largely constant energy demand until 2050 in a baseline framework (Figure 9, p.81). However, there is evidence to suggest that energy demand could be reduced significantly (as much as halved) by 2050 in Europe while retaining both the population and wellbeing increase ambitions.

The European Commission's Joint Research Centre (Tsiropoulos, Nijs et al., 2020) summarised a large number of scenarios (Teske, 2019) that would achieve net zero emissions by mid-century in the EU. All examined scenarios that achieve climate neutrality by this date reduce energy demand by at least 30% compared to 2017, but there are many (Teske, 2019) that require 45–60% reduction in energy demand to reach this goal. In general, this underscores the conclusion that the scenarios with higher demand reductions allow more flexibility on the choice of supply-side solutions.

However, studies also indicate that future potential energy efficiency improvements in buildings in scenarios from 2011 and 2018 by the EU Commission may be overestimates on the end demand side and underestimates on the supply system side. That is to say, reductions in energy demand of buildings of more than 50% in the existing building stock may be very hard to achieve, but there is a possibility of having a balanced effort on the end demands and on the supply system using district heating (Möller et al., 2019; Drysdale, Mathiesen & Paardekooper, 2018). Such a focus is in line with moving towards smart energy systems where there are synergies in reductions in the demand and the redesign of the energy system (Mathiesen et al., 2015; Hansen, Mathiesen & Skov, 2019; Connolly, Lund & Mathiesen, 2016).

Studies indicate very large benefits for further inducing reductions in end demand for heating and cooling in buildings and, in conjunction, developing the current district heating systems towards lower temperature, fourth-generation district heating systems (Lund et al., 2018; Lund et al., 2017).

Brugger et al. (2021) provide an analysis of visionary scenarios for energy demand in the EU28 and conclude that new trends such as digitalisation, sharing economy and consumer awareness will influence future energy demand and may enhance or counteract energy efficiency gains (see Figure 9, p.81). History suggests that a significant reduction in final energy demand is highly unlikely unless there are strong policy measures put in place which can trigger such mega-trends, assuming it is not triggered by economic depression or other unwanted societal problems such as pandemics. For instance, digitalisation may increase household plug loads while, on the other hand, a widespread application of automated controls could save significant amounts of energy. Wilson et al. (2020) analysed a sample of 33 digital consumer innovations which could challenge emission-intensive mainstream consumption practices within mobility, food, homes, and energy domains, from which they identified a clear but variable potential for emission reduction benefits. Yet they also conclude that some studies show emission increases from specific innovations as a result of induced demand or substitution effects that need careful management by public policy. This points to the fundamental importance of the policy environment that embeds these major societal and technological transitions.

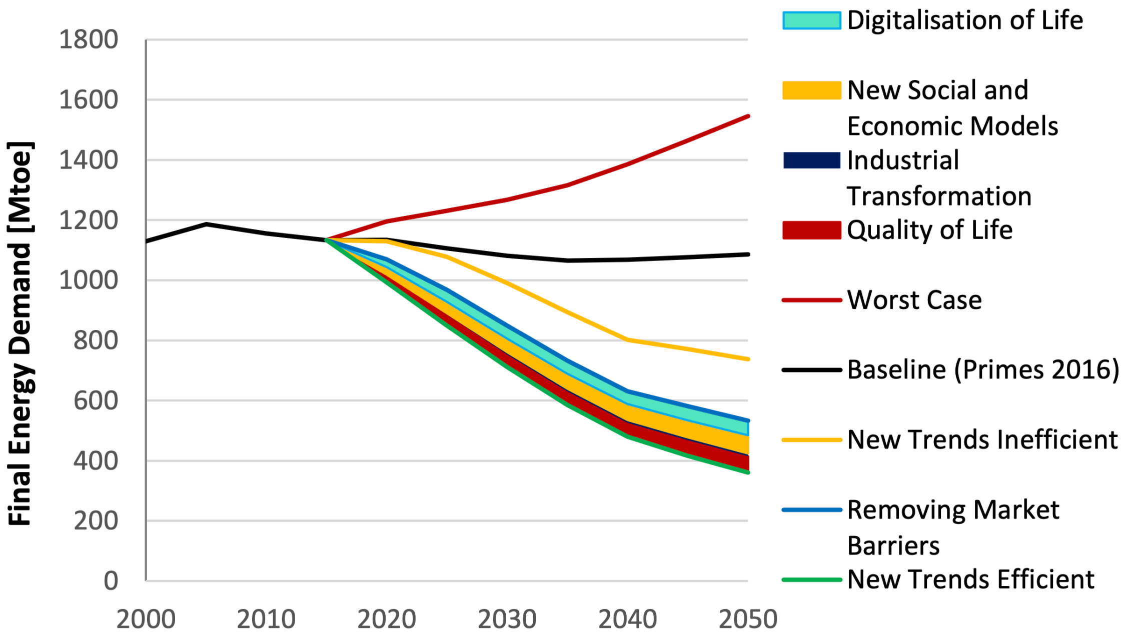

Figure 9. Final energy demand (EU-28) in four scenarios and the baseline (in Mtoe) from the PRIMES model (from Brugger et al., 2021)

Opportunities for energy demand reductions and efficiency increases

Traditionally, policies to improve energy efficiency have resorted to improving the technological efficiency of individual appliances, vehicles, or equipment, but the potential to make further improvements is not sufficient to bring the desired reductions in energy demand, partially due to the rebound effect. As indicated below ("Sectoral issues", p.95), carbon taxes that increase energy prices are also important mechanisms to influence energy demand that avoid rebounds. Attention has been expanding recently to other areas of opportunities to bring down energy demand. This includes the societal mega-trends noted above or focusing on systemic opportunities such as those in food, urban, building, material or land systems.

While this report does not have the space to cover all these approaches comprehensively, here we highlight a few selected such opportunities that represent novel trends in the thinking on energy demand.

The energy efficiency of many energy-using devices and equipment (automobiles, buildings, boilers, white goods, cooling appliances, etc.) has dramatically improved over the past few decades. This progress, however, means that many devices are getting close to their thermodynamic limits of efficiency, and while innovation can still be expected to bring further improvements, we cannot expect the same rate of improvement in efficiency of equipment to continue for long. However, advances in sensors, monitoring, big data, the Internet of Things, smart gadgets and personal phones all enable much higher levels of systemic optimisation. Smart homes, smart metering, smart appliances and smart grids are all aimed at achieving systemic integration and feedback to consumers, based on which they can contribute to higher levels of efficiency.

Furthermore, there are new opportunities through systemic integration or systemic level solutions. For instance, considering buildings as complete systems rather than sums of individual components have enabled net zero energy buildings to now become feasible and economic in all European climates, and also net zero retrofits to be achievable and paying back the investment through energy efficiency measures for all building types, including historic buildings (Ürge-Vorsatz et al., 2020). However, a large share of the buildings that will be present by the mid-century in the EU already exist. Thus, energy-efficient retrofitting of buildings is a vital task that requires more effective policy interventions and increased funding.

Equally, urban systems can also significantly reduce energy demand (Güneralp et al., 2017). The single largest energy demand category in EU countries is heating and cooling, which, when combined across both buildings and industry, accounts for around half of European final energy demand, three quarters of which is generated from fossil fuels.[25],[26] While heating is already progressing towards a much more efficient level and has stayed broadly constant since 1990, the demand for cooling has increased significantly over the same period, even if it only represents 3% of final energy demand at present. Reducing urban heat islands through green infrastructure (incorporating natural features such as trees, parks, forests, etc.) and blue infrastructure (incorporating water features such as rivers, canals, wetlands, etc.) can help to reduce cooling needs significantly without energy inputs, while cooling demand in Europe is surging, especially given the increased frequency of heat waves due to climate change. In contrast, efficient cooling technologies are important, but they can only reduce cooling energy demand by incremental percentages (Khosla et al., 2020).

Mobility should offer a large potential for energy demand reduction, but this would require new policies. In the automotive sector, improvements in energy efficiency

25 European Commission, Heating and cooling: https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en

26 Heat Roadmap Europe (HRE4), Heating and cooling facts and figures: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2017/29882_Brochure_Heating-and-Cooling_web.pdf

of engines have been counteracted by increasingly powerful engines. The ongoing electrification trend in the transport sector may result in a fundamental transformation of the fuel used in transport, but this will require smart charging strategies to manage the impact on electricity demand (e.g. to avoid evening peaks in electricity load when people arrive home) as discussed in "Sectoral issues", p.95.

Looking more broadly, a recent paper in *Science* (Clark et al., 2020) reported that shifting to low-meat diets based on health and sustainability recommendations alone could save half of cumulative food system emissions by 2050, while halving food waste can also shave off one sixth of emissions.

With increasing understanding of the problems of planetary boundaries and the apparent conflict between unrelenting economic growth and environmental degradation, the concept of 'sufficiency' is gaining traction in the academic literature (Princen, 2003; Princen, 2005; Alcott, 2008; Steinberger & Roberts, 2010; Figge, Young & Barkemeyer, 2014; Lorek & Spangenberg, 2019). This suggests that eco-efficiency is no longer enough, but sufficiency, or stagnating levels of services rather than constant growth, is unavoidable beyond a certain level of wealth. Lorek & Spangenberg (2019) even argue that sufficiency does not imply a loss of wellbeing, but rather:

> restructuring of household consumption: being satisfied with less new material goods than usually consumed today, while enjoying the existing ones, plus immaterial social and collective goods. Examples are durable household goods, plus personal relations, or leisure spent in a healthy environment. Being satisfied means that no loss of quality of life is implied: needs are to be satisfied in a different, more sustainable way, while conspicuous consumption is to be avoided
>
> *(Lorek & Spangenberg, 2019)*

Suggested policies to implement sufficiency principles include legal regulation on the macro level (obligations, bans, standards), fiscal instruments (subsidies and taxes or fees), planning, and public investment. However, economic theories argue that moving from efficiency to sufficiency will not bring the desired results because sufficiency is also subject to the rebound effect (Figge, Young & Barkemeyer, 2014). Moreover, regulatory measures such as setting efficiency standards or implementing carbon pricing tend to leave the choice set of individuals widely untouched and allow individual actors to express their preferences in their actions, within the limits of the regulation. By contrast, the set of policies discussed under the heading of sufficiency intends to directly influence individual preferences, raising a whole range of fundamental questions of civil rights and personal freedom.

Rebound effect

Stipulating efficiency standards often works as a two-edged sword due to the rebound effect. If we assume that the demand for a particular energy service in question stays constant, any improvement in efficiency resulting from a more stringent efficiency standard will lead to lower demand for energy from that service. For example, in the case of fossil fuels used for private transport, stipulating a maximum permissible average fuel consumption per kilometre would reduce fuel consumption per kilometre. And, if mobility demand stayed constant, this would translate into a general decrease in demand for fossil fuels in transport. Inevitably, however, people will react to changing circumstances through their individual decisions. An improvement in efficiency will effectively reduce the relative cost of the service and, as a consequence, demand for the service will tend to rise. In doing so, more fuel will be consumed than would have been the case if demand had stayed constant. This rebound effect will counteract some of the potential reduction in fossil fuel demand that might be expected to result from the more stringent efficiency standard. In the case of private transport, as a more stringent efficiency standard reduces the cost per kilometre travelled, demand for mobility increases.

In the end, the net effect will be an empirical matter and the range of rebound effect estimates in the literature is huge. However, neglecting this effect altogether could lead to an overly optimistic assessment of the potential effectiveness of policies.

In contrast to stipulating efficiency standards, carbon pricing generates behavioural effects that support, and perhaps amplify, the choice of more efficient ways of acquiring an energy-using service. As the service becomes more expensive, demand for it tends to be reduced as well. In the example of private mobility, carbon pricing will make the acquisition of a less fuel-intensive vehicle attractive and at the same time reduce the demand for kilometres driven. In economic terms, setting an efficiency standard implies charging an infinitely high price for using an energy service which exclusively applies to this service.

The choice of a more efficient vehicle or appliance will be made easier for households and businesses by more efficient solutions per unit of service becoming available in the marketplace. Thus, funding the fundamental and applied research leading to the development of these solutions is a sensible technology policy that would be in accordance with carbon pricing. Enhancing the set of energy-efficient options to choose from would also address the issue of efficiency, but it would work completely differently from the stipulation of an efficiency standard.

Digitalisation

The digital revolution is a prevailing global trend that penetrates the whole of society. In the case of energy, the whole value chain from supply to demand will be affected by digitalisation, opening up opportunities for smarter and more efficient use of energy, although if it is applied without careful policy considerations, digitalisation may also result in an increase in energy use (as discussed in “Future outlook on EU energy demand”, p.80).

Digitalisation accompanied by the Internet of Things (IoT), advanced data processing, machine learning, artificial intelligence, and other developments offer major possibilities to improve efficiency and manage complexity in energy systems. They also enable an important shift in the focus of our economy from the resource- and energy-intensive production of material goods to a service and digital commodity focused economy. This shift will also impact the energy system, with an increasing share of energy demand needed to power digital technologies and systems.

Digitalisation will enable predictive analytics to manage large-scale variable renewable energy schemes, but also wide-ranging automation in buildings and transport, among others, that could save large amounts of energy. Digitalisation has already shown 2–10% yield improvements and 10–30% cost improvements in capital, supply chain, and operations in energy systems.[27] IoT-connected devices are expected to increase from 20 billion in 2020 to 500 billion in 2030,[28] which demonstrates the disruptive nature and expansion of digitalisation in the coming years.

Data combined with deep learning, artificial intelligence and computational physicochemical theoretical models could also open up entirely new avenues for future energy materials such as advanced batteries, solar fuels and chemicals with potentially outstanding properties compared to the present state-of-the-art. This development has just started, for example within the European Battery programme[29]. Speeding up European efforts could enable a first-mover advantage important to early commercialisation of these science-based innovations. Mitigating the high risks involved in this process will require attention to create a critical ecosystem to scale-up laboratory research into commercial products.

Many of the benefits of digitalisation are linked to data and algorithms that will not only increase computing demand, but also the demand for electricity of data servers. Presently data servers are responsible for approximately 1% of global power demand.[30] Although the significant increase in the demand for digital services has raised concerns of a corresponding rise in power demand, a recent review (Masanet, Shehabi, Lei, Smith & Koomey, 2020) has pointed out that efficiency gains are expected to largely offset these major demand increases even for a doubling of computing demands. But as pointed out above (Figure 9, p.81) it is important to carefully assess the need for policies to ensure a continued focus on increased energy efficiency, including that of the servers.

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27 *Digital transformation in energy: Achieving escape velocity*, A. Booth, N. Patel & M. Smith, McKinsey & Company, August 2020: https://www.mckinsey.com/industries/oil-and-gas/our-insights/digital-transformation-in-energy-achieving-escape-velocity

28 *Acceleration of digitalisation*, Technology Outlook 2030, March 2020, DNV GL: https://www.dnv.com/to2030/trend/acceleration-of-digitalisation.html

29 BATTERY 2030+: https://battery2030.eu/about-us/

30 IEA, *Data Centres and Data Transmission Networks*, 2020: https://www.iea.org/reports/data-centres-and-data-transmission-networks

A challenge may be that digitalisation will most likely happen fast. To make full use of the advanced analytics possibilities associated with digitalisation, addressing the rapidly growing computing demand will be important for Europe. This will require larger efforts, for example in quantum computing, which is perceived as a future key technology in the artificial intelligence field. Europe is clearly behind China and the US in this field.

The degree of digitalisation varies among the different parts of the energy system, but it will be particularly intensive in smart energy systems such as smart grids, which are often the backbone of distributed electricity production and handle large amounts of data on power supply and demand for optimal and effective operation of energy systems. In terms of the amount of data that will be created, smart grids could have two to three orders of magnitude more connected intelligent devices than the internet, making network monitoring and management extremely challenging (Aloul, Al-Ali, Al-Dalky, Al-Mardini & El-Hajj, 2012).

It is also important to note that, although digitalisation may mitigate against traditional weather and technical failure threats in power systems, it will also introduce new vulnerabilities to cyberattacks by increasing the attack surface and increasing the potential damage such attacks can do. Potential consequences of cyberattacks include data theft, power theft, denial of power supply, disruption of normal energy system operation and even destruction of equipment. Existing cybersecurity solutions, primarily from the internet industry, can be employed only to a limited extent due to major differences between the networks. Implementation of sufficient cybersecurity measures in the energy sector relying only on internal quality assurance and certification may be insufficient, and may need stronger regulation, such as is found in the health sector. Cybersecurity has been given surprisingly little attention so far in the energy transition, considering that electrification and digitalisation are at the heart of the transition (see, for example, European Commission, 2017).

The COVID-19 crisis has accelerated the replacement of many traditional activities by digital alternatives, such as home working, remote education, training, healthcare, e-commerce and a wider range of digital entertainment and leisure alternatives. This has been replacing the need for some traditional energy-demanding activities, primarily mobility for commuting and running errands as well as many long-haul business trips. It has also made some infrastructure redundant, such as office space. While much of this is expected to rebound once the threat of infections is over, part could stay with a potentially ongoing reduction in demand for commuting and business mobility. The right policies and stimulus spending could substantially help moderate the rebound through new infrastructures as well as policies and incentives to continue the emphasis on the digital alternatives to travel-intensive activities.

5.2. Resource efficiency and the circular economy

Circular economy

The principle of circularity will be important for the energy transition to minimise the extraction of new materials and reduce the amount of waste our society generates. Whereas clean energy technologies typically do not produce air pollutants and emissions during operation, the supply chains to produce the technologies themselves may encompass harmful waste and fossil energy use, in particular when produced outside the EU.

Therefore, it will be important to make the supply chains more environmentally friendly through better logistic systems and waste management. Efficient transport chains and optimised complex logistics networks (similar to the optimisation of waste collection, waste transport and waste handling, to give just a few examples) should be applied in the recycling management of all goods in the future. Reverse supply chains should be enhanced to retrieve a used product from a customer and either dispose of it or reuse it. In turn, this will require novel business concepts to be developed, especially in the field of renewable bio-based resources (e.g. innovative reverse logistics, operational transport and material flow planning to optimise plant logistics).

A recent Innovation Roadmap on Sustainable and Competitive Future for European Raw Materials[31] addressing supply of raw materials, production of raw materials, recycling, and substitution of critical raw materials should be prioritised. This would include: fostering a sustainable supply of raw materials to feed new and existing value chains; resource-efficient processing for raw materials; raw materials in new products and applications; and closing material loops by maximising the recycling of products, buildings and infrastructure.

Material use in the construction sector

The construction sector is a major contributor to material consumption in Europe, but has not yet adapted to the circular economy. Improving material reuse in the construction sector will be important in achieving the necessary sustainability and climate objectives. These gains could be amplified through using materials from renewable sources such as timber. In the future, it would be preferable ideally to shift increasingly to reclaimed timber.

31 *Research and Innovation Roadmap 2050: A Sustainable and Competitive Future for European Raw Materials*, VERAM, 2018: https://www.etpsmr.org/wp-content/uploads/2018/04/Broch.Veram_180328_LR.pdf

Specific systems aspects of the transition pathways

The European Green Deal will require much greater sustainability effort during the construction, operation, and especially end-of-life phases in buildings. Stronger emphasis on retrofitting and renovation to improve the energy performance of Europe's older building stock will be highly important. This has important implications on the concept of the 'just transition', in that less energy-consuming buildings have the potential to reduce energy bills for tenants, assuming that the savings are passed on to them.

Assessments of environmental impacts of construction have typically focused on material extraction and processing in addition to the energy demand of operating buildings, but with less consideration for the social, economic and human health impacts of construction. These aspects need to be better integrated in the future. Construction certification systems such as the Living Building Challenge[32] and WELL Building Standard[33] are moving in this direction.

Using more wood in construction would improve sustainability in building construction, deliver a lower carbon footprint, provide good carbon storage for biomass, and provide positive health impacts (Burnard & Kutnar, 2019), while solutions exist for potential issues relating to moisture and fire. Encouraging more wood use in construction would be important to rural development in Europe. Increasing the use of forestry products such as timber in construction will require overcoming several obstacles including a greater recognition of their benefits and policy support in the European Green Deal. At the same time, it should be stressed that there is no contradiction between using more wood in construction and the efforts to develop carbon-neutral cement and concrete. Most building designs include some degree of concrete content. Karlsson et al. (2020) show that roadmaps to zero-emission construction of buildings and infrastructure consist of a number of measures of different importance.

The European Commission's New European Bauhaus[34] calls for a creative, interdisciplinary, novel movement embedded in society to imagine a sustainable future and to engage on a transformative path towards affordable and beautiful living spaces in the urban and rural environment. A key step is the transformation of the building sector into a circular model that can also counteract the escalating climate crisis. Organic building materials like wood have been identified as the material that would enable this goal. Wood and other renewable materials should have a higher share in residential and non-residential public and private buildings. The circular economy of the built environment should be further developed by investing into design solutions (design for disassembly). Furthermore, the use of renewable building materials in the renovation of existing building stock should be applied.

32 International Living Future Institute: https://living-future.org/lbc/

33 International WELL Building Institute: https://www.wellcertified.com/certification/v2/

34 New European Bauhaus: https://europa.eu/new-european-bauhaus/index_en

5.3. Efficient integration of renewable electricity

As indicated previously (section 1.3, p.26), a cost-efficient future energy system will rely on a high share of renewable electricity combined with flexible demand and energy storage. This is in line with the EU's *A clean planet for all* (European Commission, 2018), which envisions that the European electricity system will mainly be supplied by wind and solar power, accompanied by hydropower, bioenergy and nuclear power, by the middle of the century. The reducing cost of wind and solar power and their positive impact on energy security strengthens this trend. But variable renewable electric technologies also add system integration costs due to their non-dispatchable nature. So it will be of the utmost importance to develop a more strategic approach to renewable energy industries, such as offshore energy, and the supply chain underpinning them as expressed in the *New industrial strategy for Europe* (European Commission, 2020a).

It is also important to note that nuclear power still plays an important role in Europe, generating 28% of all electricity in the EU in 2018. However, new nuclear construction faces major challenges due to long lead times and high capital costs, which will limit nuclear power's future role. The ageing and decommissioning of the current nuclear power fleet makes the situation even worse.

It will be a huge challenge for Europe to develop an energy system based mainly on weather-dependent variable renewable electricity (VRE). This will be complicated by the increasing demand on electricity when other sectors such as transport, heating and cooling, and heavy industry will start to employ electrification in full for their decarbonisation measures. Therefore, a successful transition of the electricity system will urgently require efficient integration of both supply and demand systems by means of different system integration approaches. The reduction of energy demand and incorporating energy efficiency measures will be of critical importance as well (following the 'energy efficiency first' principle). In particular, this concerns the buildings and transport sectors with large potential for demand reduction. But other technologies can also contribute to better system integration. For example, heating and cooling using electric heat pumps and thermal storage can offer flexibility on a large scale. Smart charging and discharging schemes for electric vehicles provide similar functions. Combining these different energy storage options and new, more flexible demands have been shown to potentially enable an energy system in Europe that is based fully, or nearly fully, on renewable energy (Connolly, Lund & Mathiesen, 2016; Hansen, Mathiesen & Skov, 2019).

Large-scale implementation of VRE will also increase the interaction with local populations. For example, onshore wind power has already encountered local resistance in some locations (see "Social acceptance", p.69). This trend is expected to increase with the need to construct new electricity infrastructures necessary for the energy transition. To avoid rejection of technology options, participation of local populations in the decision processes and also to account for distributional effects will become very important (Bolwig et al, 2020). Smart system integration measures and optimal sectoral coupling could provide technical means to alleviate such problems to some extent.

Below, we provide a qualitative assessment of some of the measures and technologies that could contribute to managing the challenge of integrating VRE and to what degree they can be seen as no regret options. The assessment is made in comparison to a hypothetical pathway with a high VRE share and, thus, assuming that each technology reduces the VRE share (i.e. contributing to putting less pressure on expanding wind and solar). It should be stressed that this is obviously a highly qualitative assessment and that parameters will most likely depend on each other, such as the obvious link between job opportunities and economy. The latter is here seen in a wide sense, i.e. the economy-wide effects of boosting a certain technology.

Future developments in energy grids

To deliver the expected EU-wide deployment of renewable energy, the present interregional transmission will need to change from a minor trading and reserve-sharing role to one that would allow for very substantial electricity exchanges between regions and countries. This would enhance the ability of the energy systems to integrate larger amounts of renewable energy, while also improving the security of supply.

To minimise any adverse impacts from the variability of wind and solar power, and reduce integration costs, it will be important to design new market structures and products adapted to the characteristics of VRE (see "Market implications", p.93). Active demand-side management and energy storage will also play a role in this context.

Linking centres of energy demand located far away from the energy production, such as offshore, will require improving the long-distance transmission of electricity. High voltage direct current (HVDC) is a promising technology to meet the challenges for long-distance transmission, both in terms of power rating and distance covered. The losses with HVDC are also lower than with traditional high-voltage alternating current transmission, and it is easier to bury the cables underground. It should also be noted that, as the energy system will be more complex in the future, local nodes in the electricity grid could increasingly be based on direct current. These nodes could contain elements of consumption, storage and generation of electricity and would be managed and controlled by smart ICT solutions to provide a flexible element to the local power grid and thus increase the overall flexibility of the energy system.

In the future, instead of the traditional system based on synchronous machines and high voltage alternating current overhead lines, there are likely to be radical changes towards renewable generation connected through power electronic converters and growing use of HVDC underground cables, particularly related to the integration of large capacities for offshore wind in the North Sea (Pierria et al., 2017; Konstantelos et al., 2017). HVDC interconnections will act as a firewall, blocking the spread of disturbances while permitting the interchange of power, which will fundamentally enhance resilience of the future electricity system through adopting a 'grid-of-grids' design and control paradigm (Gomis-Bellmunt et al., 2021).

Sector coupling

One promising strategy for improving system integration and energy system flexibility is sector coupling, which implies sector integration (e.g. power-to-heat or power-to-mobility) with demand flexibility including different types of energy storage which should be seen in conjunction with the electrification of different sectors (Mathiesen & Lund, 2009; Mathiesen et al., 2015). Such sector coupling will be increasingly important as the share of VRE increases over time.

The successful development of sector coupling throughout Europe could increase the competitiveness of EU industry while reducing carbon emissions. If not, the economic potential from sector integration will not be realised and the value of VRE will decrease with its increasing share (Hirth, 2013).

The different ways to implement flexibility in the electricity system can be categorised into shifting, complementing, and absorbing strategies (Göransson & Johnsson, 2018):[35]

- **Shifting strategies** (e.g. charging and discharging of batteries) provide temporal local balancing of generation and load.
- **Absorbing strategies** (e.g. reduction in combined heat and power production) manage low net-load events of medium to long duration.
- **Complementing strategies** (e.g. varying mid-merit electricity generation) manage high net-load events of medium to long duration.
- In addition, there may be a need for occasional use of a **peaking strategy** to manage variations characterised by high net-load events of low duration and low recurrence (e.g. peak electricity production).

Although there is no sharp demarcation between these strategies, the proposed subdivision is designed to facilitate the understanding of the relevance and role of the different measures in reaching the desired electricity system service.

In addition, enhanced grid capacity (at all voltage levels) will facilitate the integration of VRE. At present, there is congestion both at the transmission and distribution levels;

35 Another part of flexibility is to handle uncertainty in the form of ancillary services which is also important but not of the same challenge for competitive integration of VRE.

for instance, there are examples of transmission capacity into cities hindering the establishment of new industries (e.g. data centres) within these cities. Investments in additional cross-border electricity transmission networks will reduce the need for investment in national or regional generating capacity needed to meet member state security of supply requirements, and support cost-effective, real-time system management through sharing of balancing services between member states. Furthermore, implementing the above strategies involving demand flexibility and storage will reduce the requirement to build new transmission capacity.

It is important to realise that the best way to handle the variations is system-dependent. Thus the role of sector coupling will differ between regions, depending on the energy system characteristics (e.g. if access to reservoir hydropower exists) which in turn depends on conditions for wind and solar. Successful application of sector integration is required in order to maintain security of supply. It should be stressed that there is a transition period of several decades from today's thermal generation-dominated system to a system with high shares of VRE generation. There are a number of technologies and systems which can contribute to sector coupling, such as smart charging strategies for electric vehicles, including vehicle-to-grid, power-to-hydrogen (or power-to-X), power-to-liquids, power-to-heat, flexible combined heat and power (CHP) and local prosumer systems. In addition, enhanced transmission and distribution capacity will increase possibilities for import and export between regions, which is also beneficial for integration of VRE.

An additional challenge for an electricity system with high shares of VRE is to maintain grid stability in terms of frequency control. The dominant wind turbine type (variable speed) is interfaced through converters, as are all solar photovoltaic cells (PVs)s, and does not provide synchronous inertia. Hence, the transition to a system with high shares of VRE raises the risk of insufficient synchronous inertia needed to secure frequency quality and stability. In addition to reduced synchronous inertia, operating reserves can also be adversely affected when dispatchable power plants are replaced by VRE (Helistö et al., 2019). It is therefore of great importance to develop strategies which promote measures to tackle these issues. Such strategies involve active sector coupling including new power system electronics to maintain grid stability.

The focus on VRE in electricity systems is important. However, there are other sources of renewable energy such as geothermal energy, as well as sources such as waste heat from industry fed directly into district heating systems or via large-scale heat pumps (Mathiesen et al., 2019). Without the relevant thermal infrastructure, this sector coupling is not possible on a larger scale and many synergies may not be possible.

As a result of the current energy transition, new energy players are emerging. One interesting development is aggregators of VRE, storage and flexible demand that employ information and communication technologies to offer additional controllability to renewable generation by matching the VRE fluctuations with dynamic demand and storage, even for providing ancillary electricity services (Zhang, Johari & Rajagopal, 2015). These new service providers may act as intermediaries between transmission and distribution systems, decentralised/distributed actors and the market by supporting small actors, such as prosumers or small distributed power plants, to participate in the electricity markets with all their flexible assets — VRE, storage and demand.

Another form of energy interaction is clustering and combined management of several distributed renewable energy sources connected to storage units in a configuration usually referred as a virtual (or hybrid) renewable power plant, capable of aggregating capacities together to create a single operation profile with a degree of guarantee of dispatchable power (Koraki & Strunz, 2018). In local energy communities, the exchange of energy is not limited to electricity; heat is also organised in a local environment based on renewable sources.

The inclusion of sector coupling by means of the above-mentioned strategies should be added to the cost for VRE. But it should be kept in mind that all electricity generation technologies will have a cost for being integrated in the system. The difference between the present system and a system with high shares of VRE is that this cost will be distributed in a new way, including measures on the demand side. Thus, direct comparison of electricity generation cost between (non-dispatchable) VRE and (dispatchable) thermal generation in terms of euros per unit of energy is not fully relevant. Another difference is that, with increased variability in electricity prices from an increase in the VRE share, different actors (private as well as commercial electricity consumers) will need to adapt to a more volatile electricity market. On the other hand, such integration may very well lead to reduced electricity prices and increased competitiveness for these actors (considering that a carbon-neutral system is the objective).

Market implications

During the transition period, new market designs and structures will be required, which could include different elements such as capacity markets and shorter time slots in the market, but also stronger market signals to incorporate the sector integration strategies discussed in the previous section, including encouragement of prosumer markets.

To minimise costs and maintain system robustness, for medium to large penetrations of VRE, actual power system operators rely on forecasting wind and solar generation, usually on a 24-to-36-hour time scale. This process of forecasting the power availability for the next day is not without risks, as the use of climatic models involves a non-negligible degree of uncertainty. The forecasting time scale may be reduced for better predictions in accordance with a shorter time horizon on the energy market.

Linked to this, there is a need to design new market structures and products adapted to an electricity system with high shares of VRE and to facilitate the introduction of the sector integration strategies mentioned above (Strbac et al., 2021; De Vries & Verzijlbergh, 2018). The present electricity markets were conceived and structured around the operation of fully dispatchable power plants. In a system with high shares of VRE, there may be a need to establish capacity markets or other incentive mechanisms in addition to the energy-only market which is the dominating electricity market at present. The average market price of electricity may occasionally be very low, whereas guaranteeing adequate power capacity to meet the demand in all instances will be more costly.

At present, the modest levels of VRE penetration and the very low marginal prices of VREs may be positive for consumers by inducing a reduction in electricity market prices. As indicated above, larger shares of VRE in electricity markets will reduce the value of VRE, yielding a reduction in all producers' profitability (i.e. a 'self-cannibalisation effect'), unless the above described strategies for sector coupling or energy storage can be implemented. If climate targets are to be met, there will be an expected increase in demand for electricity from transport, heating and cooling of buildings, and industry. If this demand is implemented using smart demand management strategies, it can be very flexible and use high levels of low-cost renewables, which in a functioning market will push electricity prices up. The challenge is to establish a market that can handle the transition in an orderly manner. This will require all sectors to be involved in the promotion of efficient integration of VRE, which should be possible since many end-use products are already marketed as having been produced by, or as operating on, renewable energy.

It can be concluded that the efficient integration of VRE, including enhancement of the transmission capacity within the EU, should have positive effects on important factors including security of supply and Sustainable Development Goals such as affordable and clean energy (SDG7), industry innovation and infrastructure (SDG9) and life on land (SDG15).[36] There will also be effects on the economy in a wider sense which will need to be assessed and communicated. Narratives on the impact of decarbonisation on the economy range from projecting strongly negative economic effects to potent opportunities for 'green jobs' and 'green growth'. This becomes critically important in an era in which every policy is judged on the merits of its potential to contribute to Europe's post-COVID-19 recovery. An obvious question is if and how different recovery packages can be made conditional on sustainability.

36 United Nations, Sustainable Development Goals: https://sdgs.un.org/

Sectoral issues

Transport

Pathways toward climate neutrality will depend on the extent to which the transport system can be electrified, either directly (batteries and electric road systems) or indirectly through sustainable synthetic fuels (e.g. produced through hydrogen from electrolysis), including hydrogen fuel cell cars. The latter will require significantly more electricity than direct electrification, but has the advantage of exerting less pressure on the supply of batteries and possible material issues. Most likely, there will be a combination of direct and indirect electrification with the latter for heavy road transport and aviation (Connolly, Mathiesen & Ridjan, 2014).

Biofuels may play a role, but due to limited biomass resources it is unlikely that these will be used in internal combustion engines in vehicles for road transport in the long run, due to low efficiency and the fact that electrification is an option. In a world that moves in line with the Paris Agreement, the value of biomass will increase and accordingly will be sourced to sectors and activities where substitution away from carbon-based fuels and feedstocks is difficult or associated with high costs, such as aviation and shipping. Even so, biofuels for road transport may serve as a transition fuel which is phased out when replaced by electrification. The systems for producing biofuels for road transport are basically the same as for producing aviation and fuels for shipping.

A particular challenge is long-haul, where there are presently no clear low-carbon options. Currently, batteries are too heavy and take too much of the load capacity. Possible alternatives include hydrogen fuel cell driven vehicles and electric road systems, the latter currently being demonstrated in Germany and Sweden as a means of direct electrification for heavy road transport as well as facilitating dynamic charging while driving (Taljegard, Thorson, Odenberger & Johnsson, 2019).

An electrified transport sector can contribute to efficient integration of VRE by means of establishing smart charging strategies for electric vehicles, including vehicle-to-grid (as exemplified by Taljegard, Göransson, Odenberger & Johnsson, 2019). As mentioned previously, hydrogen production by electrolysis can be a way to increase the value of VRE by utilising low cost periods for hydrogen production combined with hydrogen storage. IN turn, this will allow for important links between hydrogen for industry and transport. Thus, a hydrogen strategy should consider co-benefits between transport and industry sectors.

Heating and cooling

Heating and cooling systems differ strongly between different EU member states, both with respect to the type of heating and cooling systems and with respect to the role of heating and cooling depending on climate. The number of heating days is obviously much higher in Northern Europe than in the South. Heating and cooling strategies should always be evaluated and designed in connection with strategies on improving the energy efficiency of the building stock. Thus, in most cases it is important to follow the 'energy efficiency first' principle. But, in locations where district heating systems are available together with waste heat, it may not always be wise (or cost-efficient) to prioritise energy efficiency measures.

In Northern Europe, district heating with centralised heating plants is common in urban areas whereas domestic gas heating is more common in continental and southern Europe. Air conditioning (AC) is rare in the north, although district cooling for commercial and office buildings is expanding in countries like Finland, Denmark and Sweden. The demand for AC in cold climates is driven by increased internal heat generation from computers and other equipment, combined with better insulated buildings. For single family houses, the use of heat pumps (ground source and outdoor air) has expanded in many regions, especially in the north.

Strategies for the heating sector should take into account the development of energy efficiency measures. For example, the increased demand for heating due to new buildings may be offset by reductions in heat load due to increased building efficiency for both renovated and new buildings. In addition to combined heat and power (CHP), district heating systems can also make use of different forms of excess heat, mainly in the form of industrial waste heat, sewage water (combined with heat pumps) and heat from waste incinerators in CHP mode. From an energy perspective, there is a major potential for district heating in Europe, replacing natural gas in heating. Previous studies have shown that 46% of all excess heat in the EU-27, corresponding to 31% of the total building heat demands, is located within regions suitable for large-scale implementation of district heating (Connolly et al., 2014). However, realising this potential will require stronger recognition of the heat sector in future EU energy policy. A challenge for district heating systems is the need for major investment in new urban infrastructure which will require a clear municipal coordination and strategy. There is also a need for a general strategy on the future role for district heating, e.g. considering what future types of waste heat can be expected as well as required business models and what role district heating can have in smart cities. District heating can contribute to smart integration of VRE by means of power-to-heat combined with flexible CHP as well as smart control of heat pumps.

The future of individual natural gas heating is not obvious. The gas could possibly be replaced by renewable gas (e.g. biomethane) or a hydrogen-based system (with hydrogen from electrolysis or from natural gas with carbon capture and storage — see "Hydrogen and synthetic fuels", p.118) such as is discussed in the UK with respect to their hydrogen and CCUS strategies (SAPEA, 2018). Another alternative would be heat pumps (ground water or air) which can also contribute demand-side flexibility for the electricity system (since heat load can typically be shifted by 12 hours or so). In urban areas, a possibility is to replace individual gas heating with district heating, depending on availability of fuels and waste heat, but also urban density. As mentioned above, this may be a challenge, in that establishing a new infrastructure based on centralised heat generation will require coordinated actions and a clear municipal strategy. But in areas where excess heat can be foreseen to be available, district heating should be an attractive option. In other areas, including more rural areas, heat pumps could be a better option. Such systems can be combined with smart home concepts with solar PV and storage systems including smart charging of electric vehicles (Salpakari & Lund, 2016).

As for cooling, there are presently many inefficient cooling systems in the south of Europe in the form of individual AC systems installed in buildings with little or no thermal insulation. Increasing wealth combined with a warming climate implies a risk that the energy required for such systems will increase, both due to more AC systems installed and increased operational hours of the systems. At present, the individual AC systems have relatively low operating hours. Thus, similar to heating, there is a need for clear strategies and development programmes on improving building efficiency in integration with strategies on cooling systems.

Industry

The scope of the industrial sector is broad. Heavy industries such as the production of basic materials (cement and iron & steel), petrochemicals, refineries, and pulp and paper are typically energy- and carbon-intensive. Emissions from these industries are concentrated in relatively few locations and mitigation technologies are generally available. Instead, the challenge is the cost, which has to be compared with the EU ETS, which is the main policy measure regulating emissions from these industries. The main mitigation options for these industries include fuel shift (e.g. fossil to biomass derived fuels and hydrogen), electrification and CCUS. The latter can be applied to process emissions where there is no other mitigation option and to fossil and biogenic emissions. With respect to energy demand, electrification could be an important mitigation option, obviously requiring carbon neutral electricity generation. If the electricity system consists of a large share of VRE, sector coupling between the industry and electricity sectors would be important. Such strategic collaboration across the different sectors could reduce the total system cost. Flexibility provision by new electricity consumers enables a faster transition from fossil fuels in the European electricity system, since it will reduce the amount of VRE that needs to be curtailed and thus reduce the need for thermal generation.

5.4. Critical materials

The energy transition will have a significant impact on Europe's raw material requirements. Although there will be a decreased dependency on fuels as the reliance on renewable energy increases, there will be a steeply increasing demand for particular materials - metals such as copper, cobalt and lithium, the platinum group elements, and rare earth elements. This chapter considers issues relating to these materials and how they might impact on the energy transition.

Critical raw materials

Since 2014, the European Commission has identified and kept updated a list of critical raw materials. Their last report added four more elements in respect to 2020 bringing the list to 30 (European Commission, 2020f). Similarly, the most critical materials for different strategic technologies and sectors in the EU have been identified in a foresight study (European Commission, 2020g). From a geological point of view, sufficient materials are globally available to support a climate-neutral energy system by 2050. But the projected shifts in demand could lead to sharply increasing prices of the required resources, and even to shortages and operational disruptions in manufacturing.

With regard to renewable energy, the most critical materials are platinum and platinum group materials (PGMs), and rare earth elements (REEs), although other more common metals are considered critical, especially in view of their possible applications in competing sectors. REEs are crucial for a number of other key technologies such as battery electrodes, magnets, catalysts and alloys, while PGMs are heavily used in catalysts as well as fuel cells and other applications connected with energy (such as ICT).

PGMs are mostly sourced from South Africa, Russia and Zimbabwe, while REE supplies are dominated by China (Ferro & Bonollo, 2019). REEs are not rare per se — they are actually 200 times more abundant than gold — but they are often poorly accessible and mining them is very energy- and water-intensive (Helbig, Thorenz & Tuma, 2020). In a typical mine, several of them might be present together in minerals such as bastnasite, monazite or xenotipe (Ganguli & Cook, 2018). Their similar ionic radii make them interchangeable in the mineral structures and therefore difficult to separate during mining. In addition, REE minerals often contain radioactive thorium and uranium that have significant local environmental impacts, although these can be substantially reduced through a careful process of optimisation.

Another important primary source of REEs is aluminosilicate in ion-adsorbed clays. In this form, the REEs are simply adsorbed on the surface of the mineral, making the extraction process easier and with lower cost and environmental impact.

The extraction of critical materials is heavily contingent on prices. If demand increases, mines that had been shut down because they were not economical can reopen and small deposit mining can become viable. For the latter, economically and technologically viable extraction solutions are necessary to exploit low grade ores. In this case, it is important to take into account the timeframe from identification to exploitation, which may take decades and therefore might not keep pace with market fluctuations (Moore et al., 2020). What is critical is the speed at which the supply chain can respond to abrupt changes in demand. In this respect, commodities that can be produced as a by-product of other processes represent an asset, as producers can react quickly to changes in the market. All the mining processes should, in any case, be carefully considered for the environmental impact of extraction and the interaction with local communities in order to minimise social tensions.

Issues relating to the supply of critical materials can be countered through a diversification of supply chains. To promote this, Europe could push for bilateral commodity agreements to facilitate access to imports of raw materials without compromising high environmental and social standards. Moreover, by means of equity acquisition and long-term supply contracts, raw material processing companies could secure themselves access to important metals. And, while temporary supply bottlenecks can be cushioned by foresighted stockpiling, it would be critical to ensure that a large share of the risk is borne by private actors. Alongside imports, new domestic deposits of (for example) indium, germanium, tungsten and nickel may be discovered in Europe with enough effort (Bertrand et al, 2016; Ladenberger et al, 2018; Horn et al., 2021). In addition, exploiting deposits in the deep sea could supply numerous metals critical to the energy transition. Companies could be requested to reveal their private information (after a waiting period) regarding seismic research results and drilling data, and this data could be combined in a Europe-wide accessible raw material database.

Recycling of materials

Recycling is deemed to be one of the key issues to reduce the dependency on external suppliers. Currently, most raw materials are not sufficiently recycled: less than 5%, or even 1% in the case of REEs, are effectively recovered from waste such as e-waste. The highest potential for recycling of REEs and PGMs (other than on renewable energy devices such as wind turbines, batteries, photovoltaic systems or fuel cells) is from waste electrical and electronic equipment (WEEE). The EU-27 plus Norway, Iceland, Lichtenstein, Switzerland and Turkey are collectively one of the largest producers of WEEE, at around 20.4 kg/person/year. At present, just 35% of WEEE is recycled and the rest is deposited in landfill, exported or lost, despite being an important source of REEs and PGMs.

Materials in WEEE show important dissimilarities with primary ores as, for example, most metals are in elemental state and often alloyed with others. This introduces a new level of complexity to the recycling that increases the cost and energy demand required for extraction, and reduces the potential for recycling (Işıldar et al., 2019; Charles et al, 2020).

It is therefore important to develop new, low-impact, high-selectivity recycling methodologies able to push forward the recovery of PGMs and REEs from this important source of waste. In this sense, bioleaching (the extraction of metals from ores through the action of microorganisms such as bacteria) has proven to be a possible option, for its potentially better environmental profile, better cost-effectiveness and high level of selectivity. Different sources of REEs are also considered, such as coal and coal ashes where these elements are present in about 70 and 400 parts per million respectively, as well as in sands (in very low concentration). But extraction in these cases should be carefully considered (Papadopoulos, Tzifas & Tsikos, 2019).

Recycling can mitigate raw materials supply risks, but ideally it should be done at national level, with the material reinserted in the domestic economy. In doing so, not only are imports reduced but it is also possible to redistribute the supply mix when possible (Santillán-Saldivar et al., 2021).

Non-recycling also has a strong impact on the environment. The negative effect is more pronounced for technologies using PGMs (such as fuel cells and catalysts) as, among the critical materials, they have the highest environmental impact in the material production (Lotrič, Sekavčnik, Kuštrin & Mori, 2021).

For recycling as well as for replacing, an important issue is the detail of product composition. Data is often unavailable for intermediate or final products, complicating the recovery processes and making it difficult to assess the real impact of a supply shortage. In addition, there is a substantial lack of differentiation between the different materials despite the very different possible applications and therefore supply issues.

Another important aspect is the grade of the material needed for a specific application, that can imply different supply chains. An example in this respect is lithium: a high-grade level is needed for batteries while a lower grade is considered for lubricant (Schrijvers et al., 2020). This difference can be exploited in order to reduce the intensity of the recycling process promoting reuse.

Reuse and substitutability of materials

In order to reduce the impact of a shortage of a particular material, important roles are played by the design of the product and its production. Material selection should be considered all stages of design, taking into account performance, supply risks and sustainability requirements. An interplay between new additive manufacturing techniques[37] as well as ICT methods (such as in predictive maintenance and traceability of the goods) are important to reduce the scrapping of components and material and, at the same time, assuring long-term use of the materials and clear time frames for their recycling. Similarly, efforts to avoid manufacturing of new parts and reusing undamaged parts of the system should be considered (Lotrič, Sekavčnik, Kuštrin & Mori, 2021). In this respect, however, there is a clear need for tools to assess quality control and detect any loss in functionality, and to track material content anticipating material recyclability in line with the paradigm of industry 4.0 (Rahman, Perry, Müller, Kim & Laratte, 2020).

The substitutability of a material in a product should be analysed at multiple levels: the complete material substitution, the possibility of technological or functional substitution, and the environmental impact of this substitution (Ferro & Bonollo, 2019).

A common database with all the most important properties (physical, chemical, electrical, etc.) of the single materials reported is an important starting point towards a suitable design for reducing use of critical materials or substituting them. Although some examples are starting to appear, there are no such comprehensive databases available at the moment.

In order to reduce primary material requirements as well as possible negative impact on the environment, it is important to reduce the dissipative losses over the lifespan of a material. Despite strong efforts in recycling, even for the most common materials such as aluminium and iron, one third of the material extracted is lost each year (Schrijvers et al., 2020).

5.5. Scaling-up of energy technologies

To make a notable contribution to the energy transition, it should be pointed out that the transition in the near term will depend to a large extent on already commercialised technologies. Thus, it is not a lack of technologies which limits transition, but policy measures and perceived costs. But there is also a need for deployment of new technologies to match the scale of the energy system. In addition, the new technologies need to lend themselves to industrial-scale manufacturing processes and the necessary major financial investments and risk-taking. Bridging lab and niche-sized technologies to the industrial scale is therefore often a long and stepwise process.

An approach focusing on more granular technologies (Wilson et al., 2020), i.e. smaller and modular energy technologies, might play an important role in the energy transition

37 Processes, also known as 3D manufacturing or 3D printing, that use digital 'blueprints' to produce three-dimensional products and parts from a variety of materials.

(Dahlgren, Göçmen, Lackner & van Ryzin, 2013; Sweerts, Detz & van der Zwaan, 2020). Issues related to rapid technology deployment (e.g. short diffusion timescales, attractive risk profiles for investors, cost and performance improvement), escaping lock-in (e.g. low technological complexity, end-use efficiency and rapid renewal of capital stock), and social legitimacy (e.g. access to technologies and infrastructures, net job creation, social returns on public RDI investments) could all profit by a modular scaling of numbers instead of by scaling by size. Moreover, modular scaling of energy technologies could gain greater participation of the public in a future energy system that will be more dynamic and diverse, and where the level of participation of consumers is likely to change significantly. A significant advantage of modular scaling is the rapid learning curves possible, leading to rapid cost reduction. A clear example of the latter is photovoltaic power generation, batteries and electric vehicle charging points. Despite the apparent advantages of modular scaling, it is not a universal solution, but in many circumstances it might accelerate the energy transition. Of course, whenever tangible resources can be replaced with intangible ones, e.g., in case of ICT and digital solutions, the scalability would even be easier and quicker.

Scaling-up is also embedded in a social context and to the demand of new technologies, as the market growth will depend on the adoption of new technologies and innovations. This process is governed by 'technology diffusion' in which an innovation is distributed through different channels to consumers with different thresholds for the adoption of new innovations (Rogers, 2003). The social system, innovation characteristics, personal preferences and communication channels can all affect the penetration of a new technology to the market, leading to the typical S-curve profile for the rate of technology adoption that also demonstrates the slowness of the upscaling.

However, constraints on the upscaling of energy technologies, either by size or in a modular fashion, might still create a considerable lead time before any new technology reaches significant levels of market penetration, meaning it could still be several decades from early-stage research or prototypes to full commercialisation. For example, solar photovoltaics (PV) entered industrial scale applications in the late 1970s, but true market penetration did not start before early 2000. It had a market share of a few percent of global electricity production in 2020, with a predicted share of 20–30% by 2050 (IEA, 2021). It should be noted that solar PV is a granular technology with a favourable learning track which has led to rapid cost reduction during the last ten years (more than a 99% drop in price since late 1970s) and could indicate a faster penetration than with traditional energy sources. However, as shown by Kramer & Haigh (2009), the penetration rate of an energy technology to reach 'materiality' (i.e. 1% of the world energy mix) does not crucially differ for a variety of energy technologies considered in this study (e.g. nuclear power after the oil crisis in the 1980s).

The lessons learned and empirical observations of the scaling-up of energy technologies indicate a cautious note on how fast new technologies reach a notable market share. The commercialisation process as a whole is complex, and often leads to longer lead-times than anticipated. Therefore, though the theoretical potential of a new technology may be large, the realisable potential considering all technical constraints, socio-economic factors, or institutional barriers is often much lower. The granular aspect of the required new renewable energy technologies is therefore important and should be properly dealt with in planning the energy transition (Wilson et al., 2020). Policies with a more direct link to the scaling issue both on the technology push and market pull side may mitigate the above issues. Also, these policies will enforce the aspect of a just energy transition if regulations enable granular energy technology solutions not yet considered.

5.6. EU R&D and technology position in the energy sector

Research, development and innovation (RDI) are important for finding effective solutions for the energy transition, but also to ensure competitiveness and economic growth. EU RDI spending is around 2% (430 billion PPP[38] dollars, 2017) of total GDP, below that of the United States (549 billion) and China (496 billion).[39,40] This may negatively affect the long-term global competitiveness of European industries, including areas of importance to energy (e.g. development of new technologies such as digitisation, artificial intelligence, batteries). This could mean increasing dependency on imported technology, needed in the energy transition and in the new energy system architecture, which is technology-intensive.

The share of the public sector is higher in the EU than in the US and China, with 59% of the total RDI expenditure within the EU-27 in 2017 funded by business enterprises compared to 79% in China and 64% in the United States (Eurostat, 2020). The share of RDI personnel in the business sector is also higher in the USA and China than in the EU. This could indicate a certain structural deficiency in the innovation capacity of EU industries, which would need to be addressed in European Green Deal policies to ensure jobs and growth from the energy transition. On government spending in energy RDI, the EU is on a par

38 Purchasing power parity

39 OECD (2021), Gross domestic spending on R&D (indicator). doi:10.1787/d8b068b4-en (Accessed on 16 October 2021): https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm

40 China Is Closing The Gap With The U.S. In R&D Expenditure, Jan 2020, Forbes: https://www.forbes.com/sites/niallmccarthy/2020/01/20/china-is-closing-the-gap-with-the-us-in-rd-expenditure-infographic/?sh=701706ca5832

with the US and China.[41] Energy RDI funding has, however, declined in the EU during the last decade, which runs counter to decarbonisation commitments.

In carbon-free energy production, China and the US lead the global deployment in areas such as bioenergy, hydropower, solar PV, and wind power (REN21, 2020), partly explained by the market size. In nuclear power, the US ranks first (31% of world nuclear power), France second (15%), and China third (11%) (IEA, 2020a). In terms of industry performance, Europe ranks more highly: for example, Vestas (Denmark), Siemens Gamesa (Spain), Nordex-Acciona (Germany) and Enercon (Germany) are among the top ten in wind power (REN21, 2020). Solar PV manufacturing is dominated by China: over 80% of the volume shipped by the top 10 companies are by Chinese firms. In bioenergy, Neste (Finland) is the world's largest producer of hydrotreated vegetable oil. In addition, there are promising second-generation biofuel (lignocellulosic) companies in the EU. In batteries, the EU is gearing up with manufacturing, which is still dominated by Asian companies. As the competitiveness of technology firms is measured on a global market, not in the EU alone, the global market will be important for the success of European clean energy industries in the future.

Table 4 gives an overall evaluation of the competitiveness of European clean energy industries globally, based on the European Commission (2020e) but also making use of our own expert judgements. The table relates to the EU's industrial competitiveness and not to the technology's implementation, which may differ from the assessment in Table 6.

Europe has a good technology base for electrification and clean fuels, which are key strategies for decarbonisation. Europe's ability to use economy-of-scale strategies in maturing technologies to increase its competitiveness is more challenging than in the USA and China, meaning a more open global strategy and stronger technology-based innovations may be needed. It is also important to note that the table does not provide an assessment of the scientific knowledge base for the chosen technologies, which may differ considerably from the industrial assessment shown. For example, although the European solar PV industry is negligible compared to Asian countries, the scientific and research base is internationally of high standing.

41 IEA, Report extract, RD&D and new technologies (Accessed 16 October 2020): https://www.iea.org/reports/world-energy-investment-2019/rd-and-d-and-new-technologies

Technology / industry	Remarks
Onshore wind power	Strong competitive position
Offshore wind power	Strong competitive position and growing markets; a key technology in many EU scenarios
Solar photovoltaics	Little manufacturing in EU at either end of the supply chain
Solar thermal	Small markets in EU; solar water heating negligible
Batteries	Small market share in manufacturing, but the EU is catching up; scale-up will be challenging
Hydrogen technologies	European industries emerging in several hydrogen technologies
Hydropower	Strong competitive technology position
Power transmission	Major global cable companies in EU; HVDC[42] technology leader
Digitisation	IoT activities increase; fewer start-ups than China and US
Biofuels	Leading biodiesel industry; second generation biofuels emerging
Carbon capture and storage, carbon capture and utilisation	Few commercial activities globally; signs of emerging interest in carbon-intensive industries, also piloting of CCS in the EU
Nuclear power	Competitive across the existing value chain
Energy efficiency of buildings	Strong position (e.g. heat pumps, building energy management systems, district heating); buildings account for 40% of EU final energy use

Table 4. Industrial global competitiveness of selected EU clean energy fields (adapted from European Commission, 2020e)

The impact of COVID-19 on EU energy system operation

The COVID-19 pandemic led to partial or total lockdowns in several European countries during the first half of 2020, which in turn caused a reduction in electricity demand. EU electricity consumption dropped by 7% in the first half of 2020 compared to the same period in 2019.[43] The decline in electricity demand was considerably more pronounced during the weeks with severe lockdown measures, characterised by very significant reductions in industrial and commercial energy demand that was only partially offset by higher residential consumption. Italy experienced the largest average reduction in daily electricity consumption of 29% during the lockdown period, while the second largest drop was 21% in Spain (López Prol & O, 2020).

The drop in demand also led to a remarkable change in the electricity generation mix in the EU, showing the highest ever share of renewable generation, around 40%

42 High-voltage direct current electric power transmission system

43 IEA (2020), *Covid-19 impact on electricity*: https://www.iea.org/reports/covid-19-impact-on-electricity

until June. Across all major regions, the power mix has shifted towards renewables following the lockdown measures due to depressed electricity demand and the windy and sunny spring. From February to the first week of July 2020, weekly renewable production was higher than fossil fuel generation, although this situation reversed in July as a result of generally lower wind production. Nuclear production was much lower than in 2019, as a number of units had to extend outage duration due to delays in maintenance caused by the lockdowns. On the other hand, natural gas generation increased in the power mix, supported by low gas prices and higher carbon prices: in mid-June 2020 it became the second largest source of electricity generation behind renewables. Coal generation decreased compared to 2019.[44]

Regarding the share of variable renewable energy in the electricity mix, new records were reached during the lockdown period, in particular in Italy, Spain and Germany. Throughout the summer, several factors affected the variable renewable energy share, such as demand patterns related to economic activity and residential cooling, higher solar infeed and lower wind production. Although solar and wind generation in Europe are usually not correlated, high maximum variable renewable energy shares in some weeks have been driven by strong wind output during the day coinciding with solar generation. With summer ending, the seasonal shift from solar to wind was observed in several EU countries.

The drop in demand, combined with the large contribution of renewables and power sources characterised with low marginal costs, led to a sharp decrease in electricity prices (Zhong, Tan, He, Xie & Kang, 2020). The European electricity markets experienced the largest reduction of electricity prices in the world, with monthly average prices falling to the lowest in the last six years. EU electricity prices dropped by more than 30% until June compared to 2019. The drop in prices in April 2020, when lockdown measures were enforced in several countries, exceeded 50% for most European markets compared to the same month in 2019, while the most significant price reduction of 87.2% was observed in the Nord Pool market.

Furthermore, the occurrence of negative prices in the EU doubled until June (these occurred especially around lunchtime). Germany underwent 128 hours of negative prices in the first quarter of 2020 alone. The lowest price recorded in 2020 was –€115.31/MWh in the European Power Exchange EPEX SPOT Belgium market. The occurrence of negative electricity prices shows the importance of smart integration of variable renewable energy. Approaches such as demand flexibility and so-called 'variation management' can make use of excess electricity and thereby increase the value of wind and solar.[45]

44 ibid.

45 Craig Richard, *Negative power pricing peaks in Europe during coronavirus,* WindPowerMonthly (Oct 2020): https://www.windpowermonthly.com/article/1696090/negative-power-pricing-peaks-

Regarding carbon emissions, these dropped 8% in the EU in the first quarter of 2020. This in turn had an effect on the EU Emissions Trading System (ETS). A sharp drop in carbon prices of almost 40% in the European carbon market occurred in March 2020, driven by the surplus of emissions allowances as thermal generators were largely pushed out of electricity markets due to low demand. The pre-COVID levels for carbon prices in the ETS were around €25 per tonne, dropping to €15 per tonne in March 2020 (although carbon prices stabilised at roughly €20 per tonne by June 2020). However, recently (late May 2021) the allowance was increased to the highest level in many years to around €50 per tonne, which is believed to be an effect from the announcement of stricter climate policies within the New Green Deal.[46]

A major challenge experienced by European energy systems during the lockdown was maintaining the real-time balance between generation and demand in the electricity grids. This challenge was exacerbated by periods of very high instantaneous outputs of renewables, which created conditions that were not expected until renewable capacity increased to meet emissions targets in coming years. Lower electricity demand combined with high outputs of wind and solar led to an increase of the share of variable renewable energy, requiring more flexibility to keep the system secure. At the same time, available flexibility has been limited by the shutdown of industrial facilities that provide demand response and because dispatchable power plants did not operate, particularly in Italy, Spain and Germany, as power prices were extremely low.[47]

Although the share of renewables has jumped several years ahead of pre-pandemic expectations, electricity security has remained robust in the EU. However, the costs associated with the management of security have significantly increased. Great Britain saw an increase in balancing and flexibility costs (i.e. additional expenditure beyond energy production costs) of £200m in the months of May to July 2020 compared to the same period in 2019 (a threefold increase), highlighting the importance of flexibility in low-carbon systems (Badesa, Strbac, Magill & Stojkovska, 2021). To date, electricity systems in the EU have maintained robust reliability, but continuous awareness will be needed from system operators, regulators and governments (McCarthy, R. & Laurent, V., 2020).

The challenging lockdown period has provided some valuable insights related to the future trends that electricity systems are expected to experience. Even though

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europe-during-coronavirus

46 M. Elkerbout, L. Zetterberg, '*Can the EU ETS weather the impact of Covid-19?*', Report, Centre for European Policy Studies (June 2020): https://www.ceps.eu/ceps-publications/can-the-eu-ets-weather-the-impact-of-covid-19/

47 IEA (2020), *Global energy review 2020: The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions*: https://www.iea.org/reports/electricity-market-report-december-2020/2020-global-overview-the-covid-19-pandemic

electricity demand is expected to increase in advanced economies in the coming decades due to the electrification of transport, heating and cooling sectors, net demand (i.e. demand minus renewable generation) is expected to further decrease due to an even higher rate of increase of renewable penetration to meet the emission targets. Some of the lessons learned during the COVID-19 pandemic include the need to achieve flexibility from zero-carbon sources (for example, energy storage and frequency support from renewables). Otherwise, it will not be possible to reach a net zero emissions electricity mix, since flexibility and stability services are currently predominantly provided by synchronous thermal generators (such as gas-fired power plants).

Furthermore, the pandemic could change consumer behaviour going forward. It is expected that some employers will encourage remote working at least partially, given the savings in office space, reduced traveling costs and other personal costs associated with traditional in-office working. This could lead to some decreases in demand in the mid-term and change consumption patterns, again increasing the need for cost-effective provision of flexibility to the electricity grid to maintain security of supply.

Chapter 6. Technology aspects in the energy transition

To a large extent, the transition of the energy system will depend on the large-scale penetration of renewable energy in the form of wind and solar power. These technologies are expanding rapidly. Therefore, in this chapter we focus on the technologies and fuels for which there is more uncertainty whether they will be deployed at all, and if so, to what extent. We consider their specific characteristics, the role they play, and how and at what scale they will integrate into the future energy system.

There are multiple technologies and approaches that will play a role in the future energy system across all sectors. A qualitative literature review of these is provided in Table 5, which breaks the system down into the constituent sectors and addresses the opportunities, current issues, challenges, and promise of disruptive technologies for the key technologies, along with policy and investment options for each sector as indicated in the literature reviewed.

Table 5. Qualitative matrix of key technologies for the energy transition
This is a very large table which we supply as a separate spreadsheet. To download it, click or scan the code above, or visit www.sapea.info/energy-matrix/.

Within this broad range of technologies and approaches are a number of selected major technologies that have been identified with particular challenges that need to be addressed if they are to release their full potential for the energy transition. Below, we focus on these in greater detail, highlighting the role they could play and the challenges they face.

6.1. Nuclear power

Nuclear energy is an important energy source in Europe. It is employed in 13 EU member states, with a total of 106 nuclear power plants producing 26% of the EU's electricity. France has the largest proportion of nuclear power (70% from 56 plants), while eight other countries (Belgium, Bulgaria, Czechia, Finland, Hungary, Slovakia, Slovenia and Sweden) source over 30% of their electricity from nuclear power.[48] The nuclear sector has major employment effects, with direct employment of 240 000 people.[49]

Different member states will view nuclear power very differently in the energy transition. For example, the Federal Constitutional Court in Germany has defined nuclear power as a high-risk technology, whereas Finland and France will use significant amounts of nuclear power in the future.

The EU considers nuclear power as part of its future energy mix to reach a climate neutral economy (European Commission, 2018). The International Energy Agency (2019b) likewise sees nuclear as part of the global strategy to reach the Paris Agreement targets.

However, in industrialised countries including the EU, the use of nuclear power has begun to reduce due to the ageing nuclear power plant fleet not being replaced with new reactors, mainly for economic reasons, but also for political reasons and lack of public acceptance linked to concerns over nuclear waste and safety. In the EU, only four new nuclear power plants are under construction, while seven are planned and fifteen proposed.[50] Some of the falling capacity has been compensated for by lifetime extensions and power increases from existing plants. COVID-19 has had negative effects on the revenues from nuclear power due to decreased power demand, also postponing any investments, though technically the plants have performed well during the lockdowns providing dispatchable capacity.

A new generation of small modular reactors could emerge in the 2030s, for example for large-scale local heat production. Likewise, nuclear power can be linked to large-scale production of hydrogen. Both examples of technology development would support the EU's decarbonisation plans.

To fully realise the future potential of nuclear energy in Europe, several challenges need to be addressed. One important question relates to compliance with the EU taxonomy

48 World Nuclear Association, *Nuclear Power in the European Union*: https://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx

49 Forum Nucleaire, *L'énergie nucléaire dans l'Union européenne*: https://www.forumnucleaire.be/theme/dans-le-monde/lunion-europeenne#:~:text=L'emploi%20dans%20le%20secteur,nucl%C3%A9aire%20dans%20leurs%20t%C3%A2ches%20pr

50 World Nuclear Association, *Nuclear Power in the European Union*: https://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx

for environmentally sustainable economic activities. In particular, this would require a demonstration of the sustainability of nuclear power as well as addressing the concerns of the public.

We have identified a set of issues which should be overcome, as follows:

- New nuclear power plants should meet stringent regulatory safety requirements and make full use of lessons learned from past accidents.
- The regulatory framework for the security of nuclear power, including physical protection and non-proliferation, needs further development under the International Atomic Energy Agency and Euratom auspices to cover the new situations created by novel technologies and new nuclear countries, and appropriate agreements with newcomer countries should be sought to minimise the need to establish new uranium enrichment or spent fuel reprocessing facilities.
- Decommissioning of nuclear power plant and radioactive waste management needs a coherent European strategy for more uniform practices across Europe, also sharing deep geological repositories of radioactive waste, which have already been successfully demonstrated.
- The nuclear industry in Europe needs to restore investors' confidence to build new reactors on time and within given budget frames, even with higher safety standards than today.
- The economics of nuclear power plants will further be challenged by decreasing marginal costs of electricity through increased use of wind and solar power, which may need new market mechanisms to credit them for their dispatchability.
- Continued research and development work, e.g. within the Euratom agreement, will be important to introduce the next generation reactors such as small modular rectors, but also further develop accident-resistant nuclear fuels (so-called 'accident-tolerant fuels') to improve reactor safety further. In the long run, work on fourth-generation fission reactors could offer high-yield and versatile reactor designs for the market.

Meeting the above strategic agenda for nuclear power will require recognising nuclear power as one of the feasible technical options in the European Green Deal. It will also require better cooperation between the key stakeholders such as industries, utilities and governments to increase the efforts on safety and security relevant issues. A better dialogue with civic society is also necessary, as nuclear power enjoys low acceptance among the population in general.

It is also important to note that nuclear power is absent from the strategic themes included in the European Green Deal; therefore, the question of nuclear power's future in Europe would need dedicated communication from the European Commission. The Euratom umbrella has functioned well to coordinate European activities in nuclear power and its role should also be secured in the coming years.

6.2. Bioenergy

Bioenergy is the main source of renewable energy in the EU (59%),[51] albeit with substantial heterogeneity across the EU. Its share of EU gross final energy in 2021 was 10%. Bioenergy is a versatile energy source contributing to heat, power and fuel production.

Most of the bioenergy in Europe is wood based. Close to 40% of all bioenergy in Europe stems from industrial waste or side-streams from forestry products (e.g. paper and pulp). The use of forestry-derived biomass in countries with a developed forest industry and forest management systems typically follows a cascading principle from long-lived products (for which saw timber is used), via pulpwood, to forestry residues used for energy purposes (electricity and heat or fuel production). Thus, bioenergy is not directly derived from burning timber, but from industrial side-streams. As a local energy source, bioenergy is important for the local economy and jobs.

It is important to point out that land use and sustainable biomass can contribute to climate change mitigation in two principal ways: through substitution of fossil fuels and other GHG-intensive products (e.g. cement and steel); and through sequestration and storage of carbon in soils, vegetation and bio-based products. Recognising this, the concept of 'climate-smart forestry' (Nabuurs et al., 2017; Verkerk et al., 2020) was developed to unlock Europe's forests and forest sector potential, aiming to sustainably increase forest productivity and incomes, reduce GHG emissions, remove carbon from the atmosphere, and adapt and build forest resilience to climate change. Similarly, 'climate-smart agriculture' approaches attempt to increase productivity while enhancing resilience, storing carbon, and reducing GHG emissions inherent to production. In particular, woody and grassy perennial systems for biomass production, on degraded lands and on lands not suitable for food crops, commonly serve as a carbon sink and enhance the climate benefit. In the longer term, aquatic biomass (algae) could also make a significant contribution to CO_2 capture.

Bioenergy is the only renewable source that can directly replace fossil fuels in all energy markets (production of heat, electricity, and fuels for transport). Thus, bioenergy has a role in the energy transition to provide flexibility or fuel for applications difficult to replace by clean electricity such as long-haul transport or aviation. Biomass is also an important carbon sink, a role that will increase when approaching the carbon neutrality point in 2050.

There is debate over the amount and types of biomass that could be obtained in a sustainable way. Some argue that bioenergy production should be limited to organic municipal waste and by-products in the agriculture and forest sectors, to avoid negative impacts, including carbon emissions, from land use change (Brack, 2017; Norton et al.,

51 Bioenergy Europe Statistical Report, 2021: https://bioenergyeurope.org/statistical-report.html

2019; Reid, Ali & Field, 2019). Others also include dedicated biomass production systems among sustainable feedstocks, referring to limitations of residue and waste resources and to experiences showing that deployment of dedicated biomass production systems can help avoid or reverse deforestation and offset carbon emissions by serving as carbon sinks, as well as provide other benefits such as enhanced landscape diversity and habitat quality, nutrient retention, erosion control, pollination, pest and disease control, and flood regulation (Christen & Dalgaard, 2013; Asbjornsen et al., 2013; Dauber & Miyake, 2016; Cacho, Negri, Zumpf & Campbell, 2017; Englund et al., 2020). Other studies have pointed out the necessity to better consider the carbon payback period of forest biomass when used for bioenergy (JRC, 2021). If the payback time were long, then the climate impact of bioenergy could be questionable; a short payback would be preferred.

It is important to point out that the current and future availability of biomass for energy is uncertain, as it depends on many external factors, such as population development, future dietary preferences, land use patterns, policies, energy prices and climate, among others (Smith et al., 2019). At present, EU policies do not provide adequately clear guidelines for sustainable bioenergy use in this respect, although the *Energy roadmap* (European Commission, 2011) identified a possible development path for the use of bioenergy sources, evolving from an initial phase based on harnessing existing resources to a more optimised phase where new potential sources coming from agriculture could be mobilised. Such a development would require an improved policy that needs to take a position on the sustainability of different sources of biomass and to better define the trade-off between the energy and carbon sink role of biomass, but also consider the forest management requirements. At the same time, the social dimensions related to bioenergy need careful consideration. Biogenic sink policies also need to be better specified: for example, would these sinks be better managed if they were part of the EU ETS and treated as a common asset of Europe? The role of biomass in the energy system will change over time, along with technologies and systems for using biomass and other resources for energy purposes.

Sustainable bioenergy would need to be a part of any strategy aiming at a mainly renewable energy based energy system in the EU, including specifying the forms of bioenergy that can be counted towards such renewable energy targets. Due to the importance of bioenergy for local communities, considering decentralised energy systems enabling smaller local energy systems with beneficial impacts to rural development will be important. Thus, EU policy should support locally appropriate energy projects that have beneficial impacts for local communities and rural development. Community-managed district heating systems that use locally sourced sustainable biomass, saving energy costs and empowering local communities, are one promising example of bio-based, decentralised energy systems. A second example, green biorefineries employing high process integration, can achieve high resource use efficiency, minimise waste production and energy requirements, and can convert a range of feedstocks (e.g., algae, grass, clover or alfalfa) into food, feed, bioenergy and other bio-based products (Aristizábal-Marulanda & Cardona Alzate, 2018; Schmidt, Andersen, Dieckmann, Lamp & Kaltschmitt, 2018). Regionally tailored incentives and guidelines are needed since agriculture and forestry conditions differ significantly between member states, and even between regions.

Sustainable bioenergy e.g. from lignocellulosic feedstocks, non-food crops or industrial waste and residue streams accompanied with advanced high efficiency conversion technologies, lower costs and better environmental performance can contribute significantly to energy security, reduce GHG emissions, provide a long-term sustainable alternative to fossil fuels, contribute to job creation, stimulate rural development, and generate wealth within the growing European bioeconomy.

Bioenergy as a part of a bio-based economy represents a major opportunity for the EU, but this would require aligning agricultural, forestry, renewable energy, RDI and innovation, and environmental policies. Such a strategy could have many benefits for Europe and its social development. In this context a neutral evidence-based assessment of the climate neutrality and sustainability is strongly recommended to provide a more reliable estimate of the real potential of biomass for energy use. Bioenergy could also play a more strategic role in providing an option to those sectors and applications where other alternatives are limited, such as long-haul transport and aviation.

6.3. Carbon management technologies

Within the EU, carbon capture and storage (CCS) was considered an important mitigation option for the electricity generation sector (mainly applied to coal plants) in the past, but presently the strategy seems to be to phase out coal. CCS now appears more attractive for carbon-intensive industries (e.g. cement and ceramic industries), with a large-scale demonstration project under way in Norway.[52] The steel and petrochemical industries could also benefit from CCS, though hydrogen may replace it in the long term. Combined heat and power (either biomass or waste fired) could also be linked with CCS.

Based on EU emissions targets, by 2050 fossil fuel power plants will in practice need to be phased out if they do not incorporate CCS. Globally, there is a clear need for CCS, as several major emitters such as China and India still rely heavily on coal in their energy production. Active participation of the EU in CCS technology development could therefore be motivated through possible technology export possibilities, but also to demonstrate that fossil fuel emissions could be mitigated from virtually all processes.

52 Langskip project: https://langskip.regjeringen.no/longship/

The European Green Deal emission scenarios clearly indicate increasing needs for carbon sinks when approaching carbon neutrality, which could increase the strategic role of biogenic and technical CO_2 sinks in the EU. Bioenergy with CCS (BECCS) may contribute to offset emissions in hard-to-abate sectors (agriculture, aviation, shipping) through negative emissions, but mainly in member states with well-established forestry industries. Also, many global scenarios which comply with the Paris Agreement favour BECCS (Rogelj et al., 2018). BECCS could also be applied to diverse industrial sectors, e.g. production of green chemicals, bioplastics and plastic resins. However, the policy instruments and incentives to mitigate CO_2 emissions of biogenic origin are presently too weak.

An important factor for enhancing CCS would be to establish a coordinated transport and storage infrastructure for carbon dioxide. In the Langskip project, Norway is planning to establish a storage infrastructure to handle captured CO_2 from both Norwegian and foreign emission sources. The first step will be the capture of around 400 kt of CO_2 per year from a cement factory and possibly also from a waste-fired CHP plant in Norway. There are also programmes and plans for CCS and CCU in the Netherlands and in the UK, which could push to create pan-European CO_2 storage hubs in the North Sea, but would also need the EU's policy support for broader realisation. The cost of CCS compared to carbon-free alternatives is also a challenge which needs to be addressed.

Carbon capture and utilisation (CCU) may have a role in the energy transition. Even if this approach cannot provide net carbon removal from the atmosphere or its permanent storage, it can be considered a useful way to remove carbon from industrial sectors under certain conditions, as well as displacing fossil fuel use. Other than for the production of fuels, CO_2 can be considered a valuable building block for the production of different commodities ranging from polymers to dimethyl ether. In principle, the development of CCU technologies can also promote the creation of alternative industrial value chains. However, it should be stressed that the climate benefit of CCU is determined by when, and to what extent, the carbon ends up in the atmosphere. Thus, the climate benefit from utilising CO_2 captured from fossil fuel emission sources will depend on the fuel or material that is replaced and for how long, and on whether it is applied to fossil or biogenic CO_2 sources. Thus, the carbon should preferably be used in long-lived products and, as pointed out in the SAPEA (2018) report on novel CCU technologies, CCU should only be used in cyclic mode and using carbon from renewable energy sources. Thus, CCU should not be applied in a linear mode which will result in the fossil CO_2 being emitted to the atmosphere. Since CCU will require substantial research to be commercialised, it is not obvious that there will be room for CCU before emissions must be zero around 2050.

Direct capture of CO_2 from the atmosphere ('direct air capture', DAC) may need to be deployed en masse if society fails to address climate change (Hanna, Abdulla, Xu &

Victor, 2021) since, although it is more expensive than CCS, DAC offers the possibility of addressing any emissions (it is not linked to specific emissions sources) and provides the negative emissions likely to be required to meet the Paris Agreement. The success of this option strongly relies on the possibility of developing techniques able to separate and concentrate the low atmospheric concentration of CO_2 to values suitable for storage or utilisation (Jeong-Potter & Farrauto, 2021) with a suitable cost, and energy and water consumption (Fasihi, Efimova & Breyer, 2019). It may offer an attractive alternative for hard-to-abate sectors in offsetting their residual emissions without the need to mix their business with other sectors. Some regions may have natural 'free' heat to power the DAC units, such as geothermal energy combined with favourable geological storage conditions. Several small DAC pilot tests have been built. A key challenge will be the cost of extracted CO_2, which is still too high to be competitive. DAC implementation may be driven by private initiatives for climate compensation by industries for which the cost to mitigate emissions is high, rather than from governmental climate policy.

6.4. Batteries

The increasing use of variable renewable electricity in the power system increases the relevance of energy storage and batteries. In stationary power applications, hydropower dominates electrical energy storage (99%) (EASAC, 2017), but battery storage could become a major feature in future. The IEA predicts a potential 20-fold increase in capacity by 2040 (IEA, 2020b). Batteries would mainly address short power quality issues, but advanced batteries could provide more versatile applications.

The most common battery technology presently is lithium-ion (Li-ion) with its primary market in electric vehicles (EVs). The number of EVs is expected to significantly increase, with estimates of 20–50 million globally by 2030 (IEA, 2020b). This would also mean a major boost, though with delay, in the use of cheaper second-life batteries for energy storage applications (these are used batteries from electric vehicles with 70–80% of their original capacity remaining, which is adequate for stationary applications), and an increasing contribution to power system flexibility and ancillary services important to the integration of wind and solar power (Lund, 2020). In 2019, a little over half a million EVs were registered in Europe; that could rise to some 8 million registrations by 2030. Turning used EV batteries into second-life battery reuse in stationary battery applications could mean around a maximum of 100–150 GWh of additional storage capacity a year, which is a notable capacity when compared to the maximum hourly energy demand from the EU electricity system, which is about 500 GWh. The battery capacity would then accumulate over the coming years and could grow to a significant figure in relation to the power system.

Europe presently lacks a sizable manufacturing capacity of Li-ion batteries as well as the domestic raw material supplies, in particular in lithium (78% from Chile) and cobalt (68% from Democratic Republic of Congo) (European Commission, 2020f). If this is not addressed, increases in demand may lead to supply issues and a failure to meet climate and energy policy targets, but also jeopardise the competitiveness of European car industries. Considering the global competition in electric mobility, the lack of a battery industry in Europe should be viewed as a critical weakness. As a positive sign, recent European initiatives in battery cooperation and the establishment of battery factories are welcome, but inadequate when compared with Asian competitors. Europe has less accumulated knowledge through learning-by-doing, which is important when scaling up to large giga-factories, which could be compensated through advanced manufacturing concepts such as rapid prototyping. This would require more dynamic innovation ecosystems to be established around batteries in Europe.

Changing from the original Li-ion batteries based on cobalt to lithium-iron-phosphate (LFP) chemistry could eliminate the need for cobalt but would simultaneously reduce battery capacity. Recently, improved LFP batteries with graphene cathodes have been reported showing improved performance. There are a range of other interesting Li-chemistries available such as lithium-sulphur (LI-S) and lithium-air (Li-Air), but most of these are much further from commercialisation. Flow (or redox) batteries (e.g. zinc-bromide (ZnBr)) are also in the development phase for large stationary applications but are less mature than Li-ion. Adequate research efforts in these fields would be strategically important to keep pace with possible new advances.

In terms of recycling and circular economy, Europe may be better off in general, but clearly lags behind China in global recycling of batteries. Anticipating the increase in EV use in Europe and also a sizable second-life battery market, a stronger position in the emerging second-life battery market could be beneficial to Europe. At this point, focused RDI efforts, for example in automated logistics of battery dismantling, are needed to create the necessary competitive advantage, but in particular to establish a functioning innovation chain from research through start-ups to scalable industries. To help such a battery market to emerge in the energy sector, the present regulatory framework of the electricity market needs to be updated, to enable battery storage to work both in front and behind the meter applications, to make use of multiple benefits, and become commercially attractive. For example, joint operated battery storage by transmission and distribution system operators with dynamic allocation capacity could be a possible solution (Englberger, Jossen & Hesse, 2020).

6.5. Hydrogen and synthetic fuels

Hydrogen and hydrogen-derived fuels are considered promising candidates to reduce the carbon footprint of the energy system across a range of sectors and applications, but only if these fuels are produced from low-carbon or carbon-free energy. In a fully decarbonised economy, the need for hydrogen produced from carbon-free resources could be significant. There are various ways to produce carbon-free hydrogen,[53] but currently the two main routes are:

- **Blue hydrogen.** This is made by combining carbon-based fuels (mainly natural gas) and steam in a process called reforming to produce hydrogen along with CO_2 as a by-product which is stored using CCS. Biomass gasification can also be used and, when combined with CCS, will result in a negative emission process.
- **Green hydrogen.** This is made using electrolysis powered by carbon-free electricity.

The choice of hydrogen production route will depend on a range of factors, including the costs, the availability of the required renewable energy resources for green hydrogen, and the public acceptability of CCS for blue hydrogen.

New green hydrogen routes may emerge in the future, for example through photoelectrochemical and microbiological processes, though these are still in the basic research phase. In principle, nuclear power can also be used to produce hydrogen, which is referred to as 'pink hydrogen'.

The CCS route is applicable for large systems integrated into chemical and steel clusters, linked by a pipe network to either storage or use. The renewable energy route is more fragmented and modular. Both still require development, though some of the elements such as the electrolysers are already a mature technology. Since hydrogen is costly to transport, distributed generation with local electrolysers can be an attractive option, although these will instead require a local or regional electricity 'transport' system (i.e. transmission system or large amounts of local electricity generation combined with hydrogen storage). The form of hydrogen best suited for large-scale transport has not yet been settled.

Through catalytic processes, hydrogen can be the basis for producing a range of synthetic fuels such as methane and methanol, and even longer chain fuels such as kerosene and other chemicals. Table 6 provides an overview of important fuels based on their energy density. Typically, a higher density is preferred as it is more useful as an energy service supplier, easier to store and can be used in mobile applications.

53 There are multiple methods of producing hydrogen, only some of which are low-carbon. These are sometimes given an informal colour coding to distinguish them. See, for example: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

Fuel	Production cost	Storage	Long-distance transport	Distribution
Green hydrogen	Building block for other synthetic fuels	Needs large volumes (salt caverns, huge tanks)	Liquefaction for shipping is energy-intensive	To a certain extent possible with existing gas grid to distribute pure hydrogen
Methane	Needs CO_2 source	Can use existing infrastructure	Can use existing infrastructure	Transportable
Methanol	Needs CO_2 source	Easily storable	Can use existing infrastructure	Transportable
FT diesel	Needs CO_2 source, more costly	Easily storable	Can use existing infrastructure	Transportable
Ammonia	Extra step compared to hydrogen	Storable but toxic	Possible	Serious safety issues; best for industrial use only

Table 6. Overview of some synthetic fuels/energy carriers and their main advantages and disadvantages

Synthetic fuels derived from hydrogen have advantages and limitations which will determine their relevance in the energy transition. It is yet too early to state which options would be the best, as several factors, such as costs, are still open and changing. However, it is clear that wider use of such fuels could enormously increase the need for carbon-free electricity. For example, to replace just 1% of the current global oil and gas production with synthetic fuels, around 1000 TWh and 700 TWh respectively of electricity would be needed, representing around 4% and 3% of global electricity generation (IEA, 2019a).

Hydrogen and synthetic fuels already find relevant applications in the energy economy:

- **Electricity storage** could be one important application of hydrogen or synthetic fuels to store excess wind or solar energy and also provide backup, though this would be more a niche market for green hydrogen. Hydrogen and synthetic fuels could also provide strategic fuel reserves, which is currently set to 90 days of liquid fuels in the EU. The demand for such reserves in future needs to be defined.
- Synthetic fuels for **heating** will be a niche market where electricity grids are not available as the combination electricity/heat pump is far superior in efficiency. Future smart (remote) homes could include systems combining solar PV panels with hydrogen production and fuel cells.
- The role of hydrogen and synthetic fuels may be more significant in the **transport** sector, in particular for transport modes requiring higher energy density such as long-haul and heavy transport, where batteries may not be adequate. Methanol, biofuels or liquid methane derived from renewable energy could well apply for such uses.
- Energy-intensive **industries** in particular require fuels as basic feedstocks or for their processes. Hydrogen is needed in chemical and petrochemical industries in large quantities. Also, hydrogen could help in creating carbon-free iron production.

However, the decarbonisation possibilities in these industries through fossil-free hydrogen need to be carefully evaluated on a case-by-case basis.

In conclusion, it is expected that the use of renewable-based hydrogen and synthetic fuels will be very limited in building heating and cooling due to low efficiencies and while there are alternatives available (Fraunhofer IEE, 2020; ifeu, 2018). For long-haul, heavy road transport, synthetics fuels may play a role. Replacing existing fossil-based hydrogen feedstock with green hydrogen in energy-intensive industries is also relevant. The future for hydrogen could thus be promising, not as a primary energy vector, but as an indispensable component of the future energy and chemical process system.

Public acceptability and safety need to be part of the decision process when assessing the true potential for hydrogen applications. In particular, energy systems issues with green hydrogen production need better consideration, as it has a complex relation with the electricity sector.

6.6. Natural gas (fossil gas)

The window for applying natural gas as a bridging technology from coal to climate neutral technologies is shrinking fast, since increasing natural gas usage is associated with long lead times to build the infrastructure (e.g. new pipeline networks or LNG terminals) during which time the energy system needs to accelerate its transition to net zero emissions. Thus, natural gas faces the risk of being a regret option unless there is a clear plan and possibility for converting natural gas infrastructure for alternative fuels or uses, such as hydrogen, biomass derived gas or CO_2 transport (although these would require significant technical adaptations). In addition, natural gas may be a concern for Europe's energy security.

An alternative to natural gas is blue hydrogen (see the previous section). This would put less stress on renewable resources for hydrogen production which will require much more electricity than direct electrification. Here, interaction and co-operation with Norway and the UK are important, since both these non-EU countries have natural gas resources and are developing hydrogen and CCS infrastructure.

Chapter 7. Evidence-based policy options

The European Union has set itself ambitious targets for the reduction of greenhouse gas emissions, in line with the Paris Agreement. This implies that the whole European energy system must be transformed to achieve carbon neutrality by mid-century. While there are several possible pathways towards carbon neutrality, the transition already needs to accelerate to reach the necessary intermediate targets to stay on track, and needs to take place in a strategic direction that allows the highly challenging deeper decarbonisation required in the later stages. This is important because, with infrastructure-related investments, there are many lock-in risks that can prevent Europe from later deeper decarbonisation.

Decisive regulatory actions are required that combine meeting emissions targets with other European objectives, such as economic prosperity and post-COVID-19 recovery, social balance, and a strong geopolitical position. Moreover, these choices are to be understood as a dynamic task. In the short run, emission reductions need to be realised with the current set of technologies, but in the medium term the regulatory system needs to incentivise technological developments to provide increasingly more effective solutions. However, it is also important to note that the commercially available suite of technologies already enables moving swiftly towards carbon neutrality in Europe.

Most importantly, the political strategy chosen to work towards European carbon neutrality needs to recognise European social principles of liberal democracy and a social market economy. Consequently, the transition towards carbon neutrality requires solving an enormous systemic problem, since it involves coordinating an almost countless number of individual voluntary decisions on investment, consumption and behaviour towards that objective. Correspondingly, this report does not recommend an unequivocal policy package to be implemented, but rather a set of policy options addressing various facets of the overall challenge. At the same time, it is concluded that any successful policy must involve a carbon pricing mechanism, both in the EU Emissions Trading System (ETS) and Effort-Sharing Regulation (ESR) sectors, that delivers a sufficiently high carbon price while putting the pricing in a socially just frame.

Policy options should be evaluated according to a number of key criteria, especially:

- their potential for effectively and consistently reaching the climate targets

- their quality regarding their economic efficiency at the societal level on a lifecycle basis, both in terms of avoiding the waste of economic resources and of preserving the competitiveness of the European economy
- their ability to maintain social balance and therefore the long-term acceptance of the transition
- their respect for the international nature of the challenge as a problem of strategic interaction; setting an example for an effective, efficient and socially balanced transition towards carbon neutrality is a necessary but not sufficient requirement for this overall objective

Against this background, we have developed the following policy options.

7.1. Shaping an effective and efficient regulatory strategy

In our decentralised society and economy, a large number of decisions and choices (on consumption, behaviour and investments) are necessary to achieve climate neutrality. The public sector is only responsible for a very minor share of emissions and the state cannot make individual behavioural choices for European citizens.

There are two basic approaches for the coordination of a modern industrialised society: command and control, or prices on markets. No market economy can survive without the state ensuring that individual actors adhere to the rules of the game. In practice, this results in a mixed approach: a regulated market economy. European policymakers need to decide what should be the principal coordination device in the endeavour of the energy transition.

- If policymakers decide to focus on **command and control** measures such as efficiency and production standards, bans and subsidies, they gain far-reaching control of the energy transition. In principle, command and control measures explicitly allow policymakers to shape the technology mix. To implement command and control measures that are effective and efficient, policymakers need to possess an extremely rich information set regarding current technological developments, economic implications and individual preferences.
- If **market pricing** is chosen as the principal coordination device instead, this coordination mechanism obviates the need for detailed information gathering. As there is already a functioning system for carbon pricing for the energy and industry sectors, the European Emissions Trading System (EU ETS), the most direct option would be to extend the EU ETS to all other relevant emission sectors, most importantly to mobility and heating. The overall cap for the path of permitted

emissions would need to be adjusted according to the overall reduction targets, while sectoral targets would be relegated to the background. Furthermore, policymakers would need to make a credible commitment to accept carbon prices may increase to very high levels by mid-century. In detail, the focus on market coordination would have several implications:

- Overall emission reductions would become the principal objective, while increasing the share of renewables and increasing efficiency would be understood as gauges of success in working towards carbon neutrality, but not as binding additional targets in their own rights.
- Market prices would reveal the cost of avoiding emissions for different actors and in different sectors and, hence, gather information.
- Carbon pricing would lead to additional public revenue. This additional revenue would create a wide range of options for compensating households for the burden of transition or helping them to invest in their emission reduction efforts such as net zero energy building retrofits, especially in the lower-income ranks, thus paving the way to ascertaining social balance. An additional option would be to use part of the revenue from carbon pricing for the funding of public investments such as the building of Europe-wide power grids.
- Carbon pricing would provide a means to prevent carbon leakage, since a carbon border adjustment mechanism could be based directly on observed prices.
- In principle, carbon pricing would preserve the principle of technology neutrality, since policymakers would not decide on the technologies employed to reach carbon neutrality. A technology preferred policy would require addressing externalities other than carbon emissions, such as nuclear waste or local emissions, by additional instruments. But such technology focused policies would also very effectively promote the development of new technologies.

Choosing a mix of both command and control and market-based instruments might combine the virtues of both principal approaches, but also involves the risk of creating severe negative interactions and inefficiencies if not carefully designed. Moreover, the problem is dynamic. While it seems highly sensible to implement a uniform carbon price eventually, it will be difficult to break the previous course taken in the emission sectors currently not being covered by the EU ETS. Thus, the challenge is rather that of designing a policy package in an intelligent way that serves as a bridge towards uniform carbon pricing.

In such a transitory policy package, command and control or separate carbon pricing mechanisms would accompany emission trading in sectors that are not (yet) included in the EU ETS, while at the same time working towards the integration of these sectors into a more all-encompassing EU ETS. However, for this transitory policy package to be effective for accelerating the transition, it would need to submit mobility and heating to carbon pricing immediately. It should be noted that electrification of road transport and heating (by heat pumps) will make an increased share of these sectors to be included in EU ETS. In general, it can be concluded that in the longer run there is much to gain from scrapping national and sector-specific emission reduction targets and concentrating on overall European targets instead. But regional initiatives to accelerate the transition such as the Covenant of Mayors[54] should be supported (at least as long as the overall EU climate policy is not sufficiently strong).

7.2. Supporting technical innovation

Technologies will play a key role in the successful transition of the energy system in reaching carbon neutrality by 2050 and beyond. Huge global investments in existing and new energy and end-user technologies will be needed in the coming decades, in the order of tens of trillions of euros, that also means significant new market opportunities. The dependency of Europe on imported fuel will also decrease through the introduction of efficient and renewable energy solutions, leading to increased energy security. However, new dependencies will emerge instead. Many of the new technologies rely intensively on materials that could increase the dependency of Europe on some key materials, despite the technologies themselves being manufactured locally in Europe.

Promoting generally favourable conditions for innovations and their commercialisation in Europe is an important prerequisite for the energy transition. Strengthening the European innovation ecosystem, especially the cooperation and knowledge transfer between publicly funded institutions conducting fundamental and applied research and the private sector will be a key element of this endeavour. Public-private partnerships could play a beneficial role in accelerating the commercialisation of energy innovations. Another important ingredient would be a dynamic business sector and the promotion of start-ups and digital platforms, as new discoveries often emerge from such ecosystems and platforms.

Promoting technological innovation and diversity involves not only maintaining and perhaps phasing out typical, aging, and often inefficient equipment. It also involves promoting currently commercialised best practices such as energy efficiency measures in buildings, wind and solar power, or electrification of industrial processes as well as investing in state-of-the-art options such as advanced fuels, carbon capture and storage, and offshore wind farms. Lastly, it involves steering investment in future frontier or breakthrough technologies such as fusion or algal fuels that could revolutionise how we supply and use energy in the far future. Thus, these three stages of technology evolution

54 The Covenant of Mayors for Climate & Energy Europe, https://www.covenantofmayors.eu/en/

should be carefully considered when planning an RDI strategy for Europe supporting the European Green Deal goals.

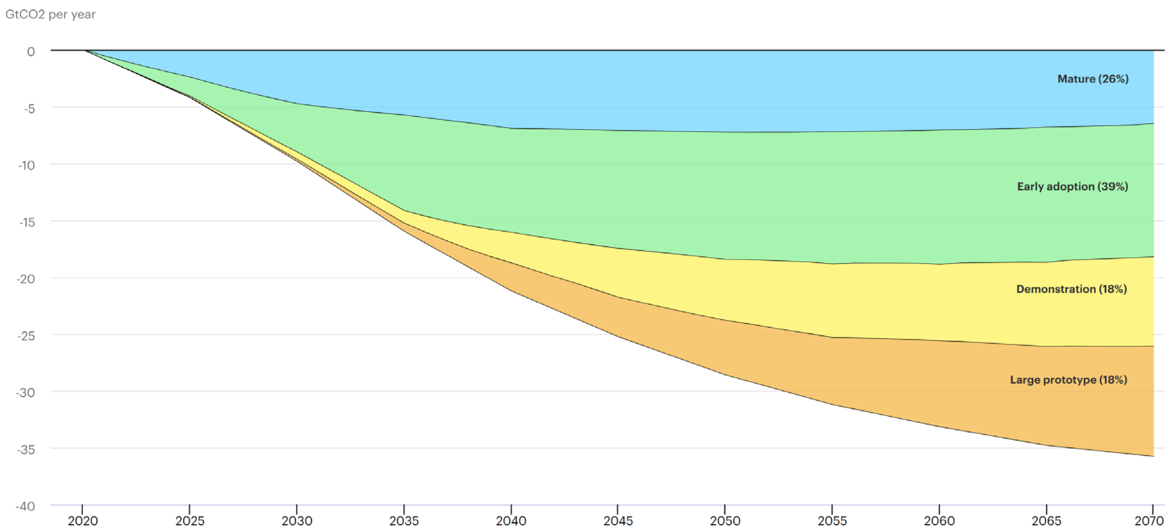

Figure 10. Critical role of demonstration and prototype technologies in carbon mitigation pathways (modified from IEA[55])

Figure 10 indicates that reaching net zero emissions in a cost-efficient way will require innovation and deployment of what we have (today's best practice), and will benefit from further new technologies (feasible and frontier). The International Energy Agency underscored this point when they noted that, in their scenarios, technologies at prototype or demonstration stage today in 2021 are expected to contribute almost 35% of emissions reductions up to the year 2070; they also noted a further 40% can come from technologies only at the earliest stages of adoption.

Thus, while it seems clear that policies which stimulate increased RDI efforts will need to be enhanced, both at the EU level and in the member states, to increase the private sector participation in these efforts, there are, once again, different options available for achieving this aim. Irrespective of the specific route taken, the funding of a rich infrastructure for innovation, especially high-performance research institutions devoted to fundamental and applied research, and the coordination of RDI efforts to provide European value-added should form the basis of any policy package. It is also likely that a strong enough climate policy will also enhance the development of efficient innovation and development of new technologies.

55 IEA (2020), *Global carbon dioxide emissions reductions in the sustainable development scenario relative to baseline trends*: https://www.iea.org/data-and-statistics/charts/global-energy-sector-co2-emissions-reductions-by-current-technology-maturity-category-in-the-sustainable-development-scenario-relative-to-the-stated-policies-scenario-2019-2070

To support technological development beyond providing this foundation for a potent European innovation system, policymakers can, on the one hand, opt for a strong involvement of the state in directing the process of searching for innovations by direct funding of research projects and the direct support of research in public research facilities. On the other hand, they can set the framework for companies to excel through the force of competition. Once again, a combination of both approaches seems natural, but its specific design requires a sound evaluation of overlaps and interactions to prevent countervailing effects.

Possible public investments comprise:

- Infrastructure whose real return lies in facilitating a European approach are favourable, such as interconnection of electricity grids, charging infrastructure, a shared CO_2 transport and storage network, or hydrogen distribution grids, among others.
- In emerging technology fields that are perceived as being of high importance to the energy transition, such as energy storage and batteries, digitalisation (including artificial intelligence) and hydrogen technologies, stronger targeted measures would be useful. This should include direct research funding in a broad field of disciplines including technical and social sciences (including economics), and engineering.
- An independent monitoring system for the European transformation process that collects evidence and shares information in a transparent fashion.
- Organising a platform offering possibilities for information and participation to advance acceptance (esp. of innovative technical solutions, of infrastructure investments, and carbon pricing), and to encourage behavioural changes.

Securing European industrial competitiveness in the future is of major concern when comparing the EU globally against key research and innovation indicators with other leading countries. If the RDI gap were not properly addressed by the EU, this may reflect adversely on the development of new energy technologies, which are important to realize the EU goals to reach full decarbonisation by 2050.

Supporting and strengthening public-private partnerships to accelerate commercialisation of energy innovations deserves attention. Securing access to critical materials needed in new technologies made in Europe will require strategies to expand and diversify the European material base, while also nourishing international relations because of the evident global interdependence that Europe has that will take new forms in the coming decades.

7.3. Geopolitical perspective remains important

Europe enjoys a leading position globally in policies set to reach carbon neutrality. Considering the challenging goals ahead, and the massive investments needed, linking EU industries more strongly to this endeavour would be of high importance. This could include and setting examples on what is achievable in terms of benefiting EU industries. Demonstrating that even an economically highly developed economy, that has so far been using fossil fuels intensively, can succeed in achieving ambitious climate targets in an economically efficient manner and without major social disruptions, should have a positive and encouraging effect, and strengthen the European negotiation position in international climate conferences. However, at the same time, its share of the global emissions is just one tenth, meaning that the European energy transformation must be embedded into a global strategy.

Currently, global measures mean that the Paris Agreement goals will not be achieved by the middle of this century. To effectively mitigate global climate change, other emitters must be incentivised to stipulate ambitioned climate policies. The EU should utilise this strengthened negotiation position to drive globally coordinated action, by strongly requesting other economies for reciprocal action. Thus, well-designed cross border adjustments in climate policy may spur regions exporting to the EU to intensify their efforts.

The same kind of 'duality' can also be found inside the EU with Europe being quite heterogeneous in terms of its capabilities to reach carbon neutrality by 2050. Some European countries, such as those in the Nordics, have favourable natural resources and conditions for a fast track towards decarbonisation, whereas many others have less favourable starting points. In general, low-income EU member states have a more carbon-intensive economy than the high-income countries, which imposes an economic challenge to the energy transition in these countries. In all member states, there are low-income groups which suffer from energy poverty who are, for example, unable to afford sufficient heating during the winter.

In its overarching energy and climate policies, Europe should pay attention to the above-described global and internal dualities to ensure success in carbon reductions, as follows:

- Europe should strengthen its diplomatic efforts to ensure that key countries and economies commit themselves to the Paris Agreement goals. This would also give stronger justification to the high decarbonisation targets in Europe. Striving for uniform rules globally, such as global carbon emission pricing, enables different pathways to be followed and would most likely provide the best economic efficiency to Europe and globally. Such a scheme should also be subject to compensation for social imbalances.

- To prevent carbon leakage and to preserve the competitiveness of European industry, a carbon border adjustment mechanism can be employed. But, since Europe strongly benefits from international trade, such trade barriers should be avoided wherever possible. In fact, international partners, such as the US, should be convinced of implementing analogous climate policies or, best, introduce an emission trading system and link it with the EU ETS. Support programmes for developing countries in their capability to implement adaptation and mitigation strategies should be tied to the requirement to join the EU ETS or implement their own system of carbon pricing.
- The pathways towards carbon neutrality inside Europe may differ between member states, but maintaining common European goals accompanied by compensations of consequent distributional effects and social issues would be advisable. Financial support to low-income EU member states and social groups is also necessary. Striving for economic efficiency in these measures will provide the best outcome, thus prioritising those measures that have the lowest societal cost and highest impact. In some cases, viewing the measures from a systemic and lifecycle view, may change the order of prioritisation, but in general, following the economic efficiency rule will yield the optimal path as long as external costs and benefits (multiple impacts) are adequately included in the economic calculations.
- European policies supporting modernisation of economies in low-income countries that could include transformation of workforce skills could help to increase productivity and reduce the carbon intensity of their economies. Paying due attention to economic efficiency in the policies and measures, but compensating possible social imbalances, would be a good guiding principle.

7.4. Strong system integration key for expanding electrification

The role of electricity and electrification in decarbonising energy systems and society is seen as a critical component of the energy transition both globally and for the EU. This development has been driven by the notable price decrease and rapid market penetration of the variable renewable electricity technologies such as wind power and solar photovoltaics, whose share of electricity will grow over time. It is also accompanied by major progress in electrified energy end-use technologies such as heat pumps, electric vehicles (batteries), digital equipment and others. This transformation will gradually turn the architecture of the power systems from a fuel- to a weather-dominated, non-dispatchable system with more uncertainty in delivery than in the present system.

An electrified energy system could be subject to new types of threats, such as cyber attacks or extreme weather events. In addition, the coexistence of old and new power system types along the transition encompasses challenges for their integration and simultaneous operation. To ensure the adequate reliability, resilience and efficiency of the future energy system of Europe, energy system integration and flexibility considerations that mitigate the possible issues described above will be necessary. Policy considerations should include:

- Past experiences in EU member states illustrate that national power systems having good access to energy storage capacity such as hydropower reservoirs, either domestically or through adequate transboundary power transmission capacity, have been able to effectively handle high shares of wind power and pursue a faster track in decarbonising their energy systems. Whereas, in isolated cases or with thermal generation only, integration of variable renewable electricity has encountered multiple challenges. Therefore, stronger European efforts and policies to improve the power transmission infrastructure in Europe and transboundary capacity between the countries would be welcome to provide better spatial integration of resources and better flexibility for the integration of intermittent sources.
- Recognising that large European infrastructure initiatives are long term in nature and that the pace of development in new technologies is quick, measures in the short term may also be necessary to deal with the present particularities in the member states. This could include, for example, sector coupling measures, energy efficiency (an 'efficiency first' principle), and decarbonising measures in buildings and building smart charging infrastructure for electrical vehicles.
- Both short-term and long-term policies would benefit from addressing the rapidly changing market conditions in the power sector and enable an adequate business base for the necessary investments from the private sector. For example, addressing European wide market barriers to sector-coupling and battery storage at the electricity distribution system level, ensuring acceptable revenues from power network investments, and reforming the power market to include compensations for secure, dispatchable, and low-carbon forms of generation could support stronger system integration. Such policies could support an emerging second-life battery market for stationary applications which would be beneficial to the member states in their system integration plans.

7.5. Technology diversity should be maintained

Although the present trend indicates that variable renewable electricity and electrification will play a key role in the European decarbonisation pathway, and that this may deserve additional efforts to accelerate and scale-up, maintaining a broad emission-free technology and policy base would be well justified for the following reasons:

- The European energy mix is very heterogeneous, with each member state having its own particularities, energy structure and lock-ins that need their own considerations to find the best solution. European policies that are inclusive rather than exclusive in terms of solutions could provide the best total outcome.
- As policies are seldom able to pick winning technologies of the future or to predict future technology disruptions, nourishing research, development, and innovation capabilities in Europe in general rather than focusing on a single technology should be a priority. Creating good conditions for innovations such as adequate RDI resources, skills and infrastructures, smooth innovation and commercialisation chains, and strong public-private-partnerships will be important to ensure European success in next generation clean energy, whose foundations are laid now.
- The cost of emission reductions, but also the severity of systemic issues in the energy system, will increase when approaching carbon neutrality. As a result, the role of carbon sinks, both technical (including CO_2 management) and biogenic, will increase as indicated by European scenarios. Carbon sinks could also in theory provide a means for more rapid emission reductions or flexibility to emission cutting policies. However, there are many uncertainties as well as environmental concerns about these, therefore it is important to keep these for emissions that are otherwise impossible to avoid or have already emitted excess atmospheric carbon. Europe lacks a clear policy on the way forward with carbon sinks, both biogenic and technical type (CCS) as both lack incentives. Also, biogenic or forest-based sinks, whose potential wider implications need more careful examinations, need better integration with European forest policies. Decisions are also needed on whether carbon sinks will be included in the EU ETS and whether they should be jointly handled by the EU or by each of the member states separately.

7.6. Policy must stimulate behaviour alongside technology

As much as 72% of global greenhouse gas emissions can be ascribed to household consumption, the remaining share being related to public consumption (Hertwich & Peters, 2009). This makes decarbonation as much about household decision-making, demand and behaviour as technology. To address this nexus of demand-side options, lifestyles, barriers and required behavioural change to decarbonise lifestyles, it is necessary to better diagnose which behavioural determinants should be targeted by policy intervention and how to balance use of ‘carrots’ and ‘sticks’ to achieve necessary consumption changes. Indeed, while many policies focus on technology, far fewer focus on behaviour. As just one example, although some countries have put in place demand-pull policies to spur energy innovation including carbon pricing and beyond, these are inconsistent and fragmented. More than 140 countries currently have policies in place for electricity and power, and 70 countries for transport but only 23 countries for heating and cooling demand.[56]

This misalignment between policy and behaviour is unfortunate because, as discussed in Chapter 4, p.66, the potential emissions reductions to be achieved by targeting behaviour can be very large.

Policies are needed to shape and stimulate such behaviour because so many barriers prevent it from occurring. Research has shown for instance that consumers practically ignore renewable power systems or energy efficient practices because they are not given accurate price signals about electricity consumption; intentional market distortions (such as subsidies) and unintentional market distortions (such as split incentives) prevent consumers from becoming fully invested in their electricity choices. As a result, newer and cleaner technologies that may offer social and environmental benefits but are not consistent with the dominant paradigm continue to find little use The 'avoid-shift-improve' framework, originally designed to promote widespread climate change mitigation in the mobility sector (Creutzig et al., 2018), includes policies that avoid carbon-intensive activities (such as travel or eating meat), shift practices (for instance to walking or cycling), and improve innovations (such as solar panels or electric vehicles).

Very recent projections from the International Energy Agency reveal the extremely large potential for behavioural change to capture emissions reductions. Figure 11 illustrates that efforts across heating and cooling, driving, air conditioning, working and flying could in aggregate save more than 1.2 billion tonnes of CO_2 by 2021 and more than 2 billion tonnes by 2030.

56 Laura Diaz Anadon, *Technological Change in Energy and Green Industrial Policy*, February 17, 2021, Sussex Energy Group Keynote Lecture, https://www.ceenrg.landecon.cam.ac.uk/news/2021-sussex-energy-group-keynote-lecture-technological-change-in-energy-and-green-industrial-policy

Figure 11. The large carbon emissions reductions to be achieved by behavioural change in the near-term (2021–2030) (IEA, 2021)[57]

In sum, individuals can alter many of their daily practices to substantially reduce emissions: they can, for instance, use less energy-intensive goods and services, drive more efficient cars, and purchase better electric appliances.

When forming energy and climate policies, it is important not to view citizens as passive recipients loosely connected to climate change, but rather as active participants whose lifestyles play a central (and disruptive) role in contributing to energy and climate problems. Therefore, behaviour could be just as important as developing new technology and would deserve a much stronger role in the policy framework of the Green Deal.

57 IEA (2021), Impact of behavior changes on carbon emissions in the net zero emissions by 2050 case, 2021–2030: https://www.iea.org/data-and-statistics/charts/impact-of-behaviour-changes-on-co2-emissions-in-the-net-zero-emissions-by-2050-case-2021-2030

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Art. 192 TFEU, Consolidated version of the Treaty on the Functioning of the European Union, PART THREE - UNION POLICIES AND INTERNAL ACTIONS, TITLE XX - ENVIRONMENT - Article 192: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A12012E192

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- Prof Andreja Kutnar, University of Primorska & InnoRenew CoE (Slovenia)
- Prof Andreas Löschel, University of Münster (Germany)
- Prof Peter Lund, Aalto University (Finland): co-chair (until 11 May 2021) and chair (from 12 May 2021)
- Prof Marianne Ryghaug, Norwegian University of Science and Technology (Norway)
- Dr Alessandra Sanson, National Research Council (Italy)
- Prof Sabine Schlacke, University of Münster (Germany)
- Prof. Dr. Dr. h.c. Christoph M. Schmidt, RWI Leibniz Institute for Economic Research (Germany): co-chair and Working Group member (until 11 May 2021)
- Prof Benjamin Sovacool, Sussex University (United Kingdom) & Aarhus University (Denmark)
- Prof Goran Strbac, Imperial College London (United Kingdom)
- Prof Diana Urge-Vorsatz, Central European University (Hungary)
- Prof Brian Vad Mathiesen, Aalborg University (Denmark)
- Prof Richard van de Sanden, Eindhoven University of Technology & The Netherlands' Energy Research Institute DIFFER (The Netherlands)

The above experts were identified with the support of:

- acatech
- CNR, INFN, IIT and Politecnico di Torino (Consortium representing Italy as observer at Euro-CASE)
- Danish Academy of Technical Sciences (ATV)
- National Academy of Technologies of France (NATF)
- Norwegian Academy of Science and Letters (DNVA)
- Norwegian Academy of Technological Sciences (NTVA)
- Polish Academy of Sciences
- Royal Flemish Academy of Belgium for Science and the Arts (KVAB)
- Royal Swedish Academy of Engineering Sciences (IVA)
- Spanish Royal Academy of Sciences
- The Netherlands Academy of Technology and Innovation (AcTI)
- The Royal Netherlands Academy of Arts and Sciences (KNAW)
- Young Academy of Europe

Annex 2. Dissenting view

As per paragraph 4.5.2. of the SAPEA Quality Assurance Guidelines (https://www.sapea.info/publications/quality-assurance/), 'Dissenting views, reporting controversies and uncertainties', while all Working Group members agreed on Chapter 3 of this report, one member wished to convey a divergent view on the content of sections 3.1 to 3.9 inclusive:

> Professor Pantelis Capros does not agree with the content of sections 3.1–3.9. His view is that the **Mixed** (or **Mix**) energy transition scenario is the most cost-effective approach among the three scenarios examined, thanks to a balance between bottom-up/regulatory measures and a strong carbon pricing signal. This scenario extends a reinforced ETS carbon pricing scheme to road transport and buildings and at the same time removes non-market barriers, helps individuals to adopt rational choices, develops infrastructure and pushes technological maturity via stringent standards. Without such strong bottom-up/regulatory policies, the carbon pricing instrument is ineffective, as is the case for the **Cprice** or **Price** scenario. Similarly, the balance between bottom-up/regulatory and strong carbon pricing measures is superior to an approach neglecting or weakening the strength of the carbon pricing signal, as is the case of the **Reg** or **Regulated** scenario. The **Mixed** or **Mix** scenario is also superior regarding the possibility to address energy poverty and other social adverse effects because it includes the regulatory measures that can address such issues directly, while in addition the strong carbon price is able to collect public revenues to finance social support.

Professor Brian Vad Mathiesen is joining this view.

Annex 3. Background

Scoping phase

The topic *A systemic approach to the energy transition for Europe* originally stems from the Euro-CASE Energy Platform, which published a concept paper in October 2018, *How to meet the future challenges of the European energy system*, and a report entitled *Energy transitions in Europe: common goals but different paths* in October 2019.

A SAPEA Task Force was set up led by Euro-CASE and chaired by Eberhard Umbach of acatech, which was comprised of experts nominated by Academia Europaea, ALLEA, EASAC and Euro-CASE. The task force built on the work of the Euro-CASE Energy Platform. Its main task was to develop a draft concept paper for the Group of Chief Scientific Advisors.

The Advisors agreed to organise a SAM Scoping Workshop which was held in Brussels on 12 December 2019. It was attended by 30 participants including:

- Rolf Heuer, Elvira Fortunato and Carina Keskitalo from the Group of Chief Scientific Advisors
- Yves Caristan for the Lead Academy Network Euro-CASE and the SAPEA Board
- the members of the Task Force
- thirteen DG representatives (from DG ENER, CLIMA, RTD, JRC, MARE, SG and EPRS)

The purpose of the workshop was to better understand the exact needs of the European Commission and how the SAM could best contribute. Part of the workshop was a participatory foresight exercise carried out by the Foresight on Demand team,[1] using the concept paper and the report prepared by the Euro-CASE Energy Platform as a basis for the brainstorming discussions. The main outcome of the workshop was that a draft scoping paper should be developed in the framework of the SAM.

Euro-CASE, with the support of a scientific writer, drafted a proposal for a topic related to the energy transition which was endorsed by the SAPEA Board. The draft was then discussed at Commission level with input from scientific experts. The Chair of the Advisors at that time, Professor Rolf Heuer, proposed to Mariya Gabriel, Commissioner for Innovation, Research, Culture, Education and Youth, to consult the Advisors on the topic

1 https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/shaping-eu-research-and-innovation-policy/foresight_en

of a systemic approach to the energy transition in Europe. Thereupon, in March 2020, Commissioner Gabriel gave the mandate to the Advisors to deliver a scientific opinion on the topic of a systemic approach to the energy transition in Europe. The mandate, in the form of a scoping paper, contained the following question:

> How can the European Commission contribute to the preparation for, acceleration, and facilitation of the energy transition in Europe given the present state of knowledge on the possible transition pathways?

The scoping paper proposes in addition to have an impartial, independent and systemic approach with insight of experts with a multidisciplinary background in order to provide a robust, information-based anticipation of future requirements for the energy transition in Europe.

Responsibilities and working structure within the SAM

Euro-CASE served as Lead Academy Network for the topic. Antoine Blonce, Euro-CASE Scientific Policy Officer, led the coordination of this project for SAPEA.

The SAM Coordination Group was initially chaired by Rolf Heuer, at that time Chair of the Advisors, with other members (Elvira Fortunato and Carina Keskitalo) also attending. The Coordination Group was then chaired by Nebojsa Nakicenovic following the departure of the above-mentioned Advisors from the Group. The representatives for SAPEA were Yves Caristan supported by Antoine Blonce (for the Lead Academy, Euro-CASE) as well as the two working group co-chairs accompanied by a scientific writer, Alan Walker.

Dulce Boavida initially coordinated this project from the SAM Unit, providing inputs on the EC policy documents related to the energy transition and supervising the organisation and hosting of the SAM Coordination Group meetings, followed by Ingrid Zegers and Nicola Magnani after her departure from the SAM Unit at the end of 2020. Both coordinated the Coordination Group meetings, the stakeholder meeting of the Advisors and the handover of the publications. The SAM Coordination Group met four times online, in April and September 2020 and in January and March 2021.

Working group set-up

Following the completion of the scoping phase, Euro-CASE proceeded to assemble a SAPEA working group. Euro-CASE nominated two co-chairs, which were approved by the SAPEA Board.

A call for nominations of experts was then published and sent to all the member academies of the five SAPEA networks. The deadline for nominating experts was 28 May 2020 and a selection committee was established to propose working group members to the Board.

Following the SAPEA Quality Assurance procedures,[2] the Selection Committee was composed of the co-chairs of the working group, the SAPEA Board representative for the Lead Network (Euro-CASE), another SAPEA network Board representative, and an 'external' topic expert. The Selection Committee was therefore composed as follows:

- Peter Lund, co-chair of the working group
- Christoph Schmidt, co-chair of the working group
- Yves Caristan, Lead Network SAPEA Board representative (Euro-CASE)
- Ole Petersen, other SAPEA Network Board representative (Academia Europaea)
- Neven Duic, 'external' topic expert (nominated by the Croatian Academy of Engineering HATZ and EASAC)

The selection committee highlighted the fact that the 119 nominations received were of very high level and they had to meet twice online to consider all the CVs received and select potential experts for the working group. The committee's first meeting was held on 12 June and the second one on 18 June 2020. The committee's shortlist was approved by the SAPEA Board at the end of June 2020 and the working group was composed of 18 experts and 2 co-chairs, so 20 members in total.

The SAPEA selection criteria were all met:

- inclusion of at least 1 Fellow of young academies: one Young Academy of Europe Fellow was included
- at least 30% female working group members: 35% female working group members included
- wide geographic coverage across Europe: 16 countries were represented

Following SAPEA's Quality Guidelines, working group members submitted their declarations of interests to SAPEA. These forms were then pre-assessed by Antoine Blonce supported by Jacqueline Whyte, at that time Senior Scientific Policy Officer at SAPEA. Desk research on all candidates was undertaken in addition to gather more information about interests. No conflicts of interests were detected before the experts submitted their first contributions to the report. The experts' signed declarations of interests are available on the SAPEA website for a duration of 6 months following publication of this report.[3]

2 https://www.sapea.info/publications/quality-assurance/

3 https://www.sapea.info/topics/energy-transition/

Working group meetings

The WG met nine times. All meetings were held online:

- 10 July 2020
- 11 September 2020
- 16 October 2020
- 13 November 2020
- 11 December 2020
- 15 January 2021
- 12 February 2021
- 12 March 2021
- 25 May 2021

Between November and February, the decision was taken to temporary split the working group into two subgroups: one focused on the socio-technical aspects led by Peter Lund and one focused on the socio-economical aspects led by Christoph Schmidt. The socio-technical aspects subgroup was composed of 12 experts, while the socio-economical aspects subgroup was composed of 8 experts. Each subgroup met three more times, in addition to the nine meetings of the full working group. Synergies between the two subgroups were of course required. Therefore, some experts were part of the two subgroups, and the outcomes of each subgroup were shared at each full working group meeting.

The two co-chairs and the scientific writer also worked to ensure that the individual contributions of each experts were fused into one comprehensive draft encompassing all the systemic approach for the energy transition's aspects.

Literature review

Euro-CASE commissioned Harper Adams University to run a literature review for this project, as well as responding to specific requests made by working group members. The Harper Adams team attended every working group to consult with the WG members, thus guiding their literature search. They provided regular updates on their search results with a database that includes keywords matching the items the experts were working on while drafting the report.

A Quick Scoping Review (QSR) was chosen to review the academic and grey literature relevant to this topic. QSRs are a method of evidence synthesis that follows structured, transparent protocols that aim to minimise the bias in the collation and appraisal of evidence (Collins et al., 2015). QSRs are seen to be more robust and reliable than traditional literature reviews but quicker and less costly than full rapid evidence assessments or systematic reviews. A QSR therefore represents a good compromise for addressing the requirements, timescale and budget of this review. This QSR was conducted following the Defra/NERC guidelines to produce Quick Scoping Reviews and Rapid Evidence Assessments (Collins et al., 2015). This approach is closely aligned with systematic mapping methodology (James et al., 2016), a form of systematic review that allows multiple questions to be addressed at one time as is required in this review.

SAPEA expert workshop

The Expert Workshop took place on 29 January 2021. The list of invited experts was prepared by Euro-CASE and the co-chairs and updated following a discussion via email with the SAPEA Board members, and with the support of the SAPEA Scientific Policy Officers.

In the end, 15 experts attended and provided comments on the report. Of these, five were from the private sector, five from renowned NGOs (WWF, Chatham House, European Environmental Bureau, Climate Action Network International and International Institute for Applied Systems Analysis) and five from academia, thus ensuring a balanced representation from the different stakeholders. They represented 8 EU countries and there was a 33% female representation — thus matching the WG Selection Committee criteria from the QA Guidelines.

The expert workshop report is available on the SAPEA website.[4]

Peer review

Following the SAPEA Quality Assurance Guidelines, a minimum of 3 peer reviewers were needed to undertake a double-blind peer review process: peer reviewers do not know who the working group members are (and vice versa) until the report is published. The peer reviewers' expertise should cover all the various aspects of the report.

In addition to these rules, peer reviewers were identified and chosen by the different SAPEA Networks with an appropriate geographical and gender balance.

Following these directions, five peer reviewers were identified (from four different countries, four different networks and including two female scientists) covering the technical, regulatory, economical and social aspects of the report.

4 https://www.sapea.info/topics/energy-transition/

Fact-checking

A third-party fact checking of the final draft of the ERR was performed by Ea Energy Analyses, Denmark, commissioned by Euro-CASE. Their findings are detailed in Annex 5, p.164.

Plagiarism check

A plagiarism check was run by Cardiff University using Turnitin software.

Handover and publication

An official handover to the European Commission was organised on 29 June, following which both the ERR and the SO were simultaneously published.

Annex 4. Policy landscape related to the energy transition in Europe

Frederico Rocha, Charlotte Sinden

Driven by the urgent need to mitigate anthropogenic climate change, societies globally are transforming the ways in which they produce and use energy. Within European Union policy, ambitious climate targets have been set in recognition that decarbonising energy systems is critical. This annex conveys how EU energy policy has evolved over time, mapping out the key initiatives put forward within the Energy Union to meet climate and energy goals.

EU policy action leading up to the Paris Agreement

In January 2014, the European Commission outlined a package of strategic documents building on previous policy concerning climate and energy. This set of measures includes the 2030 climate & energy policy framework,[5] a strategy focusing on the transition to a low-carbon economy.[6] Actions include measures addressing greenhouse gas emissions, renewable energy and energy savings. The framework was discussed by national leaders and eventually subject to political agreement by the European Council in October 2014.[7]

Based on this political guidance, in February 2015 the Commission put forward the so-called Energy Union package. Crucially, this set of documents includes a framework strategy setting out the EU's Energy Union.[8] The Communication determined five dimensions for EU-wide integration:

- energy security
- internal energy market

5 Communication on a policy framework for climate and energy in the period from 2020 to 2030 (COM/2014/015).

6 The package also included a Communication on Energy Prices and Costs in Europe (COM/2014/021) and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme.

7 European Council Conclusions on the 2030 climate & energy framework (169/14).

8 Communication on A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy (COM/2015/80).

- energy efficiency
- decarbonisation
- research, innovation and competitiveness

The package also comprised a Communication setting out the EU's objectives for the Paris climate conference (COP21).[9]

The Paris Agreement

197 nations adopted the Paris Agreement during the COP21 conference in December 2015, marking a historic turning point for global climate action. Recognising that climate change is a global problem that requires international cooperation, the Paris Agreement is a legally binding framework established to substantially reduce greenhouse gas emissions. Its primary goal is to limit global warming to well below 2˚C and pursuing efforts to limit it to 1.5˚C.

Reflecting on this achievement, the European Commission published in March 2016 a Communication outlining the key features and main achievements of this international agreement.[10] The EU formally ratified the agreement in October 2016, thus enabling its entry into force on 4 November 2016.

Fourth Energy Package: *Clean energy for all*

Aiming to deliver on the objectives set out by the Energy Union strategy and on the commitments under the Paris Agreement, the Commission published in November 2016 the Fourth Energy package — also known as the *Clean energy for all* package or *Winter package* — led by the Communication on *Clean energy for all Europeans*.[11] The package comprised initiatives on energy performance of buildings,[12] risk preparedness in the electricity sector,[13] renewable energy,[14] energy efficiency,[15] and the internal market

9 Communication on The Paris Protocol — a blueprint for tackling global climate change beyond 2020 (COM/2015/081).

10 Communication on The Road from Paris: assessing the implications of the Paris Agreement (COM/2016/110).

11 Communication on Clean Energy for all Europeans (COM/2016/860).

12 Directive (EU) 2018/844 on the energy performance of buildings.

13 Regulation (EU) 2019/941 on risk-preparedness in the electricity sector.

14 Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources.

15 Directive (EU) 2018/2002 on energy efficiency.

for electricity,[16] as well as on the role of the Agency for the Cooperation of Energy Regulators.[17]

The *Clean energy for all* package also included an initiative aimed at ensuring the implementation of the Energy Union strategy in a coordinated and coherent manner across its five dimensions.[18] Importantly, it introduces the concept of National Energy and Climate Plans (NECPs). NECPs are the framework for EU Member States to outline their climate and energy goals from 2021–2030, ascertaining how they intend to pursue decarbonisation pathways while fostering innovation, investment and growth.

While the draft laws were all tabled by the European Commission on 30 November 2016, their final adoption took place on several dates between 2018 and 2019 following negotiations between the co-legislators, which include the Council of the European Union and the European Parliament.

Energy security, energy markets and the impact of consumers

Despite the importance of a policy framework explicitly supporting the climate and energy targets set at EU and international level, the European Commission also focused on addressing other challenges facing the energy sector and its users, whether individual or institutional, in the context of the wider Energy Union strategy.

In July 2015, the Commission published the so-called *Summer energy package*, which focused on energy efficiency and the impact of energy markets on consumers. The package aimed to further strengthen the EU's position ahead of the COP21 conference. It included a revision of the EU Emissions Trading System[19] and a revision of rules on energy labelling,[20] a strategy setting out a new deal for energy consumers[21] and the launch of a consultation for a new market energy design.[22]

16 Regulation (EU) 2019/943 on the internal market for electricity and Directive (EU) 2019/944 on common rules for the internal market for electricity.

17 Regulation (EU) 2019/942 establishing a European Union Agency for the Cooperation of Energy Regulators.

18 Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action.

19 Directive (EU) 2018/410 to enhance cost-effective emission reductions and low-carbon investments and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme.

20 Regulation (EU) 2017/1369 setting a framework for energy labelling.

21 Communication on delivering a new deal for energy consumers (COM/2015/082).

22 Communication on a new energy market design (COM/2015/340).

This was followed by the so-called *Energy security* package, published in February 2016 against a backdrop of geopolitical tension in the EU's neighbourhood. This package recognised the importance of gas in the EU energy mix. It aimed to address the prospects of gas crises and improve coordination and support between member states in any gas supply disruption. It included measures addressing EU gas supply security[23] and energy agreements between EU and non-EU countries,[24] a strategy concerning liquefied natural gas and gas storage,[25] as well as a strategy for heating and cooling.[26]

In July 2016, the Commission published a package focusing on the transition to a low carbon economy. The leading Communication[27] once again highlights the importance of the 2030 climate & energy policy framework. It was accompanied by the draft laws for a regulation on use of lands and forests[28] and for the Effort-Sharing Regulation[29], which sets binding annual greenhouse gas emission reductions and thus implements commitments under the Paris Agreement.

Climate neutrality and further energy integration: the European Green Deal

Following mounting concerns that allowing temperatures to rise more than 1.5°C will have catastrophic effects on the planet, the European Commission published in November 2018 the Communication on a *Clean planet for all*.[30] This document sets out a long-term vision and roadmap for future climate and energy policies beyond the Fourth Energy Package, and advising climate neutrality for 2050.

Under new leadership, the European Commission published in December 2019 its European Green Deal,[31] a strategy cutting across all policy fields and reaffirming an

23 Regulation (EU) 2017/1938 concerning measures to safeguard the security of gas supply.

24 Decision (EU) 2017/684 on establishing an information exchange mechanism with regard to intergovernmental agreements and non-binding instruments between Member States and third countries in the field of energy.

25 Communication on an EU strategy for liquefied natural gas and gas storage (COM/2016/049) and Regulation (EU) 2017/1938 concerning measures to safeguard the security of gas.

26 Communication on an EU Strategy on Heating and Cooling (COM/2016/051).

27 Communication on accelerating Europe's transition to a low-carbon economy (COM/2016/500).

28 Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry into the 2030 climate and energy framework.

29 Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030.

30 Communication on A Clean Planet for All: A European strategic long-term vision for prosperous, modern, competitive and climate neutral economy (COM/2018/773).

31 Communication on a European Green Deal (COM/2019/640).

ambition to make Europe the first climate-neutral continent by 2050. In January 2020, the Sustainable Europe Investment Plan,[32] the investment pillar of the European Green Deal, was unveiled. The Plan includes the creation of the Just Transition Mechanism to support those adversely affected by energy transition. The first branch of this mechanism is the Just Transition Fund,[33] focusing on economic diversification of those regions most affected by climate transition.

The Green Deal proposed a vast set of measures, not least the so-called European Climate Law, aimed at writing climate neutrality into law. The draft law was eventually tabled in March 2020 and amended in September 2020 to reflect more ambitious climate targets.[34] Those targets received political endorsement by member states in December 2020.[35]

Building on policy implemented by the *Clean energy for all* package and on the vision introduced by the European Green Deal, the Commission published in July 2020 a strategy pushing for a more integrated energy system in the European Union.[36] The NECPs were subject to an assessment published in September 2020,[37] which drew on the priorities under the Green Deal and the economic recovery plans following the COVID-19 pandemic.

In September 2020, the Commission also set out its so-called Renovation Wave Strategy,[38] aimed at doubling rates of building renovation to make them more energy- and resource-efficient.

EU Emissions Trading System

The EU Emissions Trading System is the world's first major carbon market and also an essential feature of the EU's effort in reducing greenhouse gas emissions cost-effectively.

32 Communication on the Sustainable Europe Investment Plan (COM/2020/021).

33 Proposal for a Regulation establishing the Just Transition Fund (COM/2020/022) and Amended proposal for a Regulation establishing the Just Transition Fund (COM/2020/460).

34 Proposal for a Regulation on establishing the framework for achieving climate neutrality (COM/2020/080) and Amended Proposal for a Regulation on establishing the framework for achieving climate neutrality (COM/2020/563). The amendment was framed by the Communication on the 2030 Climate Target Plan (COM/2020/562).

35 European Council meeting (10 and 11 December 2020) — Conclusions (22/20).

36 Communication on Powering a climate-neutral economy: An EU Strategy for Energy System Integration (COM/2020/299).

37 Communication on an EU-wide assessment of National Energy and Climate Plans (COM/2020/564).

38 Communication on a Renovation Wave for Europe — greening our buildings, creating jobs, improving lives (COM/2020/662).

The existing policy framework emerged in 2003[39] and it has been revised on a number of occasions thereafter (the latest one adopted as part of the *Summer energy package*). Several reports on the functioning of the carbon market have been published over the years, the latest of which was in November 2020.[40]

The European Green Deal and the latest climate targets set by the EU led to the intention to further revise and possibly expand the scope of the EU ETS.

Energy infrastructure

Energy infrastructure is seen as an essential element for energy transition as envisioned in the Commission's Clean Planet for All and European Green Deal. Key legislation was adopted in the framework of the *Clean energy for all* package. Additionally, the Trans-European Network for Energy (TEN-E)[41] is a policy focused on linking the energy infrastructure of Member States. In 2017, the Commission took stock of progress in developing the EU's energy networks through TEN-E.[42] In December 2020, a draft law was tabled to revise TEN-E guidelines[43] to align them with the latest climate targets and political context.

In this context, a number of Projects of Common Interest have been selected since 2013 to support the EU in fulfilling its energy policy and climate objectives. These projects must demonstrate substantial impact on energy markets and market integration in at least two countries, improve competition on energy markets and deliver diversification of energy sources.

Critical raw materials

Critical raw materials have been seen as important elements of wider strategies over the years, from circular economy to industrial policy, trade and biodiversity. Access to resources is also perceived as a strategic matter for implementing the European Green Deal.

39 Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC.

40 Report on the functioning of the European carbon market (COM/2020/740).

41 Regulation (EU) No 347/2013 of the European Parliament and of the Council on guidelines for trans-European energy infrastructure.

42 Communication on strengthening Europe's energy networks (COM/2017/718).

43 Proposal for a Regulation on guidelines for trans-European energy infrastructure (COM/2020/824).

The European Commission published its Raw Materials Initiative (RMI) in November 2008,[44] aimed at ensuring a level playing field in access to resources in third countries, fostering a sustainable supply of raw materials from European sources, and boosting resource efficiency and recycling.

The creation of a list of critical raw materials was then established as a priority action — the first one was published in 2011,[45] followed by reviews in 2014,[46] 2017[47] and 2020[48]. These documents also provided reviews on RMI implementation (together with a further report in 2013).[49] In July 2017, the European Commission revised the methodology for establishing the EU list of critical raw materials.[50]

Diversification of energy sources and technological aspects of energy production

A diverse landscape of energy sources is an essential feature of the EU's Energy Union objectives in areas such as energy security and energy integration. The methods and pollution related to securing a diverse energy mix have also been considering in EU policy.

For example, the Commission published Communication in 2014 addressing the exploration and production of hydrocarbons (such as shale gas) using high volume hydraulic fracturing[51] as well as a Recommendation setting out minimum principles for exploration.[52] A framework for the safety of nuclear installations was also adopted in 2014,[53] whereas existing rules on management of spent fuel and radioactive waste have

44 Communication on the raw materials initiative: meeting our critical needs for growth and jobs in Europe (COM/2008/0699).

45 Communication on tackling the challenges in commodity markets and on raw materials (COM/2011/025).

46 Communication on the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative (COM/2014/297).

47 Communication on the 2017 list of Critical Raw Materials for the EU (COM/2017/490).

48 Communication on Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability (COM/2020/474).

49 Report on the implementation of the Raw Materials Initiative (COM/2013/442).

50 European Commission (2017). Methodology for establishing the EU list of critical raw materials — Guidelines.

51 Communication on the exploration and production of hydrocarbons (such as shale gas) using high volume hydraulic fracturing in the EU (COM/2014/023).

52 Commission Recommendation 2014/70/EU on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing.

53 Council Directive 2014/87/Euratom amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations.

been in place since 2011.[54] The latest Directive on the quality of petrol and diesel fuels is from 2015.[55] The importance of natural gas was highlighted in the Commission's 2016 *Energy security package*.

The EU's 2030 climate & energy framework acknowledged the role of safe geological storage of carbon dioxide — also known as carbon capture and storage (CCS) — in reaching long-term targets when it comes to greenhouse gas emissions. A legal framework supporting this technology, known as the CCS Directive,[56] was adopted in 2009. This Directive has been amended on a number of occasions over the years. Reports on its implementation were published in 2014,[57] 2017[58] and 2019.[59]

The European Green Deal also identified a number of matters concerning diversification and technological aspects of energy transition.

The potential of hydrogen has been noted as essential in supporting decarbonisation. The Commission's hydrogen strategy[60] was unveiled in July 2020, alongside its Communication on furthering energy system integration. A strategy addressing offshore renewable energy[61] was published in November 2020. In December 2020, the Commission tabled an initiative aimed at modernising rules on batteries and waste batteries.[62]

The reduction of methane emissions was also listed as a priority — the Commission published a strategy addressing that matter in October 2020.[63] Coal regions across the EU were highlighted in the context of the Just Transition Mechanism, which recognises the importance of coal in the existing energy mix but also the need to transition to cleaner forms of energy.

54 Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.

55 Directive (EU) 2015/amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

56 Directive 2009/31/EC on the geological storage of carbon dioxide.

57 Report on the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide (COM/2014/099).

58 Report on the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide (COM/2017/037).

59 Report on the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide (COM/2019/566).

60 Communication on a hydrogen strategy for a climate-neutral Europe (COM/2020/301).

61 Communication on EU Strategy to harness the potential of offshore renewable energy for a climate neutral future (COM/2020/741).

62 Proposal for a Regulation concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending

Regulation (EU) No 2019/1020.

63 Communication on an EU strategy to reduce methane emissions (COM/2020/663).

Report progress in implementing the Energy Union strategy

Since the publication of the Communication setting out its Energy Union strategy in February 2015, the Commission has also published a number of reports assessing the implementation of measures across the five dimensions and providing guidance for the months ahead. The first report was published later in 2015,[64] followed by the further reports in 2017,[65] 2019[66] and 2020.[67]

64 Communication on the State of the Energy Union 2015 (COM/2015/572).

65 Communication on the Second Report on the State of the Energy Union (COM/2017/053), and the Communication on the Third Report on the State of the Energy Union (COM/2017/688).

66 Communication on the Fourth Report on the State of the Energy Union (COM/2019/175).

67 Communication on the Fifth Report on the State of the Energy Union (COM/2020/950).

Annex 5. Fact-checking methodology

In May 2021, SAPEA requested Ea Energy Analyses to undertake a fact-check of the report *A systemic approach to the energy transition in Europe*. The fact-check, which was performed on the version of the report dated 31 May 2021, took place in three phases.

At first, we carefully went over the report identifying all figures or statements that were deemed potentially relevant to 'Fact-check' for each chapter. The statements were divided into two types based on the aim of 'Fact-check', which are:

- **Items to fact-check:** Statements based on concrete data, in which case the validity needed to be verified.
- **Source required:** Statements without specified source, why the validity needed to be assessed.

In a second phase, all potential items to fact-check were prioritised according to their significance for the conclusions of the study. Considering time and resource constraints, only facts with medium or high significance were selected for fact-check.

Thirdly, the actual fact check was performed according to the following conditions:

- the reliability of the sender, indicated with a connected source
- date of the linked source, aiming to verify that the statements were based on as new findings as possible
- knowledge of reports or studies indicating other results

Primarily, the statements were fact-checked based on a comparison of newest investigations and reports by IEA and Eurostat, e.g. Global Energy Review reports by IEA and The EU in the world: 2020 edition by Eurostat.

As a result of the fact-check, each verified statement was categorised according to the following scale: credible, borderline credible or not credible. If a conclusion of a statement is considered borderline or not credible, the required action is formulated.

The overall conclusion of the verification was that no significant inaccuracies were identified.

The findings from the fact-check were compiled in a spreadsheet that was handed over to SAPEA and presented to the chair of the working group and the scientific writer at a video-meeting for their consideration.

The fact-check was undertaken by the following staff from Ea Energy Analyses:

- Anders Kofoed-Wiuff, Partner
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Annex 6. Extensive literature review report

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Objectives

The objective of this evidence review was to establish the state of current knowledge with respect to the European energy system. The literature search aimed to provide an overview of the evidence base by systematically searching, collating and descriptively describing the characteristics of the published and grey literature of the energy system. This will be used to support an Evidence Review Report of SAPEA which informs a scientific opinion by the Group of Chief Scientific Advisors on a systemic approach to the energy transition in Europe. With this knowledge, the European Commission will contribute to the preparation for, acceleration and facilitation of the sustainable energy transition in Europe given the present state of knowledge on possible transition pathways (European Commission, Group of Chief Scientific Advisors, 2020).

Research questions

The literature was collated in order to support the European Commission in answering the following questions:

- How can the European Commission contribute to the preparation for, acceleration, and facilitation of the energy transition in Europe given the present state of knowledge on the possible transition pathways?
    - What types of sustainable energy sources might play a role in the decarbonisation of the EU's energy system?
    - How do different sectors and carbon neutral energy carriers integrate and how can they be exploited?

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- What is known about energy availability and provision for different sectors and how does this vary over time?
- How to secure availability from global markets of affordable, environmentally friendly and socially acceptable supply of raw materials for the energy transition?
- How might the digital world play a role in the future energy system through Smart Grids, the Internet of Things, Industry 5.0 and digitalisation?
- What is known about public acceptance of the energy system?
- Which energy markets and business models will be effective and acceptable?
- What advice can be offered to make the transition acceptable and manageable for our society and business?

Scope

Literature was included if it fell into the following scope.

Inclusion criteria:

- **Population:** EU energy system, across the whole chain from energy production and supply to use in different sectors.
- **Intervention:** Sustainable energy technologies; methods to facilitate acceptable and manageable uptake in society and business.
- **Comparator:** No mitigation; comparison of different mitigation methods; no comparator
- **Outcomes:** Pathways, mechanisms, barriers, drivers and impacts related to de-carbonisation of the EU's energy system. These were captured iteratively and categorised into broad themes.
- **Study design:** Any study type based on quantitative and/or qualitative data will be included. Only published academic journal articles and conference proceedings will be included for the scientific literature. Grey literature was included from organisational databases.
- **Geographical limitations:** Policy and economic research was included from Europe only; energy demand and social impact research was included from Europe and the USA; technology and all other research was included from Europe, USA, Japan and China. Europe will be defined in geographical terms.
- **Language:** Studies published in the English language only.
- **Date restrictions:** All studies included in the review were published between 2015 and 2020. The signing of the Paris Agreement in December 2015 was influential on low carbon transition research.

Methodology

Quick Scoping Review (QSR) methodology (Collins et al., 2015) was used to search, collate and identify the characteristics of academic and grey literature relating to the energy system. QSRs are a structured method of evidence synthesis that aims to minimise bias in the collation and appraisal of evidence (Collins et al., 2015). They can be used to investigate the range, type and amount of research for large topic areas to evaluate current knowledge and identify research gaps (Arksey and O'Malley, 2005; Pham et al., 2014). QSRs are considered more robust and reliable than traditional literature reviews, yet quicker and less costly than full rapid evidence assessments or systematic reviews (Collins et al., 2015). Therefore, a QSR represented a good compromise to address the requirements, timescale and budget of this review. An a-priori protocol was prepared and used to inform the methods that were followed.

Searching for scientific literature

A comprehensive search to capture an unbiased sample of published literature was undertaken in Web of Science and Scopus. Searches were carried out in July and August 2020. The search string used to capture literature was formulated using the PICO key elements of the primary question, in addition to keywords that are specific to the secondary questions.

Search string

The following topic search (TS) string was used in Web of Science and Scopus. A wildcard (*) was used to pick up multiple word endings.

- (TS=(sustainable OR clean OR renewable OR "low carbon" OR "zero carbon")
- AND TS=(energ*)
- AND TS=("energy conservation" OR "energy transition" OR "energy use" OR "energy demand" OR innovation* OR technolog* OR "Green bond*" OR "carbon tax*" OR "emission trad*" OR mitigat* OR adaption OR adoption OR "energy label*" OR systemic OR "path dependenc*" OR transition* OR "carbon* price*" OR "free rid*" OR "green tax reform*" OR "environment* tax* polic*" OR "environment* innovat*" OR "carbon market*" OR "tax* carbon" OR "green bond" OR "fossil fuel*" OR "EU ETS" OR ETS OR "emissions trading scheme" OR "climate change" OR "climate polic*" OR "EU emissions trad*" OR "environmental agreement*" OR "cap and trade" OR "oil price*" OR "CAFE standards" OR "energy efficien*" OR "carbon emission*" OR "gas* price*" OR "coal price" OR "negative emission*" OR "paris agreement" OR "paris accord" OR "CO2 emission*" OR "Carbon Capture" OR "carbon storage" OR "carbon footprint" OR "GHG emissions" OR "greenhouse gas emissions" OR recycling OR "tax on carbon" OR "price on carbon" OR "cheap coal" OR "electricity prices" OR "environmental impact" OR "environmental performance" OR "paris climate" OR "CCS" OR "CCU" OR "environmental regulation" OR "integrated assessment model" OR "abatement cost" OR "carbon abatement" OR automobile OR vehicle OR "fuel tax" OR "energy prices" OR "global warming" OR "taxing energy use" OR "Energy justice"

OR “storage” OR decarbonisation OR decarbonization OR advice OR incentives OR prosumer OR “soci* impact*” OR “soci* acceptance” OR poverty OR “transition advantages” OR consumer* OR behaviour* OR behavior* OR “circular economy” OR “end-user engagement” OR “raw material” OR “smart grid” OR “technolog* constraints” OR “green deal” OR intermittency OR “feed-in tariff” OR “nuclear energy” OR solar OR wind OR “anaerobic digestion” OR hydroelectric OR public OR CCS OR “carbon capture and storage”)

Articles returned

91 258 and 119 428 articles were returned by Web of Science and Scopus respectively. Articles were sorted by relevance, and the first 5000 articles from Web of Science and the first 2000 articles from Scopus were imported into End Note. Initial duplicate removal using the automated function in Endnote resulted in 543 duplicate articles being removed.

The total number of articles imported into systematic reviewing software, Eppi Reviewer 4, was 1605 from Scopus and 4825 from Web of Science, totalling 6457 articles. A further 711 duplicates were removed using the duplicate removal function in Eppi Reviewer. A total of 5746 articles were screened in Eppi Reviewer 4 against inclusion criteria by abstract. The total number of included articles was 2708, which were sorted into categories based on topic area. Figure 12 illustrates the review process.

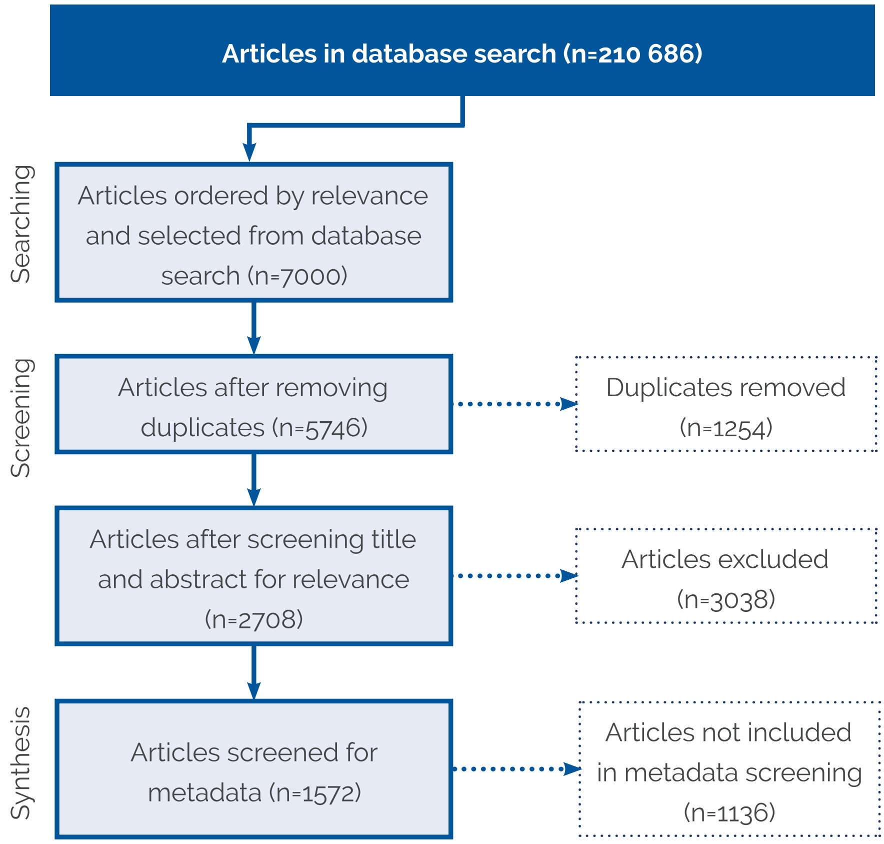

Figure 12. The review process

Metadata extraction

Metadata was extracted from 1572 categorised studies in Microsoft Excel 2016, which detailed article information and summarised the main characteristics of the studies gathered from abstracts (Table 7). Metadata was extracted from the largest and most relevant categories in the evidence base. The most relevant categories were the topic areas thought to be lacking evidence, as defined by the working group. Due to large volume of articles and limited time, the smallest categories were not included in the metadata analysis; these articles were reviewed separately by the experts in the working group.

Category	Metadata extracted
Transition	Authors, Year, Title, Country, Region, Review, Model, Sector, Subject
Policy	Author, Year, Title, Country, Region, Review, Model, Policy type, Subject
Energy demand and supply	Authors, Year, Title, Country, Region, Review, Model, Sector, Subject, Demand, Supply, Consumption, Energy management, Energy planning
Energy efficiency	Authors, Year, Title, Country, Region, Review, Model, General, Technology type, Sector, Subject
Public acceptance	Authors, Year, Title, Country, Region, Review, Model, Sector, Group, Acceptance, Perception, Engagement, Subject
Carbon tax and price	Authors, Year, Title, Country, Region, Review, Model, Sector, Subject Carbon tax/price, Tax/price impact
Technology (Wind)	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject
Technology (Biofuels)	Authors, Year, Title, Country, Region, Review, Model, Fuel type, Technology, Subject
Technology (Bioenergy)	Authors, Year, Title, Country, Region, Review, Model, Biomass type, Technology, Subject
Technology (Hydro)	Authors, Year, Title, Country, Region, Review, Model, Water, Technology, Subject
Technology (Solar)	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject
Technology (Anaerobic digestion)	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject
Technology (Carbon capture and storage)	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject, CCS supported? CCS impact? Support needed?
Technology (Other)	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject, Additional information
Raw materials	Authors, Year, Title, Country, Region, Review, Model, Technology, Subject, Additional information

Table 7. The largest and most relevant categories covering topic areas related to the energy system thought to be lacking evidence and the metadata extracted for each category

Searching for grey literature

Grey literature was searched for and screened separately to the scientific database searches. Grey literature searches were carried out in September 2020. Table 2 displays the databases and search terms used to search for grey literature. Database results were sorted by relevance, where possible. Document types included scientific and technical reports, working papers and organisation publications, dated 2015 onwards. A total of 1086 articles were screened on title and abstract against the relevance criteria. A total of 468 articles were categorised into a Microsoft Excel database of topic areas. 618 articles were excluded based on relevance.

Database	Search term	Articles screened	Articles included
Nordic Flex4RES flagship project	Nordic Energy reports	12	8
SAPEA database of academy reports	Renewable energy	13	13
European Environment Agency	Renewable energy	50	15
OECD iLibrary	Renewable energy	216	21
World Energy Council	Publications	45	36
International Renewable Energy Agency	Publications	4	4
Climatexchange – Scotland's Centre for Expertise on Climate Change	Renewable energy	5	5
DEFRA	Renewable energy policy papers	8	1
UKERC Energy Data Centre	UKERC Research Reports	55	16
The Carbon Trust	Future energy systems EU reports	3	3
EC Joint Research Centre repository	Renewable energy	400	253
European Commission	Energy	16	13
American Council for Energy-Efficient Economy	Renewable energy	77	10
International Energy Agency	Renewable energy	61	59
EUROCASE	Renewable energy	110	11
European Council for an Energy Efficient Economy	Library	11	0
	Total	**1086**	**468**

Table 8. The organisations/databases and search terms used to search for grey literature relating to energy, with the number of articles screened and categorised into main topic areas

Synthesis

Summary statistics were used in Excel to describe and establish the volume, nature and characteristics of the evidence base, alongside a basic narrative synthesis of the key findings of the literature search.

Results

Evidence base overview for all articles included in database

The categories of sub-topic areas were grouped into general themes to provide an overview of the scientific evidence base. Figure 13 displays the main themes of the literature. Most of the literature investigated energy technologies (n=700), followed by energy efficiency (n=476), economic aspects (n=389), social aspects (n=307), policy research (n=267) and energy transition research (n=212). Other (n=173) consisted of multiple subject areas; risk management, sustainable development, barriers and impact of fossil fuel use. Energy demand and environmental aspects were least investigated (n=101).

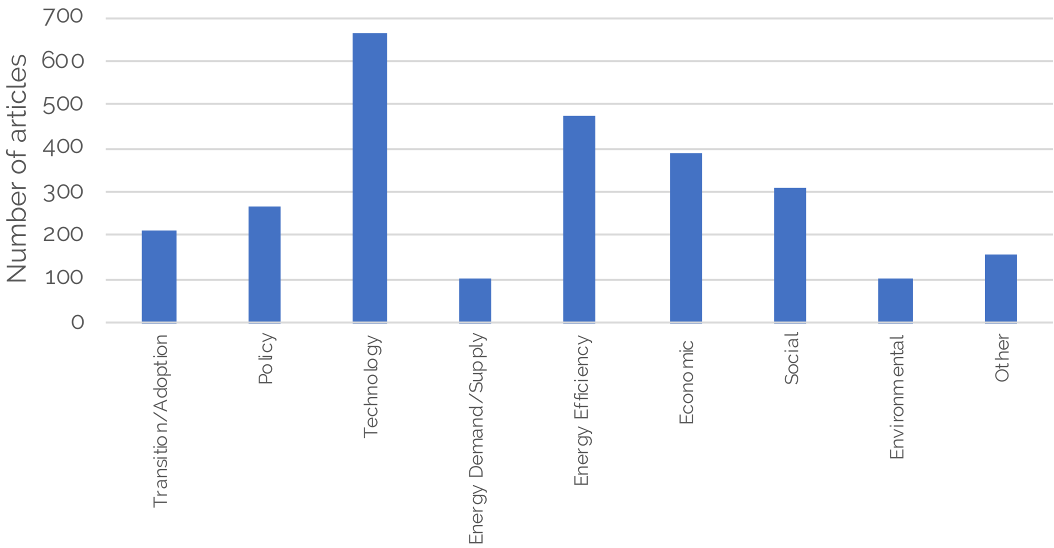

Figure 13. The main themes of the scientific evidence base
The topics in were grouped together into general themes to provide a general overview of the main themes investigated across the evidence base relating to the EU energy system.

Individual topics investigated in the scientific literature

The evidence base consisted of a multitude of topic areas. Figure 14 illustrates the total number of articles assigned to each category in Eppi Reviewer. Energy efficiency (n=476) was the largest category as this topic was not broken down by sector or subject area.

Policy was the second most investigated topic (n=267), followed by public acceptance, perception or engagement (n=237).

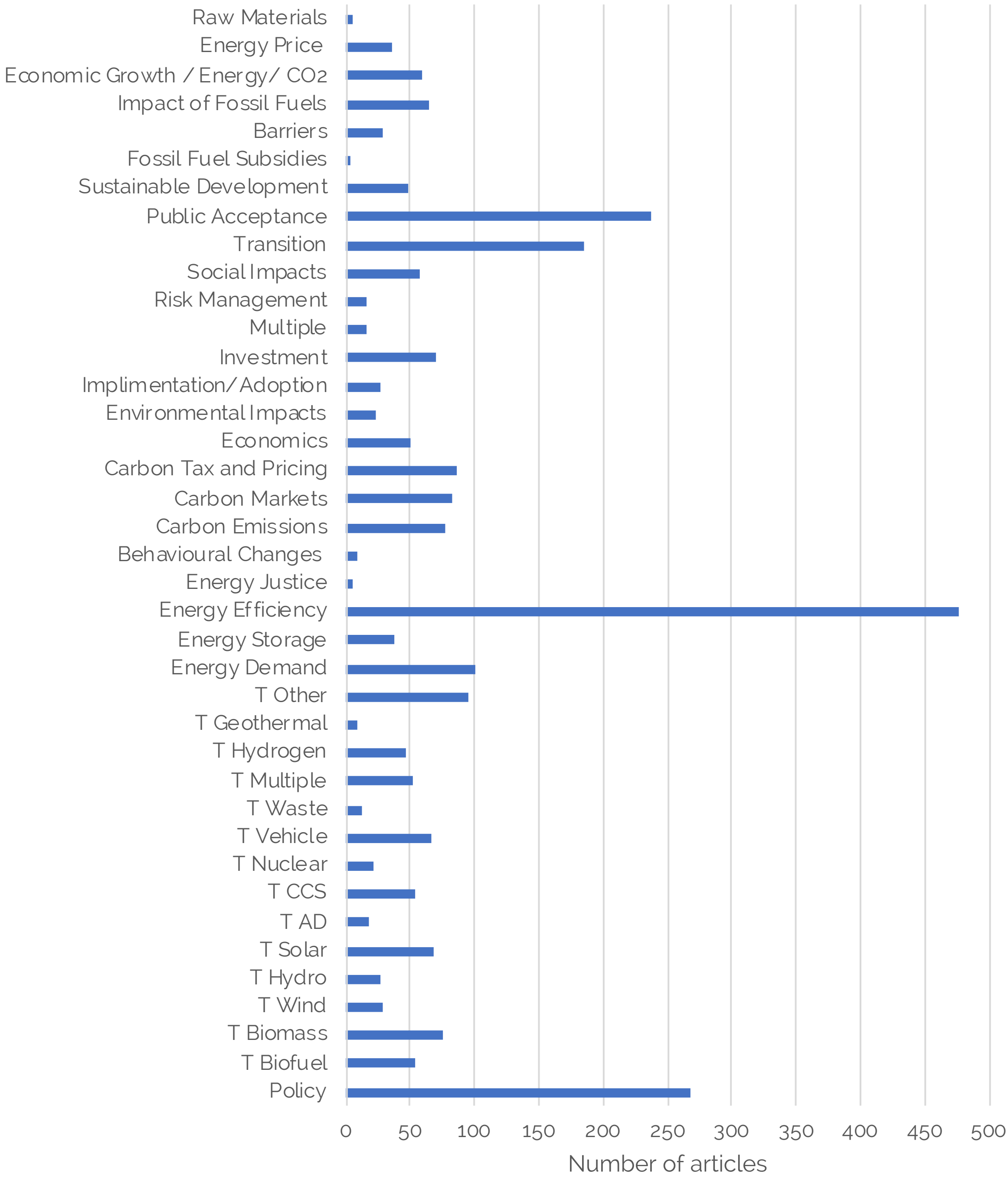

Figure 14. Total number of articles assigned to each category

There was limited research investigating raw materials, energy justice, behavioural changes and fossil fuel subsidies. There was a lack of research investigating effective business models and energy markets relating to the energy transition.

Technologies

Figure 15 displays the types of technologies investigated in the evidence base. The largest number of articles investigating the technological aspects of transition was categorised as other (n=95). This category included smart grids, smart cities, combined heating and cooling systems, hybrid power systems, microgrids and various other technologies that could not be attributed to the common specific technology types. The single most investigated renewable technology was photovoltaic and thermal solar (n=72), followed by biofuel (n=71) and bioenergy (n=69). Vehicle technologies (n=67) included electric and hybrid vehicles, electric vehicle batteries and alternative transport systems. The least investigated low carbon technologies were geothermal, energy from waste processing, nuclear and anaerobic digestion. Nuclear is a low carbon technology and not renewable.

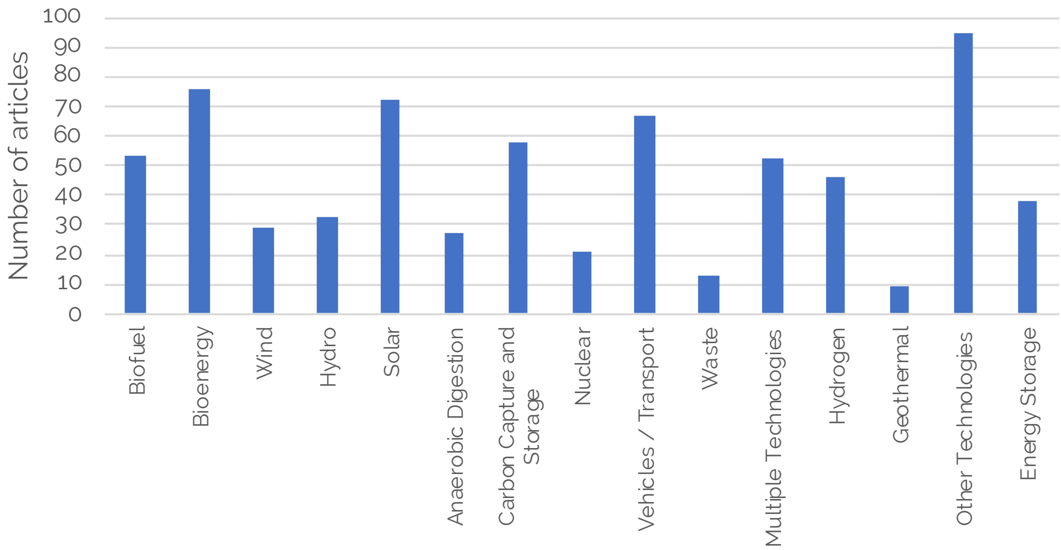

Figure 15. The number of articles in the scientific evidence base investigating different energy production technologies

Economics

Carbon tax and price (n=87), followed by carbon market (n=82) and investment (n=70) were the most investigated topics regarding the economic aspects of the energy system, energy technologies, or the energy transition in the evidence base (Figure 16). The economic growth/energy/CO_2 category investigated the relationship between economic growth and energy use on CO_2 emissions or climate impacts (n=59). A common theme within this topic area was reducing Gross Domestic Product to achieve decarbonisation goals.

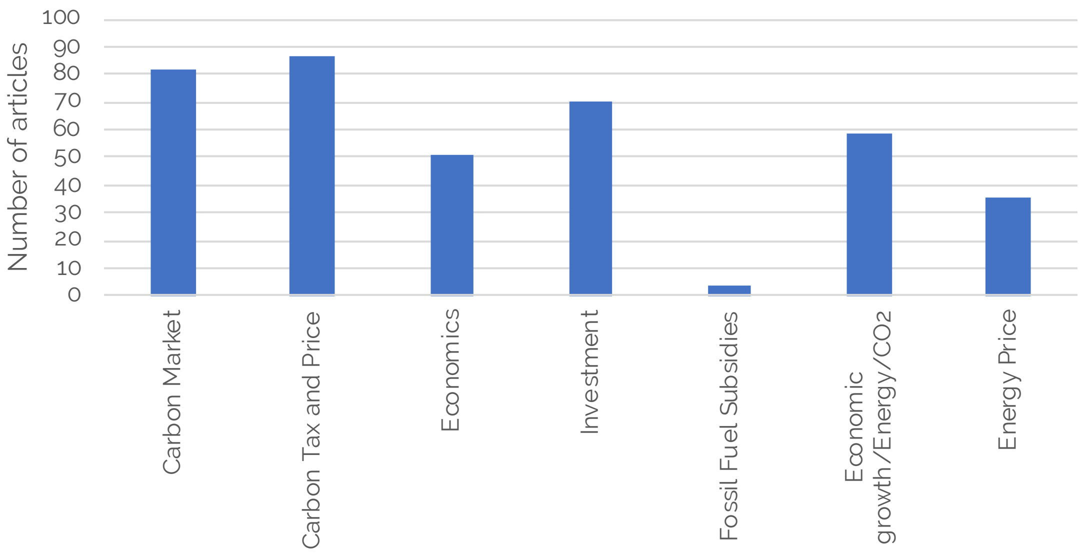

Figure 16. The number of articles in the scientific evidence base investigating topic areas relating to the economic aspects of the energy sector, energy technologies or the energy transition

Social aspects

Of social aspects, public acceptance, perception and engagement relating to the energy sector, specific technologies or the energy transition was most investigated (n=237), followed by social impacts (n=57) (Figure 17). There was considerably less research investigating energy justice and behavioural changes relating to energy.

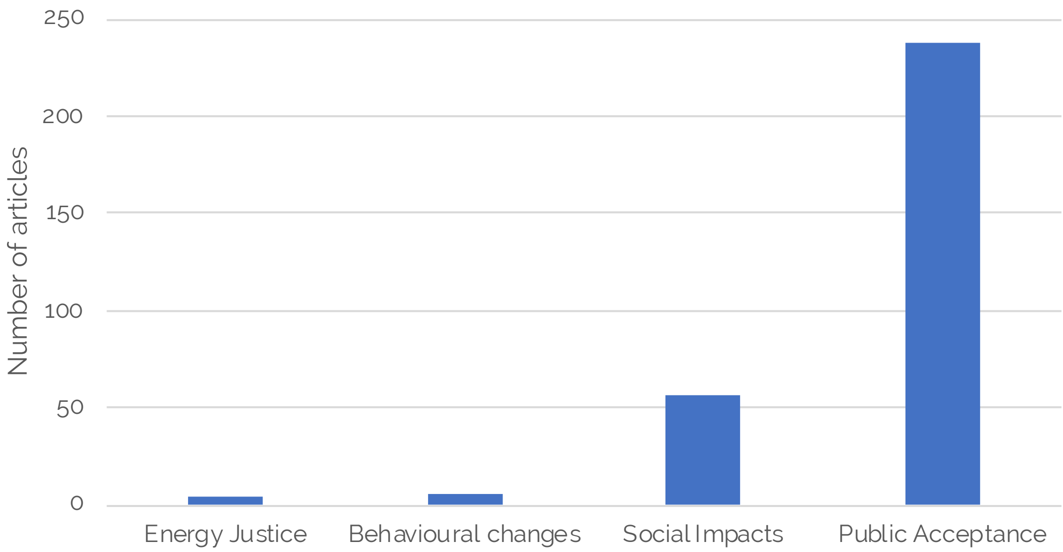

Figure 17. The number of articles in the scientific evidence base investigating social aspects of the energy sector, energy technologies or the energy transition

Metadata

The following metadata was extracted from a total of 1572 articles in the database to support the European Commission in answering the research questions.

Types of literature

Of the 1,572 studies, the majority consisted of primary research (n=1,478) and considerably less were review articles (n=94). Figure 18 illustrates the types of literature for the different topic areas.

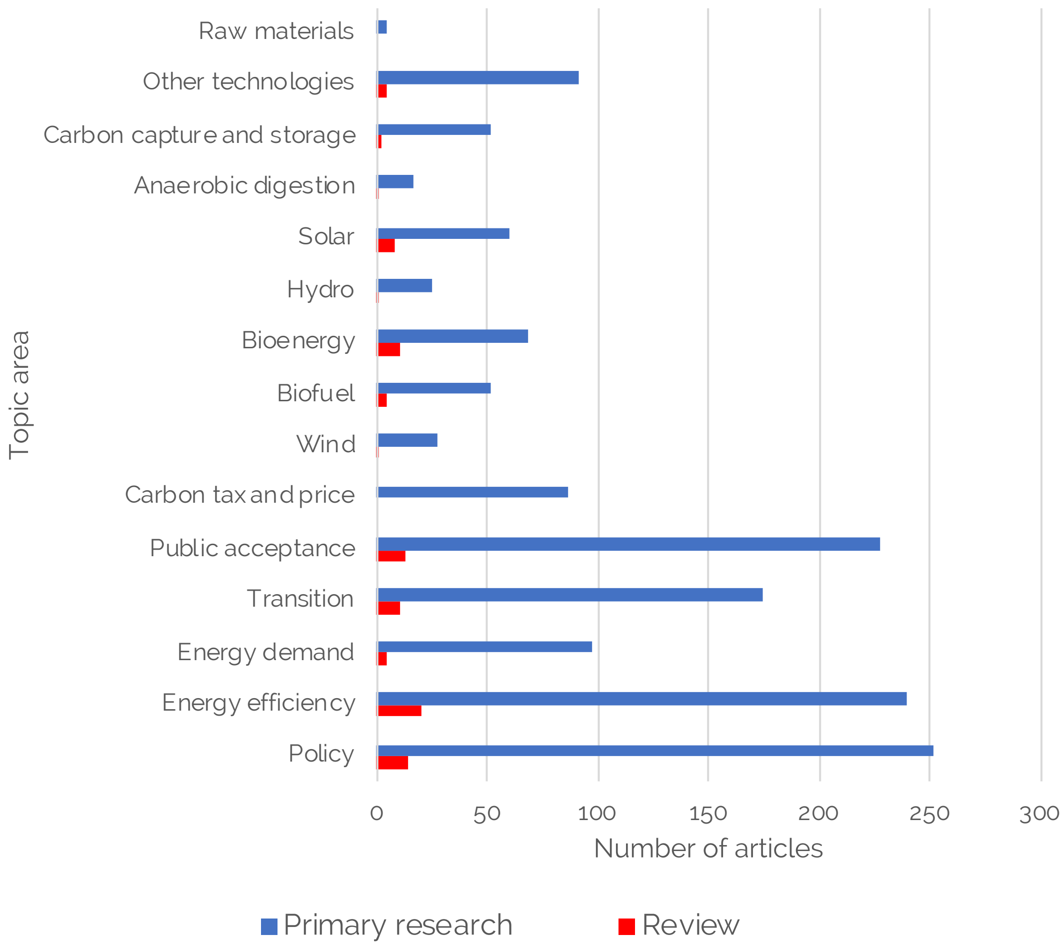

Figure 18. Types of literature in the scientific evidence base investigating the different topic areas.

Technologies

The solar research mostly investigated PV solar, followed by thermal solar. The subject areas were varied with limited patterns within the literature. Sustainability was the most common topic within the bioenergy and biofuel research, followed by energy efficiency. For bioenergy the most common feedstock investigated was woody biomass.

Transition pathways

Technological changes were the most investigated transition pathway in the scientific literature (n=53). The second most investigated pathway was implementing a carbon tax or carbon price (n=20), followed by renewable energy investment, energy production subsidies or energy pricing (n=15), increased energy efficiency or demand reduction (n=10) and increasing social acceptance of energy transitions (n=8) (Figure 19).

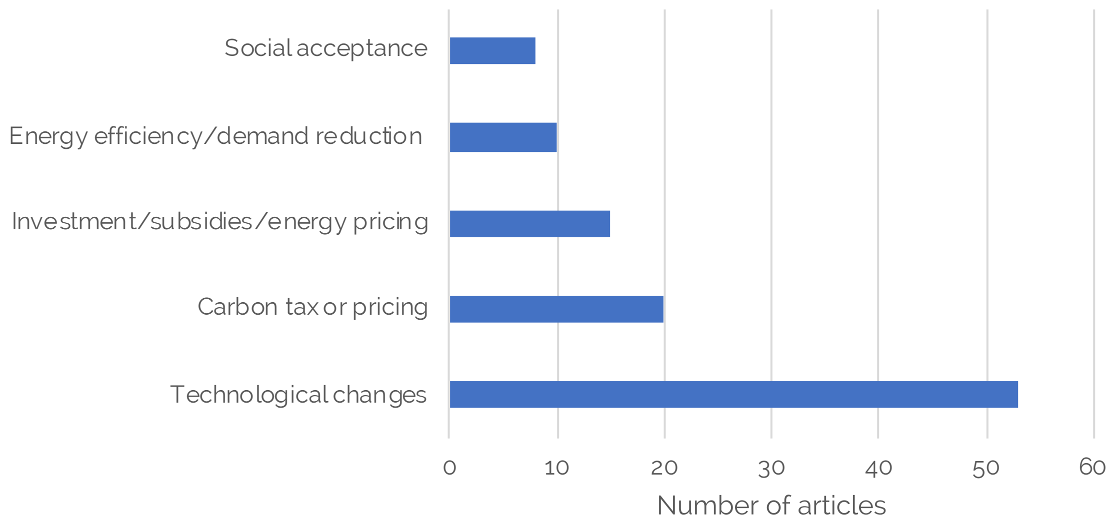

Figure 19. The number of articles investigating the main energy transition pathways in the scientific evidence base

Policy types

The main policy type investigated was energy (n=134), followed by climate (n=85) (Figure 20).

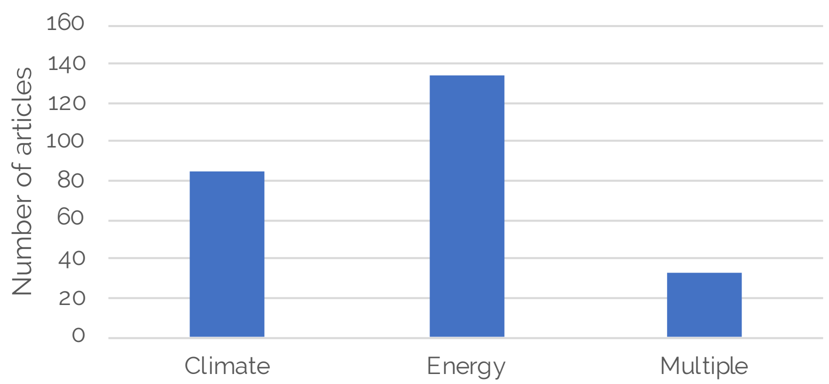

Figure 20. The number of articles in the scientific evidence base investigating different policy types relating to the energy system, energy technologies or the energy transition

Energy demand and supply

The number of articles investigating energy demand (n=46), supply (n=47) and consumption (n=45) were similar. Within these articles energy management was a key theme (n=59) as was future energy planning (n=79). (Figure 21).

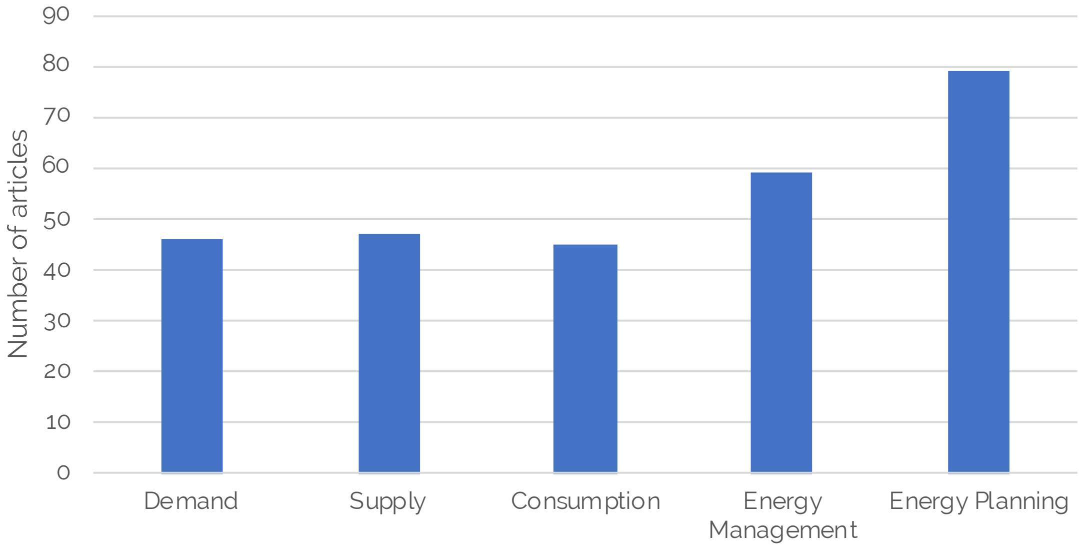

Figure 21. The number of articles in the evidence base investigating energy demand, supply, consumption, management and planning of the energy system and different sectors
The total number of articles (n=276) is higher than the total number of articles screened in the energy demand and supply category (n=100) as some articles investigated multiple themes.

Both energy demand and energy supply were mostly investigated for the energy sector. The residential sector was second most researched, followed by heating. For energy supply, the electricity sector was second most investigated. There was limited research for all other sectors.

Energy demand:

- energy 22
- residential 6
- heating 4
- electricity 2
- gas 2
- ICT 2
- raw materials 2
- agriculture 1
- building 1
- industry 1
- logistics 1
- renewables 1
- telecommunications 1
- water 1

Energy supply:

- energy 22
- electricity 4
- heating 3
- bioenergy 2
- gas 2
- raw materials 2
- renewables 2
- agriculture 1
- biofuel 1
- ICT 1
- manufacturing 1
- residential 1

- solar 1
- telecommunications 1
- water 1

Energy efficiency

The list below indicates the number of articles investigating energy efficiency in different sectors. Most of the literature investigated the energy efficiency of the building sector, followed by the energy sector, manufacturing, ICT and industry:

- building 134
- energy 99
- manufacturing 47
- ICT 39
- industry 25
- policy 17
- residential 17
- shipping 10
- economy 8
- agriculture 7
- construction 7
- NA 7
- transport 6
- water 6
- government 5
- milling 4
- retail 4
- chemical 3
- food 3
- healthcare 3
- ports 3
- distillation 2
- forestry 2
- logistics 2
- multiple 2
- paper 2
- research 2
- supply chain 2
- aluminium 1
- aviation 1
- conservation 1
- corporate 1
- education 1
- pharmaceutical 1
- planning 1
- refinery 1
- tourism 1
- trade 1

Most of the research investigated energy efficiency in urban areas, followed by the energy efficiency of technologies (Figure 22). An additional 260 energy efficiency articles were not categorised either because they were not relevant to a specific theme, or the information was not available from the abstract.

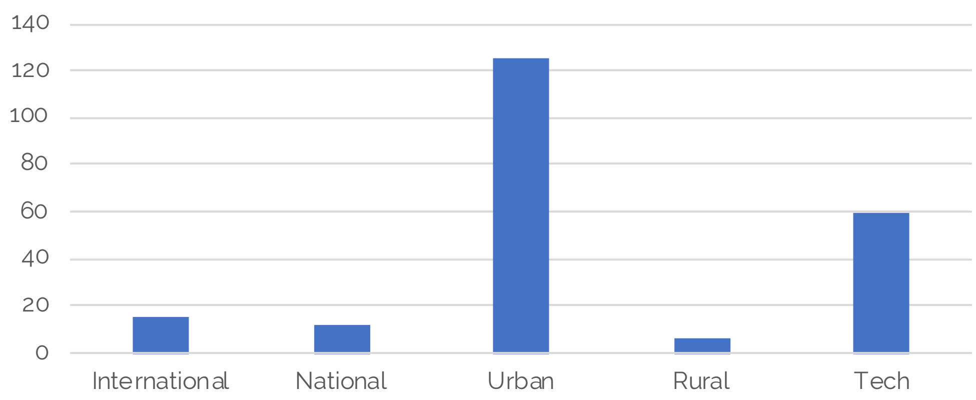

Figure 22. The number of articles investigating general sub-themes within the energy efficiency scientific evidence base

Public acceptance, perception and engagement

In the public acceptance, perception and engagement category, most studies investigated public acceptance of energy related topics (n=206), followed by perception (n=123) and engagement (n=30) (Figure 23).

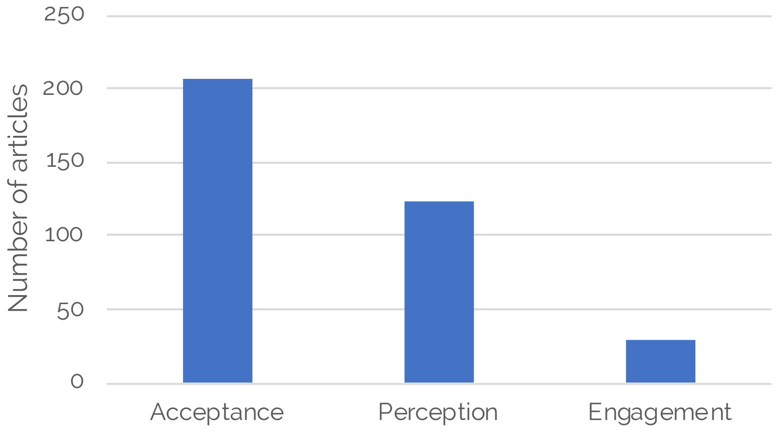

Figure 23. The number of studies investigating the public acceptance, perception or engagement of the energy sector, energy technologies or the energy transition within the scientific evidence base The number of articles (n=359) is larger than the total number of articles screened (n=228) as some articles investigated multiple aspects.

The general public was the most investigated group in the evidence base, followed by locals, household and communities. A common theme among studies investigating locals was renewable energy infrastructure, while energy efficiency and cost was mostly assessed for household groups:

- public 122
- locals 28
- household 20
- communities 16
- stakeholders 11
- consumers 10
- corporate 4
- experts 3
- investors 3
- students 3
- teachers 2
- tourists 2
- farmers 1
- institutional 1
- manufacturers 1
- recreationists 1

Public acceptance, perception and engagement of the energy sector was most investigated. Of renewable energy technologies, wind infrastructure was most assessed in relation to public, local and community acceptance.

Renewable technology:

- wind 45
- solar 11
- bioenergy 10
- biofuels 5
- hydro 5
- geothermal 3
- biogas 1
- tidal 1

Energy and technologies:

- energy 62
- electricity 18
- carbon capture and storage 4
- heating 3
- hydrogen fuel 2
- fossil fuel 1
- nuclear 1
- power-to-gas 1

Other:

- policy 26
- buildings 14
- manufacturing 3
- marine 3
- media 2
- multiple 2
- research 2
- transport 2
- economy 1

Raw materials

There was a lack of research investigating raw material supply. Six articles were screened into this category and the topic areas of the studies were varied.

Smart technologies

Ten articles in the “other technologies” category investigated smart grids or smart cities, common themes throughout the literature were infrastructure implementation and design, and challenges. One article investigated the Internet of Things, relating to technologies.

Grey literature

Grey literature overview for all articles included in database

The most common topics investigated in the grey literature were similar to the scientific literature. Figure 24 illustrates that renewable energy technologies (n=147) was most common topic addressed in the grey literature. Energy transition was the most common single topic investigated (n=106), followed my energy efficiency (n=65) and energy demand or supply (n=57).

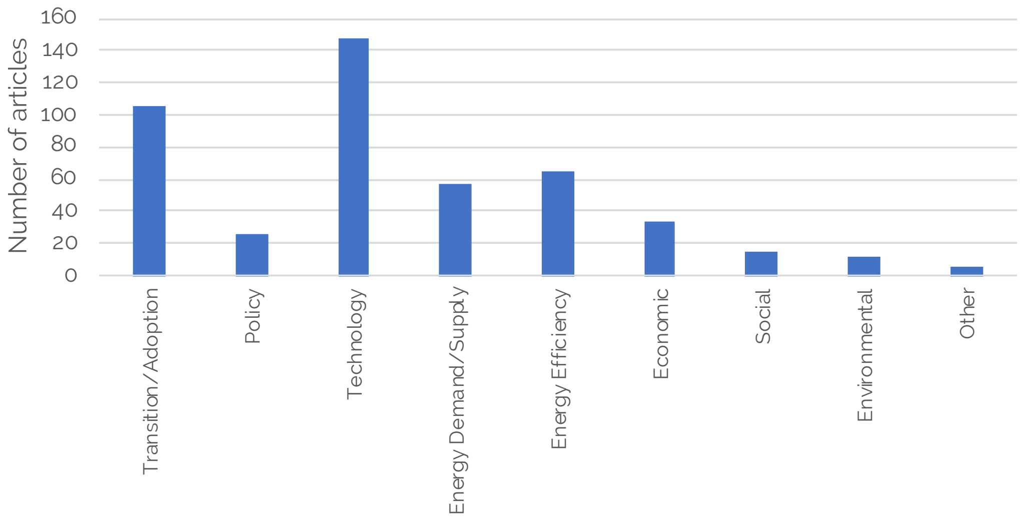

Figure 24. The key energy-related themes investigated in articles collated from organisational searches, and number of articles investigating each theme.

Individual topics investigated in the grey literature

Of all the individual topics, most of the grey literature focused on transition (n=103). The next most investigated categories were energy efficiency (n=65), energy demand (n=49), investment (n=28), bioenergy technology (n=27) and policy (n=26) (Figure 25). Grey literature investigating public acceptance, perception or engagement and environmental aspects was limited compared to the scientific evidence base. Additionally, as the grey literature search was carried out after the scientific literature search, there were reports addressing the impact of Covid-19 on the energy transition.

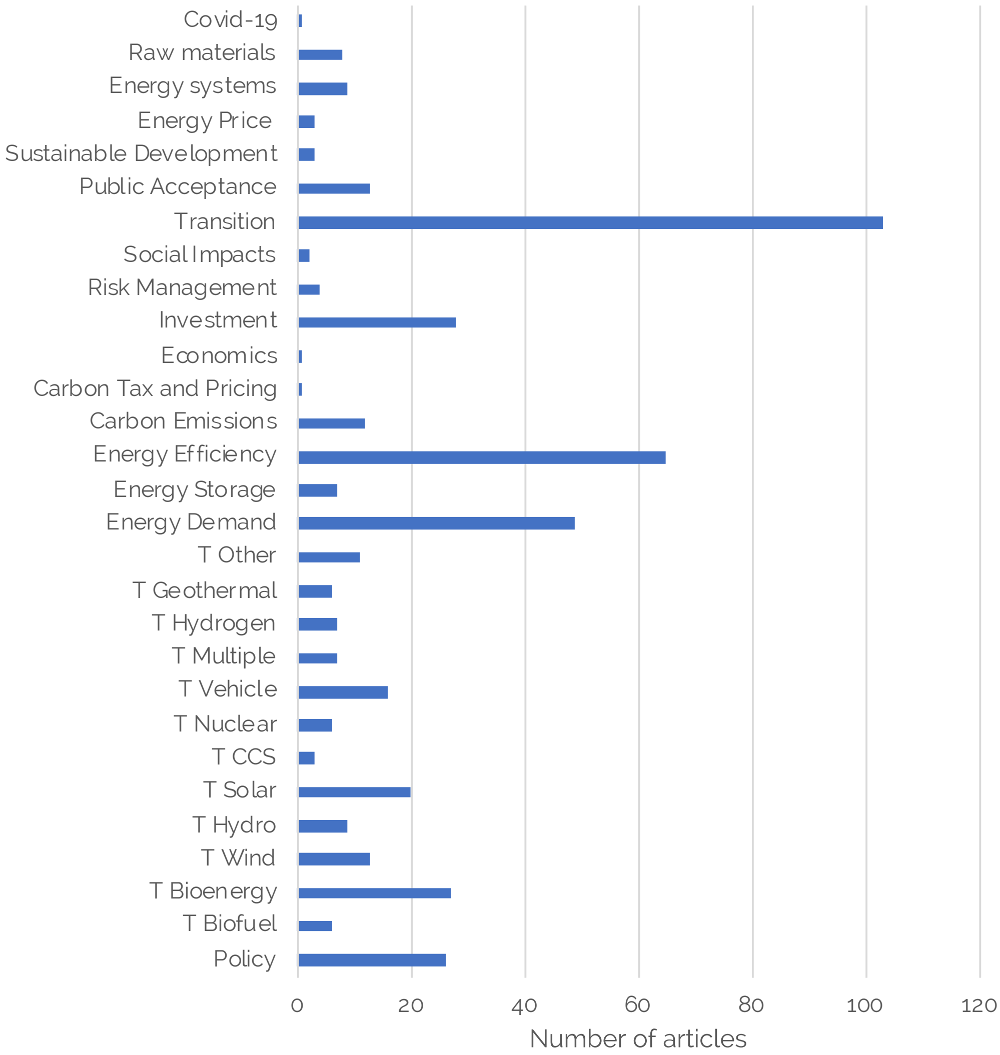

Figure 25. The topic areas related to renewable energy and number of reports investigating each topic area in the literature collated from organisational searches (grey literature)
T = 'technology'

The most investigated technology types within the grey literature were bioenergy (n=27) and solar energy production (n=20), followed by vehicle technologies (n=16). Additionally, literature investigating whole energy systems (n=9) was noticeable in the grey literature and there was research investigating the impacts of Covid-19 (n=1) on the energy transition.

Discussion

The quantity of scientific research investigating solar, biofuel, bioenergy and vehicle technologies suggests that these energy production sources and technologies may play a key role in the decarbonisation of the EU's energy system. Sustainability was a common theme in the bioenergy and biofuel literature. The grey literature followed a similar pattern; the most investigated technology types were bioenergy and solar energy production, followed by vehicle technologies. Technology was the most investigated theme in the grey literature, indicating that many organisations are investigating renewable energy technologies in preparation for the energy transition.

The research exploring transition pathways mostly investigated technological changes followed by a carbon tax or market. This indicated that scientists perceive these pathways to be most important for the energy transition. The single most investigated topic in the grey literature was transition, suggesting that many organisations are focussing their efforts and preparing for the decarbonisation of the EU's energy system.

Most of the research investigating energy demand and supply focused on the energy sector, followed by residential for energy demand and electricity for energy supply. There was limited research regarding the energy demand requirements of many sectors not related to energy production.

There was substantial research investigating the public opinion of the energy system and related policies, with a focus on local community impacts in areas where renewable energy infrastructure is increasing. This indicates that the social impacts of the energy transition are being considered in the research.

The results suggest that improving the energy efficiency of urban areas and various technologies will play a vital role in the decarbonisation of the EU's energy system. The key sectors currently focussing on energy efficiency efforts are building, energy production, manufacturing, ICT and industry.

There was a lack of research investigating raw materials, smart grids and the impact of the Internet of Things, digitalisation and Industry 5.0 on the energy transition. Research investigating smart grids and smart cities mostly explored infrastructure implementation and challenges.

The grey literature had a small number of reports investigated energy systems; however, this topic area was lacking in the scientific evidence base. Furthermore, as the grey literature search was undertaken later in the year, there was research investigating the impacts of Covid-19 on the energy transition, which may become a more prominent issue in the future.

A complete and comprehensive overview of the total evidence base could not be undertaken in this review due to the quantity of literature available and resource constraints. This review provides a five year snapshot of the most relevant literature in the evidence base rather than collating all literature on the energy system. Hence, some of the observed limitations may be influenced by this. Additionally, articles were screened on abstract only and the meta-data is based on limited information from each article. Finally, the articles were searched for in the English language only and therefore, this excluded relevant research.

The collation and meta-analysis of the literature provides a snapshot view of the present state of knowledge regarding the EU energy system and possible transition pathways, which can be used to support a scientific opinion and the European Commission in delivering policy advice on the energy transition. Further research is required to understand energy demand requirements for the EU energy transition. Additionally, further investigations into smart energy and digital tools is required in relation to the energy system.

Conclusion

There was a substantial body of research investigating the decarbonisation of the EU energy system. Of the renewable energy technologies solar, biofuel and bioenergy technologies may play a vital role in the energy transition. Technological changes were the most investigated energy transition pathway, followed by a carbon tax. Improving energy efficiency has been widely investigated in the urban building sector, energy sector and manufacturing, these sectors may be key players to achieve decarbonisation goals. The evidence base considered energy demand and supply for the energy sector, followed by residential, however, there was limited research investigating the energy demand requirements of other sectors. Public acceptance of the energy system was widely evaluated, focusing on local community impacts and renewable energy infrastructure.

There was a lack of research investigating raw material supply, smart energy, digitalisation, acceptable business models and the temporal energy demand requirements for many sectors.

The evidence base provided an overview of the topic areas and general themes investigated in the scientific and grey literature relating to energy. The quantification of the literature across the various topic areas established the topics most and least investigated, which provided an overview of what is known, what is partially known and what is currently unknown about the European energy system. The results presented here, and the collated evidence base supplied to the working group supported the European Commission in forming a scientific opinion on transition pathways for the decarbonisation of the EU's energy system.

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Annex 7. Glossary of terms

- **Bioenergy:** Energy derived from any form of biomass or its metabolic by-products.
- **Bioenergy with carbon capture and storage (BECCS):** Carbon capture and storage technology applied to a bioenergy facility which can, depending on the total emissions of the BECCS supply chain, lead to negative emissions of carbon dioxide.
- **Biofuel:** A fuel, generally in liquid or gaseous form, produced from biomass. E.g. bioethanol, biodiesel, and biogas.
- **Biomass:** Living or recently dead organic material.
- **Biogenic:** Produced or originating from a living organism.
- **Capacity market:** An electricity system market arrangement that provides payment for the provision of reliable sources of generating capacity, alongside their electricity revenues, to ensure security of electricity supply.
- **Carbon border adjustment mechanism (CBAM):** A policy mechanism that puts a carbon price on imports of certain goods from outside a particular region (such as the EU) in order to avoid carbon leakage.
- **Carbon leakage:** The situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with less strict emission constraints. This could lead to an increase in their total emissions.
- **Carbon price:** The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits.
- **Carbon neutrality:** See **net zero emissions**.
- **Carbon sinks:** A reservoir (natural or human, in soil, ocean, and plants) where carbon dioxide is stored.
- **Carbon capture and storage (CCS):** A process in which a relatively pure stream of carbon dioxide from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere.
- **Carbon capture and utilisation (CCU):** A process in which carbon dioxide is captured and then used to produce a new product. If the carbon dioxide is stored in a product for a climate-relevant time horizon, this is referred to as carbon capture, utilisation and storage (CCUS). Only then, and only combined with carbon dioxide recently removed from the atmosphere, can CCUS lead to carbon dioxide removal.
- **Circular economy:** an economic system based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.
- **Combined heat and power (CHP):** The simultaneous production of both useful heat and electricity in a single process or unit.
- **Effort-Sharing Regulation (ESR):** EU legislation that establishes binding annual greenhouse gas emission targets for member states on emissions from most sectors not included in the EU Emissions Trading System (EU ETS), such as transport, buildings, agriculture and waste.
- **Electric road system:** A road which supplies electric power to vehicles travelling on it.
- **Electric vehicle (EV):** A vehicle whose propulsion is powered fully or mostly by electricity. Includes battery electric vehicles (BEVs) whose sole propulsion is electric, and plug-in hybrid electric vehicle (PHEV) whose propulsion is mostly electric (which can be charged by an external power source) but extra power and distance are provided by an internal combustion engine.

- **European Union Emissions Trading Scheme (EU ETS):** An EU wide 'cap and trade' system for trading greenhouse gas emission allowances which effectively sets an EU carbon price.
- **Demand-side management:** Measures that aim to reduce the demand for electricity and other forms of energy required to deliver energy services.
- **Direct air capture (DAC):** Chemical process by which carbon dioxide is captured directly from the ambient air, with subsequent storage.
- **Dispatchable power:** Electricity generating capacity that can be modulated up and down as required.
- **District heating:** The distribution of heat through a network to one or several buildings using hot water or steam produced centrally.
- **DSO:** Distribution System Operator.
- **Electrolysis:** An electrochemical reaction to split water into its components of hydrogen and oxygen.
- **Euratom:** European Atomic Energy Community.
- **Flow batteries:** A type of rechargeable battery in which electrolyte flows through one or more electrochemical cells from one or more tanks.
- **Fuel cells:** A device that generates electricity through an electrochemical reaction rather than combustion.
- **Geothermal energy:** Heat generated in the sub-surface of the earth and used directly for heating or harnessed to generate electricity.
- **Green biorefinery:** An industrial system of sustainable, environment- and resource-friendly technologies for the comprehensive material and energy use or recovery of renewable raw materials in the form of green and waste biomass.
- **Greenhouse gas (GHG):** A group of gases contributing to global warming and climate change.
- **ICT:** Information and communications technology.
- **IEA:** International Energy Agency.
- **IoT:** Internet of Things.
- **IPCC:** Intergovernmental Panel on Climate Change.
- **Negative emissions:** Removal of greenhouse gases from the atmosphere by deliberate human activities, i.e. in addition to the removal that would occur via natural carbon cycle processes.
- **Net zero emissions:** Net zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon). Also known as **carbon neutrality**.
- **Nimby:** Opposition to the locating of something considered undesirable (such as a wind farm) in one's neighborhood; an abbreviation of 'not in my backyard'.
- **Nord Pool:** Nordic electricity exchange.
- **Power-to-X:** using electricity to produce other forms of final energy, fuel, and chemicals. The 'X' could represent heat, gas, hydrogen, liquid or other options.
- **PRIMES model:** One of a range of modelling tools used by the European Commission in impact assessments and analysis of policy options. It is an EU energy system model which simulates energy consumption and the energy supply system. https://ec.europa.eu/clima/policies/strategies/analysis/models_en
- **Prosumer:** An energy consumer (e.g. household) which simultaneously may also consume and produce electricity and sell it into the grid or to the neighbourhood.
- **Rare earth elements (REE):** A group of seventeen chemical elements that includes yttrium, scandium and the 15 lanthanide elements. They are metals with similar properties that have a wide range of applications in energy technologies such as

rechargeable batteries, catalytic converters, magnets, and ICT.

- **RDI:** Research, development, and innovation.
- **Second-life batteries:** Reuse of used electric vehicle batteries for stationary electric storage applications.
- **Solar PV:** Solar photovoltaics.
- **Sector integration/coupling:** The coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors.
- **Small modular reactor (SMR):** Nuclear reactors that are smaller than conventional reactors, designed with modular technology using module factory fabrication.
- **Synthetic fuel:** Traditionally, a liquid or gaseous fuel derived from a source such as coal, shale oil, tar sands, or biomass, used as a substitute for oil or natural gas. In this report, the term is used to describe a fuel derived using renewable energy sources only.
- **TSO:** Transmission System Operator.
- **Vehicle-to-grid (V2G):** Using electric vehicle battery capacity to feed electricity into the electricity grid.
- **Variable renewable electricity (VRE):** Renewable electricity sources such as solar and wind power whose output vary over time e.g. due to weather conditions.

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