Chapter 16
Summary, Conclusion and Recommendations

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Abstract This chapter summarizes insights and measures to decarbonize the European energy system until the year 2050, as analyzed in the previous 15 chapters, and emphasizes the considerable efforts required to coordinate and govern the targeted energy transition. With increasing aspiration regarding the targeted climate policy the more marked are the required efforts. The reference scenario Mod-RES seems to be well achievable from today's perspective, while much more additional efforts have to be taken to achieve the more ambitious High-RES scenarios. However, even the High-RES scenarios are less aspiring compared to the aims defined in the European Green Deal. Finally, this chapter highlights conclusions and policy recommendations for a cross-sectoral decarbonization as well as for its resulting environmental, social and health impacts.

16.1 Summary

The core objective of the book is to analyze and evaluate the development toward a low-carbon energy system in Europe up to the year 2050 with focus on flexibility options—i.e., storages, grids, electric vehicles, demand side management (DSM) and power–to–x technologies as well as curtailment to support a better system integration of renewable energy sources (RES). To achieve the target of significant greenhouse

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gas emission reductions or even being climate neutral until 2050, considerable efforts are a condicio sine qua non. Above all, robust CO_2 price incentives and a strong reduction of the CO_2 emission cap are essential. In the scenarios, CO_2 prices range between moderate 34 EUR/t_{CO2} (in Mod-RES) and 70 EUR/t_{CO2} (in High-RES) in 2030 and between 90 EUR/t_{CO2} and 150 EUR/t_{CO2} in 2050. While the Mod-RES scenario seems to be well achievable from today's perspective, but fails with regard to the targeted emission reduction in 2050, both High-RES scenarios are much more ambitious and need additional, more effective policy measures and incentives than today (cf. Chapter 2). Besides a strong carbon price incentive, results show that the following *four main pillars* are the basis of a successful climate-neutral transformation of the energy system in the next decades:

- (Significant) increase of renewable energy sources (RES) to generate almost CO_2-neutral electricity as called for in the European Green Deal—a factor of 4 to 6 of today's RES installations in 2050. Challenges occur to integrate these large amounts of additional renewable energy sources. Results have shown that in the High–RES decentralized scenario demand side flexibility (e.g. PV–battery systems, battery electric vehicles, heat pumps, etc.) is more important than in the High–RES centralized scenario, where infrastructure for sector coupling as well as power grids play a crucial role. In both High–RES scenarios back-up capacities are still highly relevant.
- Increase of energy efficiency to reduce energy consumption while maintaining the energy service levels and thus contributing to a lower energy demand at all scales and sectors (industry, mobility, buildings etc.).
- Increase of electrification by means of sector coupling (power-to-x technologies), to make use of higher shares of renewable energy sources for providing heat and mobility services.
- Use of CO_2-neutral hydrogen for energy services in particular in industry and for energy needs with high energy density.

Hereafter preconditions and instruments needed to implement strategies based on these four pillars are explicated and some related implications are highlighted.

16.1.1 Electricity Sector

16.1.1.1 Economic Incentives

A strong carbon price increase until 2050 drives the electricity supply side to a fuel switch toward gas-fired power plants[1]. Up to renewable shares of 80% across Europe, investments in electricity storage technologies are barely cost-effective. Ensuring a proper CO_2 price signal as well as support for multi-purpose use of utility-scale electricity storage is crucial in order to steer the future technology mix.

[1] It is assumed that the transformation will mainly be driven by costs (relative cost-effectiveness).

Despite the strong growth of renewable capacities substituting large amounts of fossil fuels, carbon capture and storage is necessary for remaining fossil fuel technologies (providing back-up capacities) to achieve the emission reduction targets in the High-RES scenario.

16.1.1.2 Regulations

The still uncoordinated national energy policies, manifested in the diverse national capacity remuneration mechanisms (CRMs), could lead to substantial cross-border effects in the future. Interconnectors should therefore be eligible to participate in capacity remuneration mechanisms of neighboring countries in order to avoid market distortions. Alternatively, a coordinated European capacity remuneration mechanism maybe considered.

On the electricity demand side, current conditions are not sufficient to establish functioning markets for demand side management. The participation of demand side management in the reserve markets should therefore be facilitated. Moreover, highlighting existing successful examples of demand side flexibility provision may alter the risk perception of companies and may raise additional demand side management potential.

16.1.2 Demand Side Sectors

16.1.2.1 Industry Sector

In the industry sector there are still untapped potentials of energy and material efficiency as well as process and energy carrier substitution. Depending on the industry sector and the different process various options are available to curb demand and GHG emissions. Examples are high-temperature heat pumps that better integrate different processes or electrical or physical approaches that replace thermal ones. To implement these options a broad set of measures is required to complement the main instrument, which is setting a price to carbon (through an effective cap in the ETS and through a CO_2 tax in the case of the non-energy intensive sectors). The main economic instrument needs to be complemented by specific measures such as audits, low-interest loans and ongoing education and training, fostered and complemented by entrepreneurial innovation. Next to tapping these existing potentials substantial research and development activities need to take place in the coming decade, in order to have ready new process technologies and innovations for the industry sector by 2030.

16.1.2.2 Transport Sector

A bundle of complementary measures is required to support the transition of the transport sector toward low-emission mobility. The introduction of fuel efficiency and CO_2 standards for new vehicles of all kinds represents a fundamental instrument to reduce greenhouse gas (GHG) emissions. Moreover, investments in the rail and public transport systems are needed to increase the attractiveness of these efficient travel modes. Policies supporting electric drive technologies by increasing their financial attractiveness over conventional fuel vehicles include vehicle registration taxes, road charges and fuel taxes. These measures are instrumental during the rollout of technologies (short-term), while electric drive technologies will likely be competitive in mid-term due to cost decrease based on high learning rates, especially for private car and light duty vehicles. Biofuels and synthetic fuels are less efficient options, yet reasonable for aviation and ships, where mature low-emission drive technologies will not be developed in the near future.

16.1.2.3 Buildings and Heating Sector

Current EU regulations regarding residential and tertiary buildings address only new buildings and a part of appliances. However, additional effort is required to increase the energy efficiency of the existing building stock, both in terms building technologies (e.g. lighting, ventilation, pumping) and in terms of thermal demand for heating and cooling. Indeed, for the deployment of renewable energy sources refurbishment is almost a prerequisite, due to technical reasons and due to limited availability of RES. With regard to district heating (DH), significant GHG emission reductions of 60–85% in 2050 are achievable. Particularly in countries with already well-developed district heating networks, biomass will play an important role in substituting fossil fuels. With the development of low-energy buildings, district heating and other innovative energy networks should be expanded in regions where sufficient spatial heat and cold density exists and/or if other options to tap RES are difficult or hardly feasible to implement with decentralized systems (e.g. to tap ambient heat from lakes, rivers, ground sources and to provide it to buildings in urban contexts).

16.1.3 Environmental Impacts

Two main environmental impacts could impede the transition process for a low-carbon electricity system identified in this book. Land use is significantly increasing with the expansion of renewable technologies and requires attention to be paid to infrastructure planning among EU member states with different regulations. Furthermore, the demand for metal will significantly increase. Results indicate that the transformation process to a low-carbon electricity system is highly dependent on the availability of metals to produce technologies for intermittent electricity generation.

In the case of battery based approaches for storage and mobility, metals strongly based on so-called rare earths are used.

16.2 Conclusions and Recommendations

16.2.1 Electricity Sector

16.2.1.1 Low-Carbon Supply Technologies and Flexibility Options

Besides the increase of renewable energy sources, a fuel switch toward gas-fired power plants can be observed. While CO_2 prices in Mod-RES are not sufficient to incentivize investments in carbon capture and storage (CCS) technologies, CCS becomes favorable in High-RES between 2040 and 2050 due to a CO_2 price up to 150 EUR/t_{CO2}. Since many conventional power plants in Europe are reaching the end of their lifetime in the upcoming decade, substantial amounts of new generation capacity will be required. In general, the modeling results indicate, that under the given scenario framework and the input from the model coupling within REFLEX, back-up capacities are necessary to provide system flexibility. Although the High-RES scenarios are characterized by relatively high shares of RES, CO_2 prices higher than 70 EUR/t_{CO2} are required to enforce decarbonization by avoiding investments in carbon-intensive generation technologies in the presence of an increasing electrification of the demand side sectors. High fuel and CO_2 prices can incentivize the competitiveness of low-carbon technologies like renewable energy technologies and CCS as well as flexibility options, such as storages and power-to-x. These results support existing analyses and policy recommendations, e.g., Capros et al. 2016 or Mantzos et al. 2019. Policy makers are therefore advised to continuously monitor the proper functioning of the EU Emissions Trading System (ETS) in order to ensure reasonable CO_2 price signals as early as possible. The insights gained in Chapter 10 highlight the need for a reformation of the EU Emission Trading Scheme. To enable high CO_2 prices which would provide long-term clarity and certainty in price developments, the CO_2 emission cap should be continuously adapted and synchronized with the RES expansion as well as with economic structural changes and more CO_2 emitting sectors should be included. Nevertheless, an even more ambitious RES expansion leads to significant reductions in fossil fuel-based electricity generation and at the same time increases the value of storage technologies. Furthermore, high shares of RES allow for a mix of various flexibility options in the electricity market in a cross-sectoral energy system.

With regard to utility-scale electricity storages, the assumed cost decreases of lithium-ion and redox-flow batteries (cf. Chapter 4) are not sufficient to achieve a high market penetration of these technologies when renewable electricity generation contributes to the electricity demand at shares of around 60%[2]. Even up to average RES shares of 80% across Europe, investments in storage technologies (including pump storage power plants, where specific regional conditions are essential for profitability) are barely cost-effective and therefore do not play a major role. These findings underline the importance of rapid cost decreases for electricity storage technologies as they are required for even higher RES shares, for instance, in a Green Deal scenario. In order to foster the market penetration of electricity storages, policy makers should support their multi-purpose use (e.g., the provision of ancillary services additional to the use on the day-ahead market). An increased diffusion of utility-scale storages could then in turn reduce curtailment of electricity from RES surplus feed-ins as well as decrease the need for conventional back-up capacities and thus enable savings of total system costs. Moreover, the necessity of promoting DSM could be reduced (cf. Section 16.2.1.3), as storage systems and DSM are competing flexibility options. Since DSM smooths the residual load, electricity market-based storages decrease in value – vice versa. Nevertheless, an extensive application of DSM, as in the High-RES decentralized scenario, can lead to significant reductions of positive residual load peaks, thus limiting the need for additional (conventional) back-up capacities, but also increases full load hours of flexible technologies. However, sector coupling increases electricity demand and thus more ambitious RES expansion is necessary, especially if additional greenhouse gas emissions resulting from conventional power plant capacities shall be avoided. Hence, both storage and DSM options will be needed.

A more decentralized future energy system substantially differs from a more centralized one, as the comparison within the two REFLEX High-RES scenarios reveals, particularly regarding the interactions of different sectors: In the High-RES decentralized scenario the role of the residential sector as decentral flexibility source (especially heat pumps, electric vehicles, PV battery storage systems) increases strongly and thus weakens the role of further flexibility options (like pump storages) in the electricity market. In the High-RES centralized scenario, large-scale solutions especially for sector coupling (amongst others centralized electrolyzers for H_2 production (cf. Chapter 7 and 8) and renewable integration, increase of centralized heat production (cf. Chapter 12)) become relevant. However, both (more ambitious) scenarios span a broad development of renewable expansion and should not be understood as either the one or the other, but exploiting a combination of both scenarios and making use of the renewable potentials will be essential. In both scenarios, a higher amount of renewable energies is important to achieve emission reduction targets and is a no regret strategy, as especially shown within the sensitivity analysis toward higher shares of renewable technologies (cf. Chapter 10).

[2]Although renewable energies are considerably expanded until 2050, the share only rises to approx. 60% in the High-RES scenarios, since in the same time electricity demand increases from approx. 3,000 TWh in 2014 to 5,000 TWh in 2050. Sensitivities with higher RES shares are calculated in Chapter 10.

16.2.1.2 Electricity Market Designs

Concerning the impact of electricity market designs (cf. Chapter 11) on generation adequacy, results show that the introduction of a capacity remuneration mechanism (CRM) is an effective measure substantially shifting investment incentives toward the countries implementing the mechanism. This effect is most pronounced in settings with a moderate growth of the electricity demand (as in Mod-RES), where open cycle gas turbines (OCGT) are often the most profitable investment option. Consequently, investments in peak load power plants are carried out in countries with an active capacity remuneration mechanism, while neighboring countries without an own capacity remuneration mechanism face significantly lower capacity levels and are therefore confronted with increasing wholesale electricity prices in the long run. If the electricity demand grows rapidly (as in High-RES), investments in combined cycle gas turbines (CCGT) are often economically preferable over peak load capacities. Moreover, and in contrast to open cycle gas turbines, the profitability of combined cycle gas turbines in countries without a capacity remuneration mechanism is less affected by additional investments in neighboring countries with capacity remuneration mechanism due to higher full load hours. Consequently, the wholesale electricity prices may also decline in countries without an active capacity remuneration mechanism in the long-term.

Capacity remuneration mechanism could force investments in electricity storages, if an average share of electricity from renewable sources around 80% across Europe is achieved. This is driven by the additional revenues from the capacity remuneration mechanism. However, due to the technology-neutral approach of the capacity remuneration mechanism as desired by the European Commission, the cost-effectiveness of non-storage technologies such as open cycle gas turbines increases when a capacity remuneration mechanism is implemented. However, building more peak load capacity in countries with an active capacity remuneration mechanism, drastically reduces investment incentives in neighboring countries without an own capacity remuneration mechanism.

Thus, whether positive or negative cross-border impacts of capacity remuneration mechanisms prevail, will depend on the specific setting. In general, capacity remuneration mechanisms seem to increase generation adequacy not only in countries implementing the mechanism, but also in the neighboring countries. This finding indicates that free riding occurs. In order to avoid these market distortions, a coordinated European capacity remuneration mechanism as electricity market design is recommended.

16.2.1.3 Demand Side Management

Although in some European countries favorable regulatory conditions for demand side management exist, their conditions are not sufficient to establish functioning demand side management markets and attract companies' interest. As of today, particularly small demand units are hardly participating in demand side management although on aggregate level their potential would be high. Lacks of (reliable) information and of financial benefits as well as perceived risks have empirically been identified to be relevant barriers against the adoption of more demand side management options especially in the tertiary sector (cf. Chapter 8 and Reiter et al. 2020).

Specific policy measures are required to reduce those barriers across all countries. For instance, implementation rates and the respective compliances with the EU regulation could be increased, and the varying settings in different countries reduced, allowing market players to be active in multiple countries and therefore, attracting business opportunities. Special focus has to be put on the bid size and aggregation of demand side management potentials to participate in the reserve markets.

Additionally, by showcasing existing examples of how flexibility providers can benefit from participating in demand side management markets, risk perception of companies may be altered, offering additional demand side management potentials. As the risk perception differs to a high degree between countries, specific approaches (e.g., from aggregators) are needed to highlight potential economic advantages. Besides market-based transaction schemes, information regarding technical implementation as well as the functionality of demand side management have to be provided to small- and mid-sized companies as they lack internal relevant know-how. Specific information can be best provided by independent stakeholders such as governmental energy agencies or independent energy advisors.

Larger companies with more standardized procedures regarding energy efficiency and energy demand might adopt demand side management models faster and therefore, integrating demand side management into energy management systems could support the further rollout of flexibility options on the demand side. Energy advisors and auditors can help to spread the word of advantages and disadvantages of demand side management systems.

Once again it should be emphasized, that the presence of storage systems could devalue DSM strategies and thus the propensity to invest in such options (cf. Chapter 9, 10).

16.2.2 Industry Sector

In the long-term, key measures enabling the decarbonization of the industry sector are radical changes to industrial production systems toward CO_2-neutral production processes and products (e.g., hydrogen processes and large-scale power-to-heat for steam generation and managing multi-temperature processes with industrial high-temperature heat pumps), mainly envisaged for implementation in the time horizon after 2030. Before 2030, energy efficiency improvements combined with fuel switching to biomass and progress adaption and innovation toward a circular economy are the main mitigation options. In order to have new CO_2-neutral process technologies and innovations ready by 2030, substantial research, development and innovation activities need to take place in the coming decade supported by the respective known policy measures (e.g. financing of research and development, public procurement, labelling, CO_2 price). Pilot and demonstration plants need to be built as well as new certification processes for new materials introduced. To further promote material efficiency and therefore directly reduce energy demand along the value chain, a broad policy mix is required. Implementing policies to overcome barriers to energy efficiency (energy management schemes, audits, low-interest loans, and energy service markets) is a prerequisite for other (price-based) policies to work effectively (e.g., CO_2 floor price to provide clarity for investment decisions, CO_2 tax for companies outside the EU ETS).

16.2.3 Transport Sector

In contrast to all other sectors, the transport sector increased its greenhouse gas emissions since 1990 (European Commission 2011). According to the European Strategy for Low-Emission Mobility the emissions in the transport sector need to be reduced at least by 60% in 2050 compared to the level of 1990. Hence, the emissions should be clearly on the path toward zero by mid-century and air pollutants harming public health need to be drastically reduced without delay (European Commission 2016). Considering the continuous growth of passenger and freight transport demand, strong and timely responses are required at policy level. The analysis of the transport sector in the present book (cf. Chapter 5, 6 and 7) specifically considers global learning for batteries and flexibility potential provided for the electricity sector. Results indicate that a bundle of complementary measures is required to support and accelerate the transition. In the investigated High-RES scenario, the main drivers of CO_2 emission reduction are the diffusion of low- and zero-emission road vehicles (achieving 26% reduction in 2050 relative to 1990), efficiency improvements (adding up to 44%), and alternative fuels, in particular for aviation and navigation (reaching 58%). Policies aiming at modal shift to active modes, public transport and new mobility services (e.g., car sharing, mobility-as-a-service systems, autonomous cars) can contribute in particular on the local level. Although for the overall transport system the impact in the analyzed scenarios is lower compared to other strategies, these policies still contribute to CO_2 emission reduction for about 10%.

The main findings and policy recommendations are categorized by the three main European strategies for the decarbonization of the transport sector: (i) energy efficiency, (ii) electrification of road transport and (iii) alternative fuels.

16.2.3.1 Energy Efficiency

Energy efficiency is of utmost importance, but to reach the GHG targets in case of individual personal transport, the switch to e-vehicles in combination with higher

RES expansion is highly required. The introduction of fuel efficiency and CO_2 standards for new vehicles represents a fundamental instrument to reduce overall GHG transport emissions. These standards should not only be tightened for cars and vans but also extended to heavy duty vehicles, buses and airplanes. Such standards force the automotive industry to become innovative and to change their product portfolio to vehicles with alternative zero- and low-emission powertrains. Setting interim and long-term targets beyond 2030 ensures that investments are made soon and maintained based on long-term direction. The targets have the advantage to promote innovation while staying technology-independent which is relevant for transport modes for which several competing technologies are under development.

Infrastructure for high-speed train connections for well-used routes is an option to replace domestic as well as inner-European flights. For freight, transport on railways and inland waterways are more efficient transport solutions. To achieve shifts toward these more efficient transport solutions, investments in the rail and public transport systems within member states as well as on transnational level across member states are needed, but can hardly compensate the further growth in freight transport. In the High-RES scenarios, a part of road transport share is shifted to rail and inland waterways, in particular due to respective investments in railway and waterway infrastructure, in multimodal freight terminals and increased taxation of fossil fuel-based road transport. Furthermore, the development of integrated logistics can make a more efficient use of freight vehicles, enabled also by the diffusion of digital technologies. Measures related to urban freight logistic include a huge variety of different transport operations and logistics activities ranging from road network and parking strategies, terminals and modal interchange facilities, pricing strategies, ICT-based vehicle control systems, logistics information systems, etc. Within REFLEX, these types of policies have been simulated in the High-RES scenarios, contributing to the reduction of CO_2 emissions at urban level. However, road share increased again toward 2050 with the diffusion of low-emission fuel cell and battery electric trucks, thus showing a rebound effect.

Sustainable transport modes should be made more attractive and convenient, for example by urban planning measures and infrastructure provision in favor of active modes, by increasing spatial coverage and frequency, and by developing and promoting an ICT-based, integrated and transparent multimodal mobility system. It is fundamental to sustain modal shift especially for short-distance passenger transport where the vast majority of trips are concentrated. Indeed, urban areas show the most pressing congestion challenges but have also the highest potential for behavioral change and technology transition. Modal shift is mainly achieved for the High-RES decentralized scenario on the local level for passengers. The diffusion of shared mobility schemes in European cities, enhanced by the wide spread of information and communication devices, is becoming an alternative to individual transport means thus partly alleviating the problems related to congestion, air pollution and GHG emissions by reducing the number of vehicles in circulation. Within the REFLEX scenarios, car sharing and car-pooling policies have been tested and are an option for local mobility (especially in the High-RES decentralized scenario).

16.2.3.2 Electrification of Road Transport

Subsidies for low-emission vehicles are required in the first years of technology market entrance, when vehicle prices are still relatively high. Battery electric and plug-in hybrid electric vehicles are expected to contribute to a widespread electrification of passenger transport, as they will soon become competitive with conventional oil-based cars thanks to learning effects and economies of scale in global battery production and as public charging infrastructure is deployed. Thus, subsidies for vehicles as purchase incentives or bonus malus (or so-called fee bate) systems seem only reasonable within the next few years. Furthermore, monetary advantages for homeowners with rooftop photovoltaic systems, generating electricity for self-consumption, can contribute to the diffusion of battery electric vehicles. This factor would become more relevant, if the electricity system develops in a more decentralized way (as e.g. in the High-RES decentralized scenario).

Within the REFLEX High-RES scenario assumptions fuel cell electric vehicles would lead the technology transition for long-haul trucks. Although hydrogen production is less energy efficient compared to direct electrification, fuel cell electric trucks are assumed to become a real decarbonization option. Hydrogen production has the potential to provide flexibility to the electricity system that has to cope with fluctuating electricity feed-in by renewable energy sources. In times of electricity surpluses hydrogen could be produced, stored and reconverted to electricity when needed. Research and development as well as subsidies for fuel cell technologies seem still required to achieve competitive prices.

In general, policies that support the transition to new drive technologies by increasing their financial attractiveness compared to conventional fuel vehicles are vehicle registration taxes, road charges and fuel taxes which all depend on the respective CO_2 emissions.

16.2.3.3 Alternative Fuels

Biofuels and synthetic fuels based on electrolysis and additional treatments, i.e., power-to-gas (PtG) and power-to-liquid (PtL), are less efficient options for low-carbon transport, as production requires biomass as resource and renewable electricity as energy source with low degrees of efficiency in internal combustion engines. However, they should be used for modes for which mature low-emission drive technologies will not be developed in the near future. This is mainly the case for aviation and for ships. Alternative fuels also play at least an intermediate role for road transport, if battery range anxieties result in a higher diffusion of plug-in-hybrid cars for longer distances. Moreover, new technologies for trucks might not become adequate for certain special purpose vehicles by mid-century. A clear strategy for using sustainable biofuels and synthetic fuels in selected applications (aviation and ships) is then needed. The production of advanced biofuels should be supported. When sustainable production can be ensured for certain quantities, blending quotas of biofuels and power-to-x (PtX) fuels could be established.

Greenhouse gas emissions reduction in the REFLEX scenarios is obtained assuming that transport performance grows with increased gross domestic product, income and population until 2050. Future research and policies might focus also on measures investigating how demand can be reduced while still meeting citizens' needs, for example by spatial planning measures and opportunities appearing with increasing digitalization. The three mobility packages presented by the European Commission (2018) set the right direction. Their principles should be enhanced and adopted as binding directives either on European or on national level to ensure implementation.

16.2.4 Heating Sector

In the heating sector two crucial aspects and policy recommendations can be derived based on the REFLEX results (cf. Chapter 12): energy efficiency in buildings and district heating networks.

16.2.4.1 Energy Efficiency

In the buildings sector (residential and tertiary), the potentials for improved energy efficiency are even higher than in industry. Currently, low building renovation rates limit the fast uptake of energy efficiency potentials and the switch to renewable heat sources. Currently, efficiency progress in the buildings sector is mainly driven by EU regulations like the Energy Performance of Buildings Directive (EPBD) and the Ecodesign Directive. However, these directives mainly address new buildings and appliances. Therefore, tapping additional efficiency potentials in the existing building stock requires additional efforts (e.g. subsidies, incentives, binding targets as well as removal of barriers and changes of personal behavior). To tap these available potentials, combined efforts in targeting refurbishment rates, refurbishment depths and technology change are needed. Refurbishment is a prerequisite for the deployment of RES, both for technical reasons (low heat distribution temperature enable high heat pump efficiency) and due to limited availability of RES potentials. For an effective diffusion of RES for space heat supply, the regulatory frame needs to be adapted to make RES cost competitive compared to fossil-based solutions. This holds irrespective of the underlying setting of the heat sector, i.e., whether more decentralized or more centralized.

Likewise energy efficiency in the industry sector needs to be increased. Process management and adaption to decrease useful heat temperature levels of processes and energy management between processes of different temperature levels (including cooling and freezing) offer substantial potentials to reduce final energy demand by using high-temperature heat pumps. This enables the use of renewable ambient heat sources in the respective sectors (e.g. chemicals, pharmaceuticals, food and beverage), either in centralized or decentralized ways. This reduces the need and high-exergy fuels (e.g. biomass, PtG, H_2) which should be used for remaining of high-temperature energy needs, e.g., in the cement and metal industries.

16.2.4.2 District Heating Networks

Besides heat pumps at household level (cf. Chapter 7, 9 and 10), also district heating can be a facilitator to decarbonize the heat sector (cf. Chapter 12). To allow for a more centralized provision of renewable heat and to tap the full potential of thermal energy networks (e.g. district heating networks, cold networks, ambient heat, multi-purpose etc.), economic and financial instruments (e.g. incentives, preferential loans, risk mitigation mechanisms) as well as connection regulations and strategies are needed. Respective system integration needs to be supported by regulations toward connection management and excess heat disposal. Policies can additionally support the uptake by e.g., hedging high risks in individual projects, regulating excess heat release in national emission control acts, strengthening local heat planning and providing investment grants. The management and support of specific geothermal potential zones as well as further cost reductions are needed to achieve major growth of large-scale heat pump installations for district heating supply.

The development of the district heating systems in the future depends on the district heating demand, which varies in the REFLEX scenarios. The demand increases in the High-RES centralized scenario whereas in the Mod-RES and High-RES decentralized scenarios it is expected to be lower than today. Further factors influencing the modeling results are CO_2 emission allowances prices of the EU ETS market, techno-economic parameters of processes employed in district heating systems as well as potential and costs of fuels and energy resources. Results show that significant GHG emission reductions are possible in the district heating generation sector from approximately 60% to 85% in 2050 depending on the REFLEX scenario. As a response to increasing CO_2 prices, bioenergy (mainly biomass) capacities are growing significantly. Therefore, biomass can play an important role in substituting fossil fuels in district heating generation in particular in the EU member states where the district heating networks are already well developed. Natural gas is still used due to high flexibility also in terms of the power-to-heat (PtH) production ratios.

With decreasing district heating demand, as in case of the Mod-RES and High-RES decentralized scenario, combined heat and power plants are exposed to lower district heating sales but also to lower electricity sales. With decreasing district heating demand and with a simultaneous increase in electricity demand – as in the case of the High-RES decentralized scenario – it is impossible to maintain the current relative share of electricity produced in cogeneration while meeting the cogeneration efficiency goals. In fact, in this scenario the share decreases from the current 12% to 7% in 2050. In case of the High-RES centralized scenario, the increased district heating demand has to be associated with developments of new district heating systems. Additionally, it is important to design district heating systems for low-temperature renewables sources such as ambient energy from lakes, rivers, air and geothermal ones. The transition toward higher use of bioenergy (mainly biomass) requires sustainable adequate concepts (e.g. biomass only to supply peak loads) and organizational (logistic) solutions that will minimize energy and CO_2 emissions embedded in processing and transportation.

Short-term heat storages help to smooth the generation profiles and seasonal storages increase the heat produced in summer times and consumed in winter times. The use of PtH technologies including large heat pumps depends on electricity prices but certainly helps to manage the RES electricity surplus that otherwise would be curtailed. Additionally, district heating networks allow – among others – for integrating excess heat from industrial activities. If industries are nearby, higher temperature levels can contribute to the efficient use of heat in industrial parks.

In general, district heating costs are increasing in future years. This is mainly due to the investments in new capacities, rising CO_2 prices (if fossil fuels are used) and increasing fuel costs. Therefore, it is necessary to maintain the existing or new implemented policy measures that will guarantee necessary profits for generators and keep the district heating end-user prices at competitive levels. With the development of low-energy buildings, district heating networks should be expanded in regions where sufficient spatial heat density exists in order to maintain the current district heating demand.

16.2.5 Environmental, Social Life Cycle and Health Impact Assessment

Although the focus of the energy transition is mostly on climate change, the impacts of an energy transition of health, environment and society could promote, but also impede the transition process.

With both by limiting the combustion of solid fuels and by improving combustion methods, positive impacts on the health are expected. Due to the energy transition the ambient concentration of air pollutants in 2050 will be lower compared to 2015 by around 30 times in the residential and tertiary sector, 3 times in road transport and 12 times lower in the power and district heating generation sector, respectively (cf. Chapter 15). This will increase noteworthy the air quality and by this air-borne health effect will diminish in all REFLEX scenarios. The largest of improvement in air quality regarding $PM_{2.5}$ concertation is observed in Poland with around 5 $\mu g/m^3$.

Beyond GHG emissions most analyzed environmental impacts of the transformation of the energy system follow the share of renewable energy sources at the energy provision, i.e., the impacts decline as the share of renewables increases.

Two environmental impacts could impede the transition process for a low-carbon electricity system. First, land use is significantly increasing due to renewable technologies and requires attention to be paid to infrastructure planning among EU member states with different regulations. Land use for ground mounted PV in the base year (2014) amounts to only 3% of that required in 2050 for the High-RES decentralized scenario – 950 km^2 compared to 28,864 km^2 (cf. Chapter 13). Countries with best weather conditions for ground mounted PV (France, Italy, Spain and other Mediterranean countries) have their restrictions that consider aesthetic requirements as well as the potential for resident opposition (NIMBY – not in my back yard). Second, metal depletion results demonstrate that the transformation process to a low-carbon electricity system is highly dependent on the availability of metals (finite resources) to produce technologies for intermittent electricity generation.

Looking at different social impacts, like child labor, fair salary, forced labor and workers' rights (except for health and safety), the energy transition could push to in-depth discussion about a (international) fair distribution of the gains. Following the findings in Chapter 14, in respect to the above listed categories in all analyzed scenarios the situation will be worsen. Compared to 2015. The main reason is the growing share of gas-based generation in future. Gas technologies have higher than average impact considered per unit electricity generation due to its "fuel supply chain", of which is originated mainly outside the EU, that is responsible for over 90% of total impacts caused by gas-based generation. Solar power and wind power make more modest contributions in all impact categories. Nevertheless, due to the increase in PV share in the electricity mix, solar's contribution to social impacts grows up to 2050. The contribution analysis shows that even in 2050 between 48% (for the subcategory fair salary) and 91% (for child labor) of the total contribution due to the ground mounted PV arises due to the processes "raw material extraction" and "material and component manufacture", which is also originated predominated outside the EU. Similar trends are observed for rooftop PV.

16.3 Further Aspects and Outlook

In general, the combined insights and measures to decarbonize the European energy system until the year 2050, as analyzed in this book, emphasize the considerable efforts required to coordinate and govern the targeted transition. This is especially true, as the European Green Deal – in line with the Paris Agreement – is even more ambitious with regard to emission reduction than the considered High-RES scenarios (cf. Chapter 1). The Mod-RES scenario seems to be well achievable from perspective of today's boundary conditions and some moderate adjustments, while much more additional efforts have to be taken to achieve the more ambitious High-RES scenarios. Both (ambitious) High-RES scenarios increase energy efficiency and span a broad development of renewable expansion and should not be understood as either the one or the other, but exploiting a combination of both scenarios and making use of the renewable potentials will be essential. In consequence, relevant measures have to be based on wide and stable acceptance across the member states. The support and promotion of the measures discussed influence the everyday life and coexistence of almost all EU citizens and requires the consent of stakeholders involved across all areas of society. The EU and the member states have to play a crucial role to pave the way to achieve the transformation targets.

The European Green Deal goes beyond the emission reduction in the High-RES scenarios by targeting climate neutrality until 2050 and thus the required transformation processes are even more challenging than the scenarios analyzed in this book. Although climate neutrality has not been assessed, results indicate the importance of hydrogen.

In addition to the four main pillars mentioned at the beginning of this chapter, following *preconditions for a successful transformation*, without claiming to be complete, need to be guaranteed:

- *Promotion and strengthening of European integration and harmonization of common goals across the member states, yet adopting the subsidiary principle taking individual preconditions, potentials and motivations into account, to*
  - Leverages costs and burdens,
  - To use available resources efficiently,
  - And to comprise that fact that the energy market is European, and thus to strengthen market-based solutions as well as a fair competition among flexibility options to integrate renewable energy sources.
- *Do not lose time to*
  - Improve implementation.
  - Establish long-term agreements and targets to ensure investment and planning security.
  - Further increase efforts regarding research and development (including research toward a hydrogen economy in a European energy system).
  - Strengthen a transparent communication of targets, benefits and challenges to the public based on scientific and public discussions.

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