STUDY

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Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?

Policy Department for Economic, Scientific and Quality of Life Policies
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Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?

Abstract

Sector coupling involves the increased integration of energy end-use and supply sectors with one another. This can improve the efficiency and flexibility of the energy system as well as its reliability and adequacy. Additionally, sector coupling can reduce the costs of decarbonisation. To foster the full potential of sector coupling in several end-use and supply applications, it is important that existing techno-economic, policy and regulatory barriers are removed. Furthermore, a more integrated approach to energy systems planning is needed.

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bcm	Billion m^3
CCS	Carbon Capture and Storage
CHP	Combined heat and power
CNG	Compressed natural gas
CO2-eq	Metric measure used to express different types of GHG in a universal unit based on their global warming potential, by converting amounts of other GHG to the equivalent amount of carbon dioxide
ETS	Emission Trading Scheme
EV	Electric vehicle
GHG	Greenhouse gas
Gton	Gigatons (billion tons)
IRENA	International Renewable Energy Agency
LNG	Liquefied natural gas
MENA	Middle-East and North Africa
Mton	Megaton (million tons)
MWh	Megawatt-hour (1 000 kWh)
PtGtP	Power to gas to power
PV	Photovoltaics (solar panels)
TWh	Terawatt-hour (billion kWh)
V2G	Vehicle-to-grid
WHO	World Health Organisation

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EXECUTIVE SUMMARY

The EU aims to reduce its overall GHG emissions by 80-95% by 2050 compared to 1990 levels. Achieving this objective requires a complete decarbonisation of the European energy system, which needs to be realised without compromising the security of energy supply and while keeping energy prices affordable for households and businesses.

Sector coupling can contribute to the cost-efficient decarbonisation of the energy system, by valuing synergy potentials and interlinkages between different parts of the energy system. In this study, we distinguish two types of sector coupling: end-use sector coupling and cross-vector integration. **End-use sector coupling** involves the electrification of energy demand while reinforcing the interaction between electricity supply and end-use. **Cross-vector coupling** involves the integrated use of different energy infrastructures and vectors, in particular electricity, heat and gas, either on the supply side, e.g. through conversion of (surplus) electricity to hydrogen, or at the demand side, e.g. by using residual heat from power generation or industrial processes for district heating. Several studies show that sector coupling can lower the overall costs of the energy transition.

Electrification of energy demand and end-use sector coupling is one of the core strategies in the decarbonisation of the energy sector. Electric devices are often more efficient than fossil fuel based alternatives, and the cost to produce electricity from renewable sources has recently become increasingly competitive with other electricity sources. Thus, this strategy can lead to both energy efficiency improvements and the deployment of renewable energy sources. Other renewable or carbon-neutral energy vectors can provide a complementary solution for the decarbonisation of specific end-uses that are difficult to electrify.

Electrification is a particularly suitable solution for the decarbonisation of **heat demand** in buildings, mainly through electric heat pumps. For industrial processes where energy is used to generate high-temperature heat, electrification is more challenging; in a full decarbonisation scenario, this heat demand can be supplied with renewable or carbon-neutral gas.

Decarbonisation of **specific industrial uses of fossil fuels or feedstocks for chemicals** is particularly challenging. For example, in steel production the reduction of iron is most commonly achieved with coal. However, there are innovative technologies that allow this process to be achieved using carbon-neutral hydrogen or methane. Renewable or decarbonised gas can also serve as a feedstock for the production of chemicals in a variety of chemical industries.

Decarbonisation of passenger and light-duty road **transport** can be largely realised through a shift to battery electric vehicles. For long-distance heavy-duty transport, especially freight road transport, shipping and aviation, a combination of hydrogen and hydrogen-derived synthetic liquid fuels might become suitable solutions. These fuels can be produced in either domestically or imported from areas with abundant renewable electricity resources, in power-to-liquid facilities. To provide these facilities with a sustainable source of carbon in a largely decarbonised energy system, efficient technologies for capturing CO_2 directly from the atmosphere need to be developed.

Cross-vector integration provides the energy system with increased flexibility to cope with fluctuations in energy demand and renewable energy supply. Power-to-X (i.e. power to other energy vectors such as gases, heat or liquids) can act as a sink for electricity surpluses, by using the available energy economically and preventing curtailment (i.e. energy spillage) of renewable energy installations. Improving the integration of the electricity and gas sectors would also allow an optimised use of existing gas infrastructure. Gas pipelines could be used to transport renewable energy from supply areas to areas with shortages, reducing the need to expand the electricity transmission capacity.

Gas storage could be used to cope with seasonal variations in demand and renewable energy supply, and some types could also provide short-term flexibility. Renewable gas can also be used in gas-fired power plants or fuel cells, providing low-carbon back-up capacity to generate electricity when other renewable energy resources are unavailable.

Despite the benefits of sector coupling, there are several barriers to mature and experimental end-use sector coupling and cross-vector integration. An important **techno-economic barrier to sector coupling** is that several of the technologies are not yet competitive in many applications and regions. Their performance also needs to be improved further, and design and operation standards and energy efficiency labels have to be developed. Market conditions are also restrictive, because fossil fuels are available at comparatively low prices, or due to competing, more profitable applications of certain resources (e.g. biomass). The lack of stability in regulatory and market conditions also leads to uncertainty on the business case and deters investments. Moreover, the limited availability of resources strongly shapes the viability of sector coupling technologies in specific regions. Many technologies rely on the availability of suitable infrastructure, which can require the expansion or refurbishment of existing infrastructure, or investment in new dedicated infrastructure. This can be substantial and require the development of new standards (e.g. for injecting hydrogen in gas grids).

Policy and regulatory barriers to sector coupling start with gaps in the integrated, forward-looking planning and operation of energy vectors and levels. Current energy market designs also form a barrier to sector coupling technologies, either by not internalising all positive and negative externalities of low- and carbon intensive technologies (especially through the lack of an adequate carbon pricing) or by impeding the participation of sector coupling technologies in specific markets. Furthermore, some of the gas and electricity network tariffs do not sufficiently reward the flexibility services provided by sector coupling technologies.

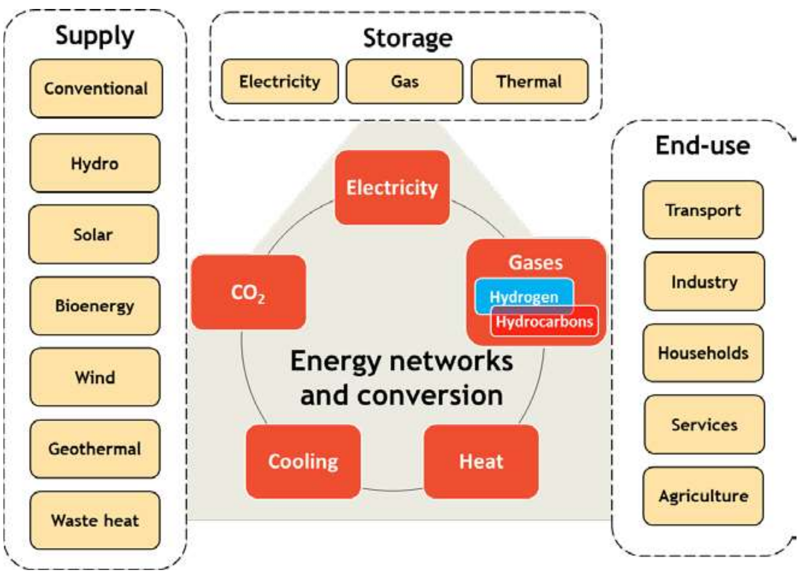
Several **policy recommendations** to overcome the identified barriers for sector coupling were developed. First, integrated planning and operation of energy infrastructure at all levels is needed, considering interlinkages between the electricity, gas and heat sectors, to ensure that new investments are future proof and minimise overall system costs. Energy policies should be consistent and provide adequate incentives for flexible, low-carbon technologies and consider the interactions of both high-level and targeted energy and climate legislation. The future role of hydrogen should be further assessed, and measures are needed to facilitate its deployment. Energy (service) markets should reflect positive and negative externalities for each participant and provide a level playing field for all technologies and vectors contributing to energy supply, system flexibility and adequacy. Therefore, aspects such as cost-reflective energy price signals, adequate carbon pricing, market accessibility and liquidity, and appropriate network tariff structures should be considered. Finally, EU policy stimulating research, development and innovation should specifically focus on integrated energy system planning and operation, and facilitate high-risk innovations.

1. INTRODUCTION

1.1. Defining sector coupling and its relation to energy system integration

Sector coupling is a concept that has been developed in Germany but has been gaining attention elsewhere in Europe. Originally, sector coupling referred primarily to the electrification of end-use sectors like heating and transport, with the aim of increasing the share of renewable energy in these sectors (on the assumption that the electricity supply is, or can be, largely renewable) and providing balancing services to the power sector[1]. More recently, the concept of sector coupling has broadened to include supply-side sector coupling[2]. Supply-side integration focuses on the integration of the power and gas sectors, through technologies such as power-to-gas. The European Commission also uses this broader notion of sector coupling and understands it as **a strategy to provide greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way**[3].

Figure 1: Coupling of the energy system sectors



Source: Based on Imperial College London (2018)[4].

This broad definition of sector coupling is very similar to that of energy system integration, which has been defined as: 'the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment'[5]. Figure 1-1 presents the different sectors of the energy system involved in sector coupling. As discussed in this document, electrification of end-use sectors plays a

1 Deutsche Umwelthilfe (2017) Sector Coupling - Using electricity for heating and transport to protect the climate.

2 Deutsche Energie Agentur (2018) Leitstudie Integrierte Energiewende.

3 DG ENER (2018) Request for services n° ENER/B2/2018-260 - Potentials of sector coupling for the EU natural gas sector - Assessing regulatory barriers.

4 Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.

5 International institute for Energy Systems Integration (2016) Energy systems integration: defining and describing the value proposition.

central role in cost-effective decarbonisation of the energy system, but further integration of the energy supply sectors can also contribute to this goal while providing additional flexibility. To distinguish between coupling of end-use sectors with the energy (mainly electricity) supply sector on the one hand and further coupling of the energy (mainly electricity and gas) supply sectors on the other hand, we will refer to these two strategies as 1) **end-use sector coupling** and 2) **cross-vector integration**. This is a pragmatic approach to highlight these complementary strategies, but other categorisations are possible.

1.2. Decarbonising the EU economy

The relevance of sector coupling is strongly related to the policy objective of shifting from our current highly centralised and mainly fossil fuel-based energy system to a more decentralised, energy efficient and renewable energy-based energy system. This transition will also facilitate the decarbonisation of the energy system and should allow the EU to fulfil its commitment under the Paris Agreement to contribute to the international effort to keep global temperature rise well below 2ºC. At present atmospheric CO_2 concentration is still steadily increasing. In the last 10 years, CO_2 concentration has increased by more than 20 ppm[6], and we are only 40 ppm below the level at which the level of certainty that global temperature rise will remain below 2ºC will drop below 66%.

The remaining global carbon budget to restrict global temperature rise to below 2ºC with a 66% certainty, is 880-1 000 Gtons CO_2-eq[7]. At the current emission rate this carbon budget will be used in 24-27 years[8]. For Europe, the total carbon budget under a 2ºC scenario amounts to about 90 Gtons CO_2-eq and under a 1.5 ºC scenario to only 50 Gtons CO_2-eq, even under a budget allocation method that favours industrialised countries[9]. With the current level of emissions, the former budget will be exhausted in 2032 and the latter in 2042. Therefore, to limit global temperature rise and the dramatic climatic change it would cause, greenhouse gas emissions must be reduced drastically and urgently.

The EU has made significant progress in reducing its GHG emissions: it is estimated that under existing policies the EU's GHG emissions in 2020 will be around 26% lower than in 1990[10], which means that the 20% target will be surpassed. For 2030, the EU has agreed to reduce its GHG emissions by 40%, but most models show that this target would not be sufficient to remain within the EU's carbon budget, not even when a favourable (least-cost) allocation method is used[11]. This means that the EU must step up its efforts to decarbonise its economy, and sector coupling can play an important role in keeping the costs of those efforts in check.

It is important to realise that the decarbonisation of the economy should not be thought of as only representing a negative burden for society. It offers the potential of new business opportunities, creating new employment and contributing to a healthier and more liveable environment. In 2016, the renewable energy sector employed 1.16 million people[12], which is equivalent to approximately 0.5% of the overall employment. Currently, the air pollution level in many urban areas in Europe exceeds the WHO health limits[13], and a substantial share of this pollution originates from fossil fuel combustion. Air

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6 NOAA (2018) Mauna Loa CO2 annual mean data - https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html.

7 Carbon Tracker Initiative (2018) Carbon Budgets Explained - https://www.carbontracker.org/carbon-budgets-explained/.

8 Own calculation based on global emissions in 2016.

9 Ecologic (2018) EU Greenhouse Gas Emission Budget: Implications for EU Climate Policies.

10 EEA (2017) Trends and projections in Europe 2017 - Tracking progress towards Europe's climate and energy targets.

11 Ecologic (2018) EU Greenhouse Gas Emission Budget: Implications for EU Climate Policies.

12 IRENA (2017) Renewable Energy and Jobs – Annual Review 2017.

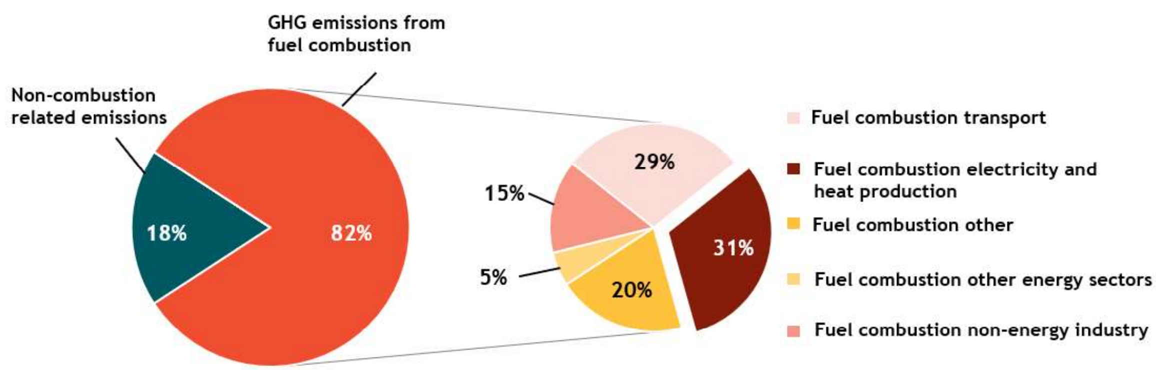
13 https://www.eea.europa.eu/data-and-maps/indicators/exceedance-of-air-quality-limit-3/assessment-3.

pollution now generates over 500 000 premature deaths a year in the EU[14]. A vast number of premature deaths could be prevented by reducing fossil fuel combustion. The shift from a fossil fuel to a largely renewable energy sources-based energy supply, will also contribute to reducing the fossil fuel imports of the EU, which currently amount to approximately 2% of the EU GDP[15].

1.3. Decarbonisation through electrification and coupling of end-use sectors

To date it is generally more attractive from an economic and technical perspective to convert solar, hydro and wind energy into electricity as an intermediate vector, rather than to convert it into e.g. thermal energy or carbon-neutral fuels or gas for heating or transport. Electrification is considered as an important way to cost-efficiently decarbonise final energy consumption[16]. Several technologies have become available at competitive prices to cost-efficiently convert renewable energy into electricity (Photo Voltaic (PV), wind turbines, etc.); this development facilitates the decarbonisation of electricity supply. However, a large part of the GHG emissions related to energy production and use do not originate from the power sector, but rather from the end-use of fossil fuels in industry, transport and buildings (see figure 1-1).

Figure 2: Share of fuel combustion in overall EU GHG emissions in 2016



Source: Trinomics (2018) Based on data from the EEA (2018) Greenhouse gas inventory[17].

A possible pathway to decarbonisation could be based on large scale electrification, where electricity would become the dominant energy carrier for buildings, transport and for heating applications in the industry. In such a scenario, most of the required energy would in the long term be provided by renewable electricity (mainly based on biomass, hydro, solar and wind energy), complemented with renewable or carbon-neutral energy (e.g. hydrogen or synthetic methane) for back-up power generation and specific applications in the transport and industrial sectors. In this scenario, the utilisation level of the gas import, transport, distribution and storage infrastructure would substantially decrease in the medium/long term, and some gas assets would become stranded and might need to be decommissioned. A decarbonisation scenario based on large scale electrification would pose

14 EEA (2017) Website article: air pollution sources https://www.eea.europa.eu/themes/air/air-pollution-sources.

15 https://ec.europa.eu/energy/en/topics/imports-and-secure-supplies and Eurostat national accounts - GDP and main components (output, expenditure and income) (nama_10_gdp).

16 Davis (2018) How 'electrifying' the energy sector can decarbonise the world. https://www.weforum.org/agenda/2018/02/how-electrifying-the-energy-sector-can-decarbonise-the-world/.

17 EEA (2018) Greenhouse gas emissions by source sector.

significant challenges to the energy system, due to the need for significant additional flexibility capacity in the electricity system, the need to substantially reinforce and extend the transmission and distribution networks, and the difficulty and high costs related to the electrification of some specific end uses.

Decarbonisation through enhanced electrification of end-uses will be stimulated by the latest energy efficiency policies and targets (in particular the 32.5 % energy efficiency target for 2030 (with a 2023 upward review clause). The resultant measures will drastically reduce the specific energy demand levels and will make high electrification scenarios more viable. For example, the Energy Performance of Buildings Directive triggers building requirements that will lead to net-zero energy buildings as of 2021, which will mostly rely on locally produced renewable electricity. Electrification of end-uses also enhances the potential of demand-side flexibility, which in turn facilitates renewable energy integration and reduces the need for back-up power generation capacity.

Considering the risks and costs of a scenario based on 'strong' electrification, an alternative scenario for the decarbonisation of the energy system could be based on the electrification of end-uses combined with a far-reaching integration of energy supply sectors and cross-vector integration. In this scenario, decarbonisation of energy demand would mainly be reached through an increased use of renewable energy in all energy end-use sectors; renewable energy-based electricity still plays an important (but less dominant) role, and it is complemented with other vectors, e.g. biogas, biomethane and hydrogen for applications which are hard to electrify, or for which a (renewable) gas based or hybrid solution would offer benefits. Sector coupling between electricity and gas and between supply and demand would allow the leveraging of synergies and would lead to a more energy and cost-efficient energy system. It would also allow for the increased utilisation of existing gas infrastructure (in particular transport, distribution and storage), which would lower the investment needs for reinforcing existing or building new electricity related infrastructure.

The combination of end-use sector coupling, and cross-vector integration increases the flexibility of the energy system and can help to optimise the use of renewable energy when it is abundantly available. For example, when electricity is cheap and abundant, it can be converted into gas (hydrogen or synthetic methane) and stored and/or transported via the gas infrastructure for immediate or later end-use. It can also be converted back into electricity during periods of insufficient renewable electricity supply (and hence high electricity prices), by using the so-called power-to-gas-to-power (PtGtP) route[18]. In addition, power-to-heat options combined with heat storage can shift heat production to moments with abundant and cheap electricity supply, while 'cheap' electricity can also be converted to a liquid fuel (e.g. methanol) for use in the industry.

Multiple studies have shown that energy system integration and sector coupling substantially reduce the costs of the transition to a decarbonised energy system. For Germany, it has been estimated that the transition to a well-integrated energy system in 2050 with a broad energy technology mix would be €600 bn cheaper than a system that is strongly dependent on electricity only[19]. In part, this is related to the fact that the optimal use of existing energy infrastructure, including gas networks and storage facilities, reduces the additional capacity needed in electricity transmission and distribution grids and for dedicated electricity storage options.

[18] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

[19] Deutsche Energie Agentur (2018), Leitstudie Integrierte Energiewende.

1.4. Increasing needs for flexibility in the electricity system

Sector coupling also contributes to the growing flexibility needs in the power system. As the share of intermittent renewable energy (wind, PV) in power generation is gradually increasing, the electricity supply becomes more uncertain and variable. For example, in Germany there have been occasions when renewable energy supplied 100 % of the electricity demand[20], although the average share of renewable energy in Germany's electricity production in 2017 was 36.2 %[21]. High availability of wind and solar energy during periods of low demand (e.g. summer week-ends) is also leading to instances of negative electricity prices on the spot market[22]. According to figures published by Clean Energy Wire[23], the number of hours with negative power prices in Germany increased in 2017 by around 50 % to 146 hours (which represents 1.6 % of the total time), while the average negative power price was minus €27/MWh. The lowest price was minus €83/MWh, which was less extreme than in 2016 (€130/MWh), indicating that power market players have learnt to deal with these situations. However, the average negative price was lower (€26.5/MWh) compared to 2016 (€17.8/MWh).

Therefore, the electricity system in Germany and other Member States with high intermittent renewable electricity capacity, is facing increasing flexibility needs to balance electricity supply and demand at any moment. To this end, several solutions are being widely used, including ramping up/down dispatchable power plants, electricity trade with neighbouring countries, energy storage (mainly pumped hydro and batteries and demand-response). However, the increasing occurrence of negative spot prices illustrates that the current flexibility potential is not enough, and that additional options need to be deployed.

The next table shows the EU Member States, where the installed wind and solar PV capacity at the end of 2017 exceeded the lowest domestic load in 2017. In actual operation the peaks and valleys of load and the different renewable electricity generation profiles will not coincide, but the table is useful to indicate the extent of the penetration of variable renewable energy sources in Europe, and their potential impact on the system. As the installed capacity in intermittent renewable energy sources will grow, while electricity demand is not expected to increase to the same extent, the need for flexibility options that can absorb fluctuations in electricity supply and demand will increase.

Table 1: EU countries where the intermittent renewable electricity generation capacity exceeds the lowest load level, data from 2017

Country	Intermittent renewable electricity capacity generation capacity	Highest electricity load	Lowest electricity load	Ratio of intermittent renewable capacity to load	
	MW			Highest load (%)	Lowest load (%)
BG	4032	7690	2739	52	147
CZ	4235	10900	4360	39	97
DE	110041	78710	35085	140	314
FI	7127	14374	5916	50	120
FR	48653	94497	30199	51	161
GB	37170	63626	21296	58	175

[20] Clean Energy Wire (2018) Renewables briefly cover 100% of Germany's power demand for 2nd time - https://www.cleanenergywire.org/news/renewables-briefly-cover-100-germanys-power-demand-2nd-time.

[21] BMWi (2018) Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland.

[22] Electricity Currents (2018) Welcome to the new normal: negative electricity prices.

[23] https://www.cleanenergywire.org/factsheets/why-power-prices-turn-negative.

GR	8220	9674	3404	85	241
HR	2760	3079	1305	90	211
IE	3696	4907	1938	75	191
IT	55718	56584	19045	98	293
NL	8426	18620	7490	45	112
SE	26137	26224	8905	100	294
SI	1446	2270	937	64	154
SK	2680	4541	2320	59	116

Source: ENTSO-E (2018) Statistical Factsheet 2017 (GB represents data as sum of England, Northern Ireland, Scotland and Wales).

Sector coupling can be an important source of flexibility in the energy system, ranging from energy storage technologies to power-to-X applications as well as demand-response solutions. The different flexibility options that can be used to manage the variability in the energy system as well as the advantages of end-use sector coupling and cross-vector integration are presented in more detail in chapter three.

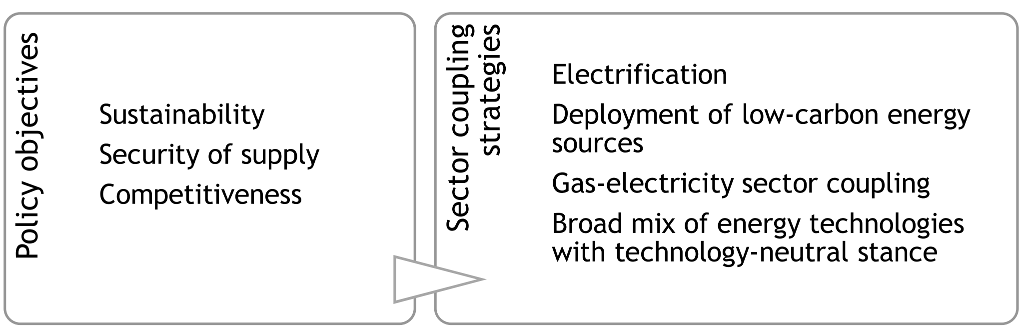
2. OPPORTUNITIES FOR SECTOR COUPLING

KEY FINDINGS

- Electrification will be one of the core strategies for decarbonising the energy sector.
- For some sectors and end-uses, electrification would be challenging; in these cases, renewable or carbon-neutral gas could be a solution.
- End-use sector coupling can facilitate increased deployment of intermittent renewable energy sources.
- Cross-vector integration between electricity, gas and heat can serve as an additional source of energy system flexibility and security of energy supply.
- The combination of end-use sector coupling and cross-vector integration is expected to reduce the overall costs of the transition to a low-carbon energy system.

This chapter focuses on the opportunities for sector coupling to contribute to the decarbonisation of energy supply and to the energy policy objectives. Figure 2-1 presents the three main policy objectives in EU energy policy and the strategies discussed in this section: electrification, deployment of low-carbon energy sources, coupling of single-carrier energy sectors (especially gas and electricity), technology-neutrality and using a broad mix of energy technologies.

Figure 3: Sector coupling strategies contributing to the EU Energy and Climate policy objectives



2.1. Sustainability of the energy system: electrification and deployment of carbon-neutral gas as key enablers

2.1.1. Electrification is the first pillar in decarbonising the energy system

Although the EU's energy system is still heavily dependent on fossil fuels –in 2016 they supplied 57 % of the EU's primary energy demand[24] - decarbonisation has begun, and is most advanced in the power sector. In 2016, renewable energy accounted for almost 30 % of the total electricity consumption in the EU[25], while the share of renewable energy in the gross final energy consumption was "only" 17 %. The recent growth in the share of renewable energy has been driven by a combination of support policies as well as rapid cost reductions in renewable energy technologies, most notably solar photovoltaic (PV) and (offshore) wind energy. The first offshore wind farms that will not receive direct financial support are currently being planned in the Netherlands, Denmark and Germany[26]. For PV, grid parity (i.e. cost competitiveness with other energy sources, e.g. fossil and nuclear, that feed electricity into the grid) has been reached in several countries in Southern Europe, with the first subsidy free utility-scale PV farms being built in Portugal and Spain[27].

Since renewable energy sources are most cost-competitive in electricity generation and have significant potential, electrification is considered as a cost-effective way to decarbonise energy demand. In some end-use sectors, such as passenger transport, electrification can be a successful strategy. Electric vehicles represent a viable and cost-effective alternative to cars with internal combustion engines, and can provide flexibility to the electricity system, by charging batteries during periods of low demand, thereby flattening out the demand profile. Similarly, electric heat pumps are an appropriate alternative for fossil-fired boilers to decarbonise the energy consumption for heating, while substantially reducing the related primary energy demand. As electric engines and heat pumps are in general more energy efficient than their fossil-based alternatives, electrification can substantially contribute to the energy efficiency improvements that are required. In the recent decarbonisation scenarios developed by Eurelectric, roughly one third of the required annual 2-2.8 % energy efficiency improvement could result from electrification[28].

Electrification of energy demand is a process which has been occurring for decades, albeit at a slow rate. Between 1990 and 2015 the share of electricity in final energy demand increased from 17-22 %[29]. In a business as usual scenario, the electrification trend is expected to continue, with the electricity share increasing to 25 % in 2030 and 28 % in 2050[30]. In scenarios where the energy demand is fully decarbonised by 2050, the electricity share is expected to grow more substantially. In the decarbonisation scenarios that accompanied the Energy Roadmap, the electricity share is forecasted to grow to 25-26 % of final demand in 2030 and to 37-39 % in 2050[31]. Other scenarios suggest even higher electricity shares, e.g. the advanced [R]evolution scenario of Greenpeace forecasts an electricity share of 43 % in 2050[32].

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24 Share of fossils in gross inland consumption in 2016. From Eurostat – Simplified energy balances nrg_100a.

25 Eurostat SHARES (2017) Eurostat/Energy/Data/Shares- http://ec.europa.eu/eurostat/web/energy/data/shares.

26 PwC (2018) Unlocking Europe's offshore wind potential -moving to a subsidy-free industry - https://www.pwc.nl/nl/assets/documents/pwc-unlocking-europes-offshore-wind-potential.pdf.

27 https://solarmarketparity.com/market-parity-watch/.

28 Eurelectric (2018) Decarbonisation pathways European Economy – EU electrification and decarbonization scenario modelling.

29 Eurostat (2017) Eurostat/Energy/Data – Simplified energy balances nrg_100a.

30 European Commission (2016) EU reference scenario 2016 - Energy, transport and GHG emissions -Trends to 2050.

31 EC SEC (2011) 1565 Part 2/2 https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

32 Greenpeace (2015) Energy [r]evolution – A sustainable world energy outlook 2015.

2.1.2. Complementing electrification with sector coupling and deployment of carbon-neutral gas

Although electrification is a viable decarbonisation strategy for several end-uses such as low-temperature heat production and light-duty road transport, the feasibility of electrification is much lower for some other energy end-uses. This holds for substantial parts of industrial energy demand, particularly for applications where energy is used as feedstock, and for parts of the transport sector, primarily freight transport by road, shipping and aviation. Decarbonisation of these end-uses requires a complementary strategy to electrification, namely the use of carbon-neutral gases or fuels.

Therefore, in the context of decarbonisation and sector coupling, the gas sector can play a complementary role, both by serving those parts of the energy demand that are difficult to electrify as well as by providing the power sector with additional flexibility through power-to-gas technologies, energy storage and gas-to-power technologies (see section 2.3). In the last decade, the demand for gas in the EU has declined, through a combination of factors, including a decrease in gas use for power generation, which was caused by a decline in prices for coal and renewable energy, the latter being complemented by financial support policies[33]. Additionally, the conflict between Ukraine and Russia and the annexation of Crimea has put the diplomatic relationship between Russia and the EU under pressure. Consequently, the EU imposed restrictions on gas imports from Russia, which further compromised the competitiveness of natural gas in the energy market as Russia is one of the cheapest natural gas suppliers[34].

The future role of gas and the gas infrastructure in the energy system will be strongly influenced by its ability to decarbonise gas supply and to replace natural gas with carbon-neutral gases, such as biomethane, synthetic methane or hydrogen. In the EU, a large potential for the expansion of biogas production exists. It has been estimated that by 2030 biogas production could reach the level of 50 bcm/yr, which is equivalent to approximately 10 % of current natural gas consumption[35]. In total, the biogas potential for Europe has been estimated to be in the order of 150-250 bcm/yr, but this also includes the use of energy crops as a feedstock. At present, biogas is mostly locally used for heat and/or power generation, and there are only installations in a few EU Member States to upgrade biogas to biomethane[36] for injection into the distribution or transmission gas grid. This slow development is caused by the costs and technical constraints associated with upgrading biogas to biomethane to a level that complies with grid quality standards. Biomethane is also not (yet) eligible for financial support and guarantees of origin in several EU Member States. Some Member States are currently adapting their support schemes to include biomethane, and the forthcoming directive for the Promotion of the use of Energy from Renewable will include an extension of the scope of guarantees of origin to include renewable gases[37]. An enabling legal and regulatory framework will have an important impact on the deployment of carbon-neutral gas. In principle, financial support should be technology-neutral and therefore should not specifically favour (or exclude) biomethane (or other carbon-neutral gases like hydrogen). A level playing between all technologies and energy vectors would allow the energy transition to be realised at least cost.

Another important way to decarbonise the gas supply is through the production of carbon-neutral gas by using power-to-gas technologies, which is an example of cross vector integration. The most obvious

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[33] The Oxford Institute for Energy Studies (2017) The future role of gas in decarbonising European energy markets.

[34] The Oxford Institute for Energy Studies (2017) The future role of gas in decarbonising European energy markets.

[35] The Oxford Institute for Energy Studies (2017) Biogas: A significant contribution to decarbonising gas markets?

[36] Upgrading of biogas to biomethane involves the removal of CO2 and pollutants in order to increase the calorific value of the gas and prevent corrosion of the gas infrastructure.

[37] http://www.europarl.europa.eu/RegData/commissions/itre/inag/2018/06-27/ITRE_AG(2018)625378_EN.pdf.

option is to use hydrogen as energy carrier. It can be produced through the electrolysis of water, and can, if appropriate, be processed further into synthetic methane or synthetic liquid fuel, by making the hydrogen react with CO_2 or CO, which, in order to fulfil the CO_2 emission obligations, should originate from biogenic sources or be captured from the atmosphere. Gas production with Power-to-gas technologies is not yet competitive with fossil natural gas, due to a combination of a low carbon emission allowance price, high investment costs, and higher prices for electricity than for gas and low electrolyser efficiencies[38]. In the longer term (2030-2050) it is likely that hydrogen production costs will reach the level of today's biogas production costs, but synthetic methane is expected to remain a relatively expensive option. At present, the focus on using hydrogen as a replacement for natural gas in the European gas grid, either by admixture or by 100 % conversion, is currently limited to a small number of countries (Belgium, Denmark, Germany, the Netherlands, and the UK), i.e. those with a high natural gas demand[39].

2.2. Ensuring system stability, reliability and adequacy and security of supply in the future energy landscape

2.2.1. Enhancing system flexibility through coupling of electricity sector to end-users and using carbon-neutral gas

Increasing deployment of intermittent renewable energy sources leads to a much higher variability in power supply. Variability occurs at different timescales (intra-day, day/night and seasonal), and requires different flexibility options. In addition to the variability in renewable power supply, electricity demand also fluctuates, but this is generally more cyclical and easier to forecast than the variability in intermittent electricity supply. For example, there is a daily and seasonal cycle in the energy demand for space heating and cooling, which can be addressed via time-of-use pricing formulas to stimulate energy management, including demand response. However, if it is not properly managed in a smart way, the variability in electricity demand could substantially increase as a consequence of the further electrification of energy demand for heating and transport. Currently, electricity demand at distribution level peaks at between 18.00h and 21.00h due to the intensive use of electric household appliances during this period. A substantially higher penetration of electrically powered heating systems and of electric vehicles, could lead to significantly higher local peaks in electricity demand, which might necessitate investments in distribution grid reinforcements and peak generation capacity. It has been shown that if 30 % of consumers simultaneously started charging electric vehicles, this could create blackouts in the electricity system[40].

Therefore, there is a need to further deploy technologies that contribute to matching fluctuations in electricity demand and supply. Sector coupling provides options to 'absorb' excess electricity supply from renewable energy sources, to store energy and to provide back-up supply in times of high demand and prices. Similarly, end-use equipment (e.g. batteries, cooling systems) can be used to balance supply and demand at any moment or to provide ancillary services to grid operators to ensure system reliability and adequacy. On the supply side, most thermal power plants can be operated flexibly, and increased interconnection of national electricity grids can provide additional flexibility.

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[38] ENEA (2016) The potential of power-to-gas.

[39] The effects of hydrogen injection in natural gas networks for the Dutch underground storages. Final Report by DBI-GUT for executing a study of the effects of hydrogen injection in natural gas networks for the Dutch underground storages, Commissioned by the ministry of Economic Affairs, Netherlands Energy Agency, May 2017 https://www.rvo.nl/sites/default/files/2017/07/The%20effects%20of%20hydrogen%20injection%20in%20natural%20gas%20networks%20for%20the%20Dutch%20underground%20storages.pdf.

[40] Marsh & McLennan Companies (2017) Blackouts - E-Mobilität setzt Netzbetreiber unter Druck.

Dedicated short term energy storage options such as batteries and pumped hydro and seasonal energy storage like gas storage facilities, can also be used to balance the energy system.

Several end-use sectors, such as industry and transport, but also specific applications in the building sector (e.g. heating and cooling), can act as an additional source of flexible electricity demand that can be used to help address imbalances between demand and supply. Demand-response technologies can be implemented to reduce electricity demand at peak hours, by switching off appliances that can also run at other times, and by switching them on when energy electricity is more abundant. By using dedicated smart IT solutions, end use appliances can be enabled to automatically respond to changes in electricity prices or to local grid constraints. Smart charging schemes could be used for electric vehicles, not only to benefit from the price volatility on the spot market, but also to avoid local grid congestion. Batteries in electric vehicles could also be used to provide reserve capacity or energy to the electricity system (vehicle-to-grid strategy), during moments of peak electricity demand and high prices. Another example of an end-use sector coupling strategy is the deployment of power-to-heat technologies to generate heat during periods of low electricity prices, and to store the heat for later use as process heat or for space heating.

Additional flexibility in the electricity system can also be provided through increased cross-sector integration, predominantly through increased linking of the electricity to the gas sector. Power-to-gas (PtG) technologies can be deployed to produce hydrogen or synthetic methane when electricity is available at low prices. The gas produced can be stored for later re-conversion into electricity. Electricity can be generated from hydrogen through the use of fuel cells or from methane in gas-fired power plants using gas turbines. Alternatively, the renewable gas produced can be used directly in end-use sectors. The hydrogen produced can also be processed into methane or liquid fuel like methanol or more complex hydrocarbons by making it react with CO or CO_2, the so-called power-to-liquid route. These fuels can be used in specific transport applications such as shipping or aviation.

2.2.2. Decreasing dependence on imported energy by shifting to renewable energy sources

The EU energy system is still highly dependent on imported fuels; in 2016 energy imports (gas, oil, solid and nuclear fuels) supplied 53.6 % of the overall primary energy demand[41]. In total, the EU spends over €1 billion per day on energy imports, which is equivalent to approximately 2 % of its GDP. Apart from decarbonising the economy, electrification and increased deployment of renewable energy will reduce the EU's dependence on imported fuels. The Energy Roadmap estimated that reducing GHG emissions by 80 % would lead to a cumulative saving on fuel imports of €518-550 bn in the period 2011-2050[42]. Apart from the high costs involved, reducing the energy import dependency also contributes to lowering the dependence on supplies from third party countries and the related geopolitical risks.

Sector coupling will facilitate the energy transition which will in turn reduce the need for fossil energy imports through far-reaching electrification of end-uses combined with increased deployment of renewable energy sources.

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41 EC (2018) Energy/topics/ Imports and secure supplies https://ec.europa.eu/energy/en/topics/imports-and-secure-supplies.

42 EC SEC (2011) 1565 Part 2/2 https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

2.3. The role of sector coupling in safeguarding Europe's competitiveness

The energy system can be decarbonised in a variety of ways. The decarbonisation strategy that will be chosen is influenced by political preferences and might differ from one national context to another. In principle, authorities should favour a technology-neutral approach towards the energy transition, as the deployment of a wide variety of technologies should in principle lead to a better overall outcome than a single technology-based approach. In the Energy Roadmap 2050 five decarbonisation pathways were evaluated based on divergent technological choices[43]. Some pathways foresee a significant role of nuclear energy or carbon capture and storage, whereas others focus more on energy efficiency and high deployment of renewables.

While the decarbonisation of the energy system can *technically* be realised in a wide variety of ways, there can be significant differences in the cost impacts of the technological options. In order to sustain public support for the energy transition and safeguard international competitiveness of European industries, it is essential that the decarbonisation of the economy takes place in the most cost-effective manner. Several studies show that the decarbonisation of the energy system is most cost-effective if a mix of different low-carbon energy carriers and technologies are used (sector coupling strategy), rather than an electricity focused/electricity-only approach[44].

Figure 2-2 shows a comparison between a fully electrified energy system combined with gas storage and a system with a broader mix of technologies and a strong coupling of the power and gas sectors[45]. The figure shows that the overall electricity generation capacity would be higher in a fully electrified system, mainly resulting from the need for gas-based back-up capacity, which would have a very low utilisation level. The scenario with high sector coupling leads to higher power-to-gas capacities, as (renewable) gas is in this scenario is used to both generate back-up power and to meet demand in specific end-use sectors like transport.

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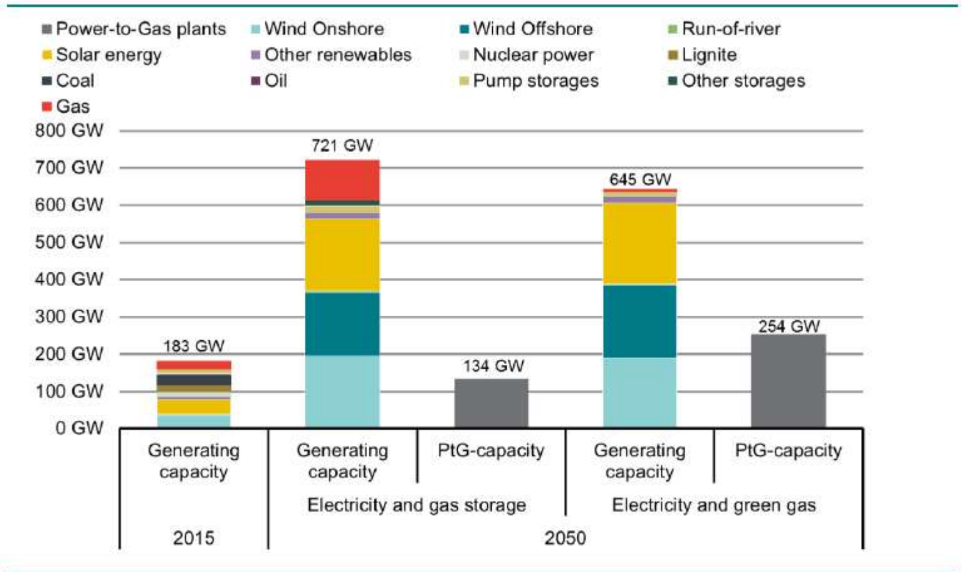
[43] EC SEC (2011) 1565 Part 2/2 https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

[44] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende; DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

[45] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende; DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

Figure 4: German electricity generation and PtG capacities in 2015 and 2050 in a fully electrified (electricity and gas storage) scenario and sector coupling (electricity and green gas) scenario



Source: Frontier Economics (2017).

The Frontier Economics study[46] concludes that sector coupling leads to a lower overall cost, mainly because of reduced investment costs, as the lower overall electricity demand and supply peaks allow for less reinforcement investments in the electricity transmission and distribution grids and require less gas-based power generation capacity. Overall, the operational efficiency of a system with sector coupling is higher as it uses the available energy and assets in a more economical way. The application of power-to-x technologies[47] in times of high electricity supply, optimises the use of energy when it is abundantly available. Also, the high gas-based power capacity in a fully electrified system is used with a low load factor (only during peak hours), which makes such a configuration relatively costly. Frontier Economics estimated that for Germany, a sector coupling scenario would generate an annual cost saving of €12 bn or an accumulated cost saving of €268 bn by 2050[48], compared to a fully electric scenario.

A recent study by the German Energy Agency DENA modelled four different decarbonisation scenarios for the German economy, which differ in the emission reduction achieved in 2050 (either 80 % or 95 %) and in the energy mix, with one scenario focusing on large scale electrification and the other on a broader mix of technologies[49]. The first remarkable result is that both scenarios achieve an 80 % GHG emission reduction, with an additional cost for the German energy system that is about as large as the additional cost estimated for the EU as a whole in the five decarbonisation scenarios that were analysed

46 Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende; DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

47 Power-to-X is a collective term for all technologies that convert electrical energy into another energy form. Included technologies are: power-to-gas, power-to-heat and power-to-liquids.

48 Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

49 DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

as part of the impact assessment accompanying the Energy Roadmap 2050[50] or in the decarbonisation scenarios developed by Greenpeace[51]. The main reasons for this discrepancy are differences in the methodology and the scope of the costs considered in the two studies. For example, the DENA study included the investment required in new vehicles in the costs of the energy transition, which makes a scenario with higher shares of electric vehicles much more expensive. The costs and benefits of different scenarios might differ strongly between EU Member States with some countries having large additional costs and others primarily cost savings. Finally, the DENA study did not discount future investments, whereas the PRIMES model used for the impact assessment of the Energy Roadmap 2050 does, which leads to cost estimates that are not comparable.

As with the Frontier Economics study, the DENA study found that the scenario that only focuses on large scale electrification would be costlier than the scenario applying a much broader mix of energy technologies and sector coupling. The difference is so large that the broad technology mix scenario achieving a GHG reduction of 95 % would be less costly than a large-scale electrification scenario achieving a GHG emission reduction of only 80 %[52]. This difference can be primarily explained by a large increase in capital costs[53] in the large-scale electrification scenario. The outcome of this DENA study suggests that sector coupling can play an important role in increasing the cost efficiency of the energy transition, but further research is needed to verify the robustness of these findings. It would also be useful to investigate whether similar results would be obtained when the decarbonisation of the energy system is analysed in other EU Member States and at the EU level.

2.4. Coupling of renewable energy deployment to the energy demand for heating and cooling in buildings

Energy consumption for heating and cooling is responsible for a significant share of the GHG emissions in industrialised countries and is one of the most important energy end-uses in the EU. In 2015, around half of the final energy demand in the EU was used for heating and cooling purposes in buildings and industry; over half of this was used for space heating and about one third as process heat in industry[54]. Peak demand for heating or cooling is a crucial aspect in the design of energy infrastructure, and in 2015 heat demand represented the highest peak energy demand among the end-uses analysed by Connolly.[55]

Several technologies are available to decarbonise the energy demand for heating and cooling through sector coupling. These include the direct use of renewable energy such as geothermal energy, solar heat, or biomass for heating purposes, or the indirect use of renewable energy via the electrification of building heating systems and the use of electric heat pumps. Cross-vector integration is also possible, for example with hybrid heat pumps or (renewable) gas fuelled combined heat and power installations (turbines, fuel cells, engines). Currently, biomass is still the most common source of renewable heating in Europe, but recently the share of electric heat pumps is increasing. The availability of geothermal and solar radiation resources for building heating is geographically limited, making end-use sector

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50 European Commission SEC(2011)1565 Impact assessment accompanying the Energy Roadmap 2050. Part 2/2 https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

51 Greenpeace (2015) Energy [r]evolution – A sustainable world energy outlook 2015.

52 DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

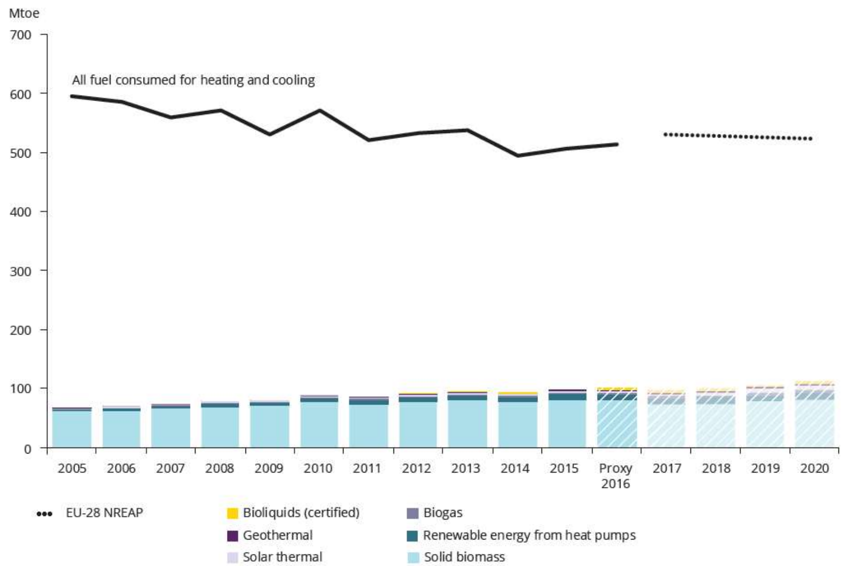
53 These capital costs include also investments in new vehicles by private individuals.

54 Heat Roadmap (2017) Profile of heating and cooling demand in 2015.

55 Connolly (2017) Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries.

coupling through electrification and cross-vector integration in most EU Member States the most appropriate route to decarbonise energy consumption for heating.

Figure 5: Trend in the use of renewable heating sources in the EU compared to overall heat demand



Source: EEA, 2017[56].

In summary, the energy consumption for heating is an area where sector coupling can contribute to decarbonisation through high-impact actions leveraging a number of solutions.[57] The main solutions are end-use sector coupling through heat pumps and to a lesser extent electric boilers, and cross-vector integration through combined heat and power for large buildings or district heating. The energy demand for cooling of buildings in the EU is currently still limited and in all European countries lower than the demand for heating regardless of their geographical location.[58] At present, the energy consumption for cooling represents on average only 5 % of the heating demand for buildings. This share is expected to increase as a consequence of the technical requirements imposed by the Energy Performance of Buildings Directive.

2.4.1. End-use sector coupling through heat pumps and renewable electricity

Figure 3-2 presents the options for the indirect use of renewable energy in heating through decentralised technologies. It indicates that electric heat pumps are the option with the best technical performance, which is confirmed by several studies analysing the potential of power-to-heat in Europe and specific European countries.[59] Heat pumps are attractive because of their high coefficient of performance; they provide about three times more thermal energy than their electricity consumption,

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56 EEA (2017) Renewable energy in Europe – 2017 Update - Recent growth and knock-on effects.

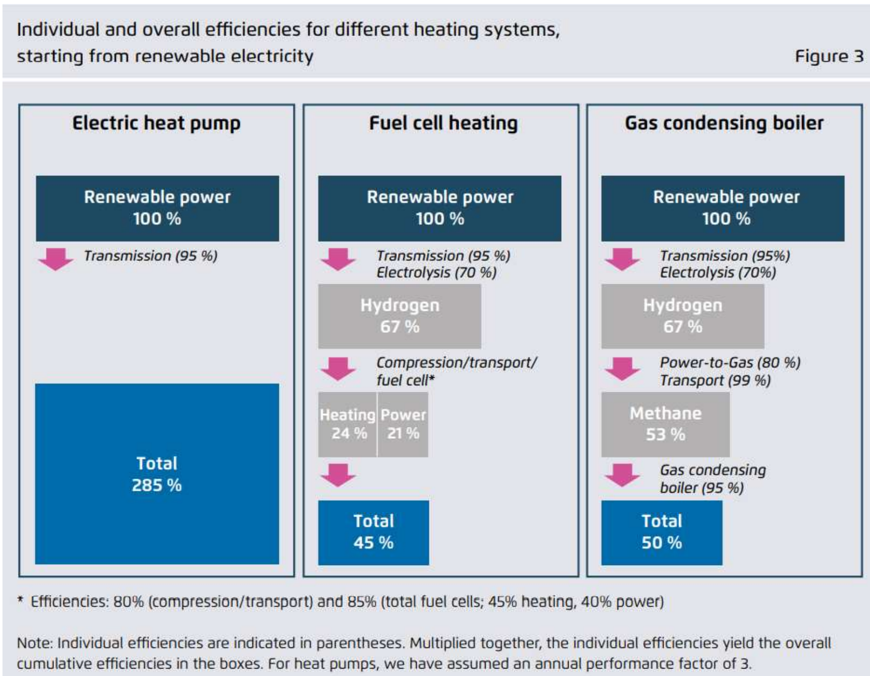
57 Bloess et al. (2017) Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials.

58 Connolly (2017) Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries.

59 Connolly (2017) Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries.

while other technologies have a coefficient of performance of less than 1. Bloess *et al.* indicate that electric resistive boilers and combined heat and power (CHP, the main approach to large buildings and district heating) can be valuable alternatives or supplementary options to heat pumps.[60]

Figure 6: Comparison of the energy efficiency of different heating solutions with indirect use of renewable energy



Source: Frontier Economics, 2018.[61]

The stock of heat pumps in Europe reached almost 10 million units in 2016, which is still very low compared to the European housing stock. Heat pump sales stagnated between 2008 and 2013 at around 750 000 units per year, although sales have increased since then. Heat pumps are theoretically reversible and are therefore also able to provide cooling for buildings. Of the more than 800 000 heat pumps sold in Europe in 2015, more than 450 000 were reversible. Reversible air-air units are generally deployed in warmer climates, with ground-source heat pumps being used in colder climates.[62]

2.4.2. Cross-vector integration through district heating and renewable energy sources

Regarding cross-vector integration solutions, at present district heating meets 12 % of European heat demand and has an important share of building heat demand in some European countries such as Denmark (51 %) and Poland (34 %), with biomass being the most frequent form of renewable energy source used. Germany has the highest number of district heating networks in Europe (1,342 in 2014), followed by Denmark (394). District heating based on renewable energy sources is expected to increase in several European countries according to the analysis of the International Renewable Energy Agency

60 Connolly (2017) Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries.

61 Frontier Economics (2018) The future costs of electricity based synthetic fuels.

62 SETIS (2015) Heat Pumps: Technology Information Sheet.

(IRENA), and some technologies are already competitive with non-renewable district heating in some countries. District cooling is not significant in Europe.[63]

District heating complements the end-use sector coupling strategy of heat pumps as one of the main solutions for decarbonising heat demand in buildings in Europe, and there is significant potential for both sector coupling strategies. CHP usually has some form of thermal storage, providing flexibility to the power, heat and gas systems. Further gains can be achieved with the development of so-called combined cooling, heat and power, which would advance the coupling of the cooling end-use sector.[64] District heating can also use multiple renewable energy sources such as biomass, waste heat and solar thermal.[65] Heat pumps and renewable energy based district heating with a CHP installation are complementary, as the former should preferably operate during periods of low electricity prices, while the latter should operate during high-price periods.[66] The opportunity also exists to connect heat pumps to heat distribution grids[67], which would advance decarbonisation through electrification, and provide further system flexibility and coupling between the electricity and heat sectors. There are significant opportunities for the decarbonisation of the demand for heat in European buildings within the strategies of end-use sector coupling and cross-vector integration, and also significant synergy potentials between these strategies.

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63 IRENA (2017). Renewable Energy in District Heating and Cooling – A Sector Roadmap for REMAP.

64 INSIGHT_E (2014) Synergies in the integration of energy networks for electricity, gas, heating and cooling.

65 Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.

66 Bloess et al. (2017) Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials.

67 Bloess et al. (2017) Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials.

3. HOW CAN SECTOR COUPLING BE ACHIEVED?

KEY FINDINGS

- Electrification can be used to decarbonise a major share of heat demand in buildings and passenger and light-duty road transport.
- Decarbonisation of industry will require a combination of electrification, increased use of hydrogen and biomass/gas and potentially CCS.
- Power-to-gas technologies can act as an important sink for surplus renewable electricity and provide low carbon energy for industrial and transport applications.
- In the long term the use of renewable synthetic fuels might be a viable option for large-distance shipping and aviation.
- Synthetic fuels might be produced domestically or imported from areas with abundant renewable energy resources.
- End-use sector coupling can act as a source of flexibility to absorb fluctuations in electricity supply and demand.
- Cross-vector integration between the power and gas sector can be used to produce gases for seasonal storage or to provide back-up power.

The previous chapter highlighted the benefits of sector coupling and its contribution in reducing the overall costs of the transition to a decarbonised energy sector. This chapter presents the technologies that can be implemented to achieve (more) sector coupling. The first three sections focus on end-use sector coupling and cross-sector integration, whereas section 3.4 focuses on cross-vector integration.

3.1. Coupling of renewable energy deployment to industrial energy end-uses

3.1.1. Industrial energy demand can be partially electrified, but other decarbonisation strategies are also needed

Energy demand in industry is still heavily dependent on the direct use of fossil fuels. Currently, the share of electricity use in industrial energy demand is around 31 % and although there is a significant potential for further electrification, some specific processes would be very difficult to electrify (e.g. when energy is used as feedstock for industrial processes). A recent study by Eurelectric estimates that in 2050 between 38 and 50 % of industrial final energy demand could be electrified, depending on the level of ambition in the modelled scenarios[68]. Figure 3-3 gives an overview of the industrial processes that can be electrified relatively easily, and the processes for which other decarbonisation strategies such as the use of biomass and CCS would be likely to be needed.

[68] Eurelectric (2018) Decarbonisation pathways European Economy – EU electrification and decarbonization scenario modelling.

Figure 7: The maturity of decarbonisation strategies for various industrial processes

Source: Eurelectric, 2018[69].

Electrification of industrial energy demand can be applied to the core manufacturing processes or to utilities that are used for supporting activities[70]. Even though a large share of energy use in industry is related to core processes and a substantial potential for electrification exists, the conversion of the process technology from fossil fuel-based technology to electricity-based technology often requires shutting down production processes which can result in substantial economic losses. This acts as a barrier to the implementation of innovations for the electrification of processes. Another important aspect to be considered is the difference between flexible and baseload electrification. The electrification of flexible processes, that do not need to run continuously, presents an opportunity to contribute to balancing the electricity system, via demand-response technology. The production of chlorine using electrolysis is an example of a process that could be applied as an industrial demand flexibility option[71].

Replacing all fossil-based feedstocks by synthetic fuels produced by using electricity would lead to vast increases in electricity demand. Dechema estimated that to reduce GHG emissions from the European chemical industry by 84 % would, also taking into account the expected demand growth for chemicals, increase electricity demand from roughly 611 TWh in 2014 to 1 900 TWh in 2050[72]. Beyond the challenge of supplying the necessary electricity, many industrial processes could be more cost-efficiently decarbonised through strategies other than end-use sector coupling through electrification.

[69] Eurelectric (2018) Decarbonisation pathways European Economy – EU electrification and decarbonization scenario modelling.

[70] Berenschot, Energy Matters, CE Delft & Industrial Energy Experts (2016) Electrification in Dutch process industry.

[71] Berenschot, Energy Matters, CE Delft & Industrial Energy Experts (2016) Electrification in Dutch process industry.

[72] DECHEMA (2017) Low carbon energy and feedstock for European chemical industry.

3.1.2. Electrification is challenging for the decarbonisation of HT heat demand

There is substantial potential for electrifying low-temperature processes in industry with heat pumps, which represent approximately a quarter of industrial energy demand. However, part of this low-temperature heat demand is currently not provided by dedicated heating technologies, but rather by residual heat from high-temperature heat processes[73].

Heat pumps are being developed for high-temperature energy uses (>200ºC), but are not yet commercially available. High-temperature heat demand represents 37 % of industrial energy demand[74] and this heat demand can still be electrified through the use of electric boilers. Alternative decarbonisation strategies are the combustion of biomass, renewable methane or hydrogen in large industrial boilers.

Biomass is only available in limited quantities and it is therefore important that it is used in those applications where it adds most value. These applications include the use of biomass as a feedstock for the chemical industry or as aviation fuel. The transition from a linear to a circular economy will also require increased substitution of abiotic materials with bio-based ones, which will increase the demand for non-food biomass and indirectly the demand for arable land.

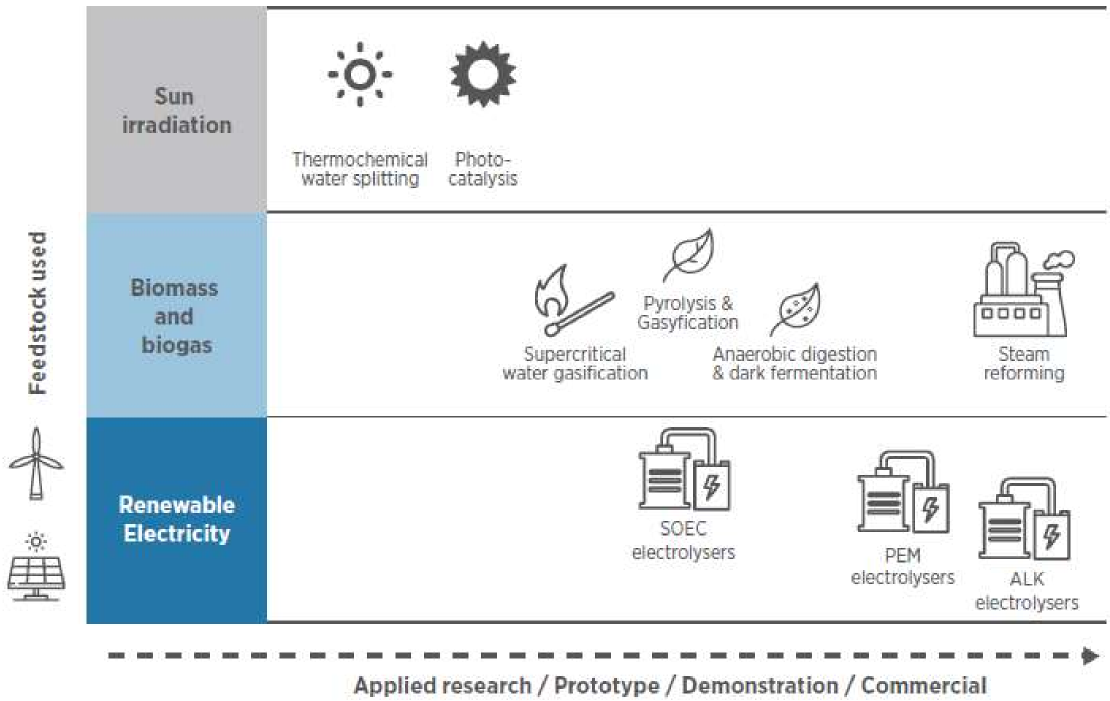
3.1.3. Hydrogen use in industry

Hydrogen can play an important role in the decarbonisation of industry, as it can meet specific end-uses that are difficult to electrify. Hydrogen can be used for high-temperature heat production, as a feedstock in the chemical industry or as a reductant in steelmaking, thereby replacing coal or gas-based processes. Currently, hydrogen is usually made from fossil methane through steam reforming, but in the future energy system hydrogen could be produced from renewable electricity through electrolysis. An overview of the different hydrogen production technologies and their technical maturity is given in figure 3-4.

[73] Heat Roadmap (2017) Profile of heating and cooling demand in 2015.

[74] Heat Roadmap (2017) Profile of heating and cooling demand in 2015.

Figure 8: Development stages in hydrogen production technologies



Source: IRENA, 2018[75].

There are several electrolyser technologies that differ in their efficiencies and costs. At the moment, alkaline electrolysis is the only process that is applied commercially for power-to-gas applications. The process has an efficiency of 67-82 %[76] and the capital costs are between 1 000 and 2 000 EUR/kW$_{el}$[77]. Proton Exchange Membrane (PEM) electrolysis is a technology that is currently only used in niche markets but has a large potential for future cost reductions. At present, the capital costs are in the order of 1000 EUR/kW$_{el}$, but they could decline to around 700 EUR/kW$_{el}$ by 2025[78]/2030 and 400 EUR/kW$_{el}$ in 2050[79]. PEM technology also has the advantage that it can ramp its load up or down quite quickly, which makes it very suitable for the provision of grid flexibility services[80] (see section 3.4.2 a). It can even provide ancillary grid services such as frequency control without compromising the hydrogen output. Combining hydrogen revenues with revenues from energy system flexibility services can help to improve the business case of hydrogen production. The efficiency of PEM electrolysis currently lies in the same range as that of alkaline electrolysis[81].

Solid Oxidiser Electrolyser Cells (SOEC) are a relatively new technology which operate at high temperatures to reduce the electricity input required[82]. This technology has a large potential for sector coupling, as it could use waste heat from industry or from CSP plants. The advantage of this technology

[75] RENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.
[76] Carmo *et al.*, 2013. A comprehensive review on PEM water electrolysis.
[77] ENEA (2016) The potential of power-to-gas. http://www.enea-consulting.com/wp-content/uploads/2016/01/ENEA-Consulting-The-potential-of-power-to-gas.pdf.
[78] IRENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.
[79] ENEA (2016) The potential of power-to-gas.
[80] IRENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.
[81] Carmo *et al.*, 2013. A comprehensive review on PEM water electrolysis.
[82] ENEA (2016) The potential of power-to-gas.

is that high efficiencies can be reached (80-90 %) at a relatively low cost. Due to its novelty, capital costs for commercial-scale Solid Oxidiser Electrolyser Cells are still unclear.

Hydrogen is currently used as a feedstock for the production of several chemicals. The largest use (84 %) of hydrogen for chemicals is in the production of ammonia. In this process hydrogen is made from natural gas, which then reacts with atmospheric nitrogen (N_2) to form ammonia., The EU currently produces around 12 Mtons of nitrogen fertilizers each year[83], of which ammonia represents the largest share. Ammonia production accounts for 24 Mtons of CO_2 emissions each year[84]. In the future, this fossil-based hydrogen production process could be substituted by hydrogen production from renewable electricity.

Hydrogen is currently also used as an intermediate feedstock in methanol production. In this process hydrogen is produced from natural gas and subsequently the hydrogen reacts with CO_2 to form methanol. The main current use of methanol is as a building block for the synthesis of other chemicals, but in the future, it could also be used for transport applications. As with other hydrogen consuming processes in industry, the methane-based process could be replaced by hydrogen generation from renewable electricity in the future.

Hydrogen is also used in refineries, for sulphur removal, changing the chemical properties of the hydrocarbons produced (isomerisation and de-aromatisation) and cracking of long hydrocarbons into the gasoline (C_8) range[85]. Refineries in Europe currently consume 2.1 Mtons of hydrogen each year[86], of which a small part is generated in the refining process but the majority is produced by steam reforming of methane. It has been calculated that substituting the natural gas derived hydrogen with hydrogen produced by using renewable electricity could reduce the upstream emissions from the production of transport fuels by 90%[87].

One of the major sources of GHG emissions is the steel industry, accounting for approximately 123 Mtons CO_2-eq of GHG emissions, which is equivalent to approximately 3 % of all GHG emissions generated in the EU[88]. The majority of primary steel is produced in the so-called blast-furnace basic oxygen furnace (BF-BOF) process. In the first step of this process iron is produced from iron ore in a blast furnace, through the reaction of carbon monoxide derived from the coke fuel with the iron ore which reduces the iron to its elemental form. Coke is pure carbon, which is mostly derived from coal. Subsequently, in the basic oxygen furnace a large share of the carbon content is removed, by oxidation forming carbon monoxide and to a lesser extent carbon dioxide. Other impurities such as silicates, sulphur, manganese, and phosphates are also oxidised and these oxidised compounds end up in the slag, a by-product which is separated from the steel. The BF-BOF process accounts for 85 % of the overall GHG emissions in the steelmaking process[89].

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83 Fertilizers Europe (2018) Industry facts and figures 2018.

84 EEA (2018) Greenhouse gas emissions by source sector.

85 Linde Group official website. Hydrogen in refining. http://www.linde-gas.com/en/processes/petrochemical-processing-and-refining/hydrogen_applications_refineries/index.html.

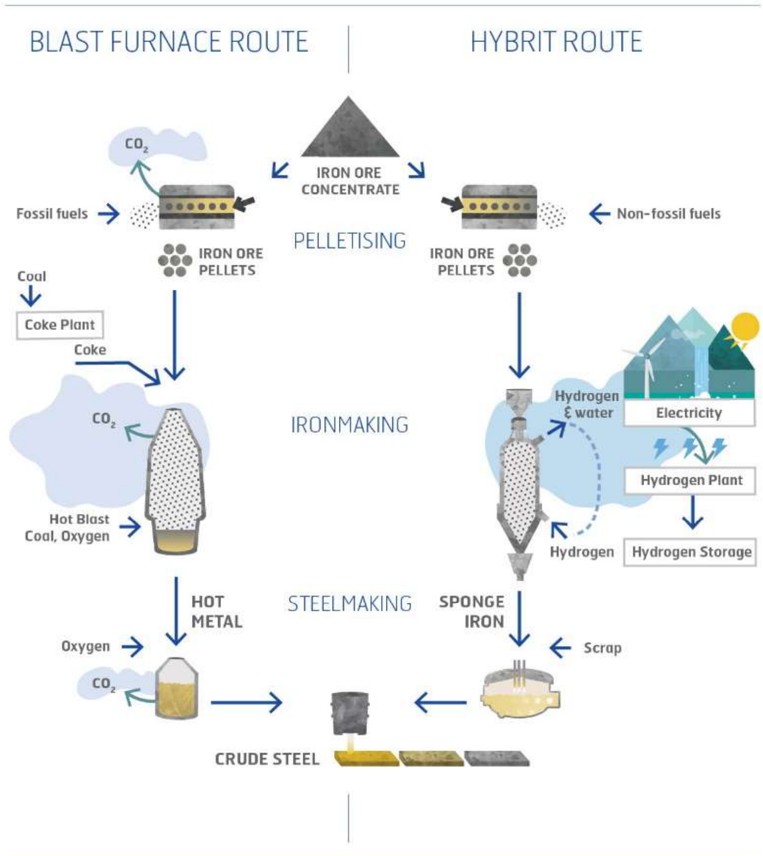
86 Hydrogen Europe official website. Decarbonise industry. https://hydrogeneurope.eu/decarbonise-industry.

87 Hydrogen Europe official website. Decarbonise industry. https://hydrogeneurope.eu/decarbonise-industry.

88 EEA (2017) Trends and projections in Europe 2017 - Tracking progress towards Europe's climate and energy targets.

89 McKinsey (2018) Decarbonisation of industrial sectors: the next frontier.

Figure 9: Comparison of the conventional BF-BOF steelmaking route (left) and the Direct Reduced Iron process based on renewable hydrogen (right)



Source: http://www.hybritdevelopment.com/steel-making-today-and-tomorrow.

Instead of using the BF-BOF route for steel production, steel can also be produced by directly reducing iron ore using natural gas, oil or hydrogen, the so-called direct reduced iron (DRI) process. This reaction generates lower levels of GHG emissions than the reduction of iron in the blast furnace. A DRI process using natural gas reduces emissions by over 40 % compared to the BF-BOF process[90]. The sponge iron formed in the DRI process is then fed into an electric arc furnace (EAF), usually after mixing with scrap, to remove impurities and turn the iron into steel. The Swedish steel manufacturer SSAB is currently working on a pilot project, Hybrit, where hydrogen is used for the reduction of iron in a solid state (Figure 3-5). The advantage of using hydrogen instead of hydrocarbons during the iron reduction process is that no carbon is added to the iron, which later needs to be removed to form high quality steel. The Hybrit demonstration pilot will run until 2024. Subsequently, in the period 2030-2040 SSAB is planning to replace all its blast furnaces by hydrogen-based DRI processes. In Linz, Austria, a similar project was started in 2017 under the hydrogen joint undertaking. This project, called H2Future,

[90] McKinsey (2018) Decarbonisation of industrial sectors: the next frontier.

involves a 6 MW electrolyser that will use hydropower to produce green hydrogen, which can be used for DRI in the steel plant of Voestalpine[91]. The test phase will start in 2019.

Another innovative technology for low-carbon steel making that is currently being investigated, is the direct electrolysis of iron ore to reduce iron by directly using electricity. As this process only requires electricity this molten oxide electrolysis route has gained attention from the steel industry as a possible way to reduce GHG emissions. However, to date this technology is still in an experimental phase, so commercial iron production using this route might be possible in the future, but only in the long term.

In summary, hydrogen can be an important part of the solution for decarbonising a wide range of processes in industry, where the direct use of electricity is difficult or even impossible. The fact that the demand for hydrogen for industrial purposes as well as for some applications in the transport sector (see next section) is expected to increase, illustrates that sufficient affordable hydrogen supplies need to be available in the future energy system. This hydrogen can be produced in the most cost-effective way if the electricity and gas sector become more integrated. This cross-vector integration will be discussed in section 3.4.

3.2. Coupling of renewable energy deployment to the transport demand

3.2.1. Electrification will play a key role in decarbonising the transport sector

Currently, the transport sector has the lowest share of renewable energy use of all end-use sectors. In 2016, 94 % of the energy demand in transport was met by oil-based products[92]. Decarbonisation of the transport sector is essential for the EU to achieve its climate change mitigation objectives, as this sector is responsible for one third of the final energy use in the EU and 23 %[93] of all GHG emissions. The largest share of the energy use (57 %)[94] and GHG emissions (58 %)[95] of the transport sector originate from passenger car transport.

The EU originally focused on increasing the use of biofuels in road transport, but due to the limited availability of sustainable biomass, the potential contribution of biofuels to the overall decarbonisation of the transport sector is rather limited. In the last few years, electrification has emerged as one of the most promising solutions for decarbonising passenger road transport. Although the share of electric vehicles (EVs) in total car sales is still only around 1 %, sales of EVs have increased substantially in many European countries over the last few years. A large share of these cars are currently hybrid vehicles and plug-in hybrids, but the share of fully electric vehicles is expected to increase as battery technology improves, leading to improved driving ranges and reduced costs.

The total cost of ownership (lifetime costs) of battery electric vehicles is currently higher than that of cars with internal combustion engines (gasoline and diesel cars), but a break-even point might be reached as soon as 2023[96]. As a consequence of the increasing attractiveness of electric cars after 2020, forecasts suggest that by 2030 electric vehicles (including hybrids and fuel cell vehicles) will account for over 70 % of total car sales if strong climate mitigation policies are pursued.

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91 http://www.voestalpine.com/group/en/media/press-releases/2018-04-16-H2FUTURE-on-track-construction-starts-at-the-worlds-largest-hydrogen-pilot-facility/.

92 Eurostat (2017) Eurostat/Energy/Data – Complete energy balances nrg_110a.

93 EEA (2018) Greenhouse gas emissions by source sector.

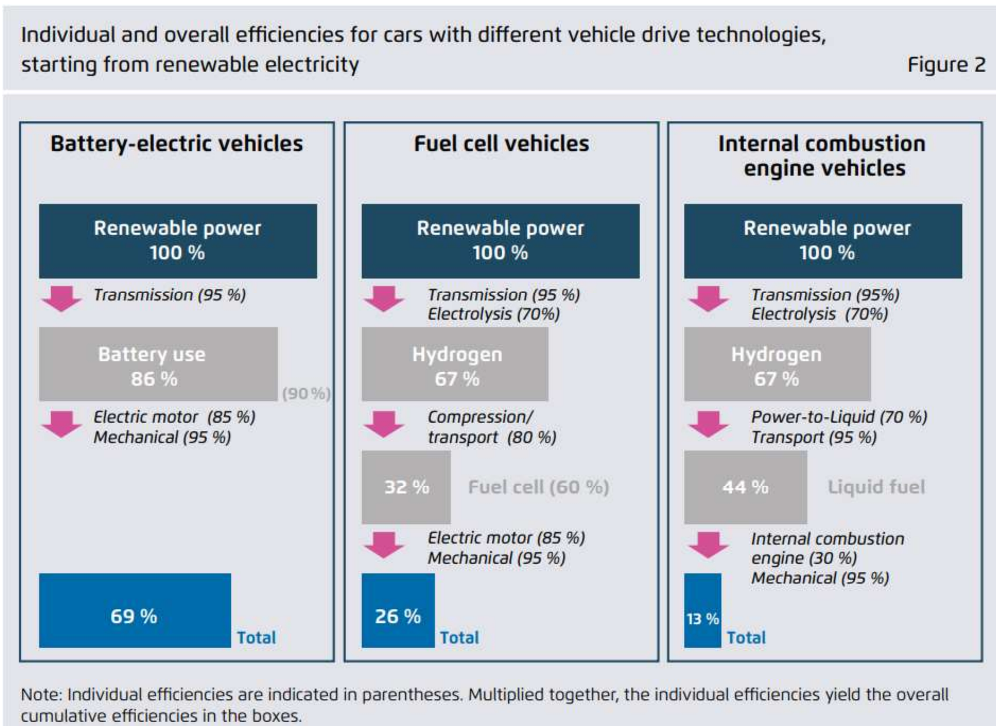
94 European Commission (2016) EU reference scenario 2016 - Energy, transport and GHG emissions -Trends to 2050.

95 European Commission (2016) EU reference scenario 2016 - Energy, transport and GHG emissions -Trends to 2050.

96 ING (2017) Breakthrough of electric car technology threatens European car industry.

Electric vehicles will not only be attractive from an economic viewpoint, but they are also the most efficient option in terms of energy use. Several organisations and companies are promoting the use of hydrogen in the transport sector, and although hydrogen will definitely be an important solution for some specific transport modes, it is not the most energy efficient option for decarbonising passenger car transport. A recent study compared the overall efficiencies for different combinations of energy carriers and drivetrains and the battery electric vehicle came out as the most efficient option, with an overall efficiency of 69 % (figure 3-6). The lower efficiency of cars fuelled with hydrogen relates to the fact that the hydrogen is produced from electricity with some energy losses. In a fuel cell electric vehicle, the hydrogen is then converted back into electricity, involving losses, in order to run the electric engine. As battery charging is a relatively efficient process, with losses in the order of only 10 %, a battery driven electric vehicle is more efficient than a fuel cell electric vehicle. If hydrogen is used in a conventional internal combustion engine, the efficiency is lower than that of gasoline or diesel cars.

Figure 10: Comparison of the overall efficiency of different car drivetrains, based on the use of renewable electricity



Source: Frontier Economics, 2018[97].

Due to the large efficiency losses and high investment costs related to electrolyser technology (see section 3.2), the economics of hydrogen use for passenger transport will be less favourable than the economics of electric vehicles. Currently, hydrogen is competitive with the use of bio-based CNG in the transport sector, but to become competitive with untaxed fossil fuels, the capital costs for hydrogen would need to be halved and cheap electricity (price < €20/MWh) would need to be available for at

[97] Frontier Economics (2018) The future costs of electricity based synthetic fuels.

least 6 000 hours a year[98]. These conditions are unlikely to be met in the foreseeable future, which means that financial incentives would be needed. In the short to medium term (up to 2030) hydrogen could only compete with taxed gasoline if produced from untaxed electricity. In 2050, hydrogen would be competitive with gasoline, even with electricity prices up to €80/MWh (including taxes).

3.2.2. Electrification of passenger cars poses challenges and solutions for balancing the electricity grid

A high penetration of electric vehicles will have a significant impact on total electricity demand and, if not managed correctly, also on peak electricity demand. Several studies have shown that if electric cars were charged in a non-coordinated way, this could require capacity reinforcements in local electricity grids. For this reason, and also to optimise their charging based on electricity market conditions, it is important that appropriate smart solutions are developed and implemented. For example, charging could take place at night-time when electricity demand in general is lower. In order to promote such smart charging, flexible time-of-use electricity tariffs need to be developed to stimulate charging during off-peak hours. There is also a need for IT solutions that can manage the time of day when a vehicle is charged, in order to minimise the charging costs through charging at off-peak hours when electricity prices are lowest[99].

While a high market penetration of electric cars could create local problems in electricity grids if their charging is not properly managed, a large pool of electric vehicles could potentially act as a collective battery that actually contributes to the balancing of the electricity grid. Smart charging of vehicles could be used to absorb excess electricity at moments of abundant supply and vehicles can provide electricity back to the grid in times of peak demand. With the current state of battery technology, where batteries can only undergo a relatively low number of charge/discharge cycles, vehicle-to-grid (V2G) applications would increase the rate of battery degradation and thus shorten the life of the battery pack. Therefore, engaging in V2G activities will be unattractive for EV owners, unless proper payment mechanisms are developed to compensate for the battery degradation. However, when participating in the reserve capacity market the capacity that is offered is often not effectively utilised, whereas capacity providers are remunerated for reserving the capacity regardless of whether it is used or not. This could improve the business case for engaging in V2G activities. A study from the UK shows that the economic value of V2G is largest for participation in capacity markets and wholesale trading, but less for incidental peak demand reduction and short-term reserve services such as those provided on the Short-Term Operating Reserve (STOR) market[100]. Another challenge is that most manufacturers of electric vehicles do not currently support electricity flows from the car battery back to the grid.

3.2.3. Decarbonisation of road freight will require a combination of technologies

Until recently biofuels and hydrogen were considered as the only fuels available for the decarbonisation of heavy-duty road transport. However, in recent years the first fully electric trucks have been announced[101]. As with passenger cars, the limited driving range due to the current state of battery technology is a barrier to the uptake of fully electric trucks in the short term, although ranges

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98 ENEA (2016) The potential of power-to-gas. http://www.enea-consulting.com/wp-content/uploads/2016/01/ENEA-Consulting-The-potential-of-power-to-gas.pdf.

99 Mwasilu *et al.* (2014) Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration.

100 Gough *et al.*, 2017. Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage https://www.sciencedirect.com/science/article/pii/S0306261917301149.

101 https://www.tesla.com/nl_NL/semi?redirect=no; https://www.daimler.com/products/trucks/mercedes-benz/mercedes-benz-electric-truck.html.

of over 800 km have already been announced for trucks that will be brought to the market in the next few years[102]. The installation of overhead catenary lines along some main road freight routes for has also been proposed in order to allow for charging on the move[103].

In addition to full electric trucks, hybrid solutions will play a role in the medium term. Hydrogen can also be used as a fuel in heavy duty road transport, despite its disadvantages in terms of overall energy efficiency. The first hydrogen-fuelled trucks have recently been put onto the road[104]. CNG and LNG-based vehicles can also be used to reduce emissions in the short term, as bridging technology between today's diesel engines and future electric and H_2-based technologies.

3.2.4. Decarbonisation of shipping and aviation will involve synthetic fuels, biofuels and green gas

In contrast to road transport, liquid fuels are expected to retain their dominance in shipping and aviation. In the aviation sector, overall energy demand is expected to increase despite forecasts of efficiency improvements, because of sustained growth in demand for (passenger) air transport. Between today and 2050, demand for air transport is expected to double[105], if no stringent policies are implemented to reduce demand. In aviation, the most viable short-term solution for decarbonisation is biofuel. In the longer-term synthetic fuels and hydrogen might become additional solutions[106]. Experiments have been done with electric aircrafts, but this has been extremely challenging, largely due to the low energy density and high weight of batteries among other issues[107].

In the shipping sector, electrification is challenging for ships travelling larger distances, primarily due to the difficulty of storing sufficient amounts of energy on board. Therefore, renewable liquefied or compressed natural gas (LNG and CNG) as well as hydrogen and various synthetic fuels, especially methanol, have been suggested as promising decarbonisation strategies for long distance shipping[108]. For short-distance shipping, e.g. for ferries, electrification could be a solution[109].

3.2.5. Substantial use of synthetic fuels can lead to cost reductions in the energy system overall

From an energy efficiency perspective, electric vehicles are a better option than vehicles using hydrogen or synthetic fuels, as the use of the latter involves more energy conversions leading to larger losses. However, from an overall optimisation and cost minimisation of the energy system perspective meeting a substantial share of transport sector energy demand with synthetic fuels could be more cost effective. This can be explained by the fact that the use of hydrogen and synthetic fuels reduces the requirement for additional investments in electricity transmission and distribution infrastructure[110]. These cost reductions outweigh the costs resulting from the increase in energy losses. A similar argument can be made for the use of hydrogen for heating s, in such cases the decision not to electrify

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102 https://www.tesla.com/semi.

103 Siemens (2017) eHighway – Innovative electric road freight transport. https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/mobility/road/electromobility/ehighway/documents/ehighway-2017.pdf.

104 Fuel cells bulletin (2017) Toyota unveils hydrogen fuel cell drayage truck for feasibility study at Port of Los Angeles - https://doi.org/10.1016/S1464-2859(17)30135-9 ; https://nikolamotor.com/two.

105 European Commission (2016) EU reference scenario 2016 - Energy, transport and GHG emissions -Trends to 2050.

106 IATA (2015) IATA Sustainable aviation fuel roadmap; Kadyk et al., 2018. Analysis and Design of Fuel Cell Systems for Aviation.

107 Roland Berger (2017) Aircraft Electrical Propulsion – The Next Chapter of Aviation?

108 OECD/ITF (2018) Decarbonising Maritime transport https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf.

109 Yale Environment website: https://e360.yale.edu/features/europe-takes-first-steps-in-electrifying-worlds-shipping-fleets last retrieved on 30/08/2018.

110 DENA (2018) Leitstudie Integrierte Energiewende - Impulse für die Gestaltung des Energiesystems bis 2050.

the demand can also reduce the costs related to the refurbishment/replacement of end-user equipment (e.g. boilers).

3.3. Supply-side options for sector coupling: integration of electricity and gas systems

The concept of sector coupling was originally developed as a strategy to maximise the electrification of end-use sectors and increase the integration of the electricity sector with end-use sectors. However, the increased integration of different energy carriers (cross-vector integration) has recently gained attention, particularly with regard to the far-reaching integration of the electricity sector with the gas sector. Cross-vector integration can; increase the flexibility of the energy system as a whole, contribute to security of supply and reduce the overall costs of the transition to a decarbonised energy system (see section 2.3).

3.3.1. Growing shares of intermittent renewable energy sources increasingly lead to imbalances in the electricity system

In recent decades, the share of renewable sources in the energy supply of Europe has grown substantially, especially in the power sector. In 2016, renewable energy accounted for almost 30 % of the electricity demand, whereas its share in the overall final energy consumption was 'only' 17 %.

Hydropower has traditionally been part of the electricity generation mix in Europe, making it the first, and still main, renewable contributor to Europe's energy supply[111]. However, in the most recent decade the growth in renewable electricity generation capacity has primarily come from wind energy and PV-solar (Figure 3-7), although recently the growth in PV has slowed. For the last eight years, the majority of newly added electricity generation capacity has been from renewable energy sources[112]. In 2016, renewable energy accounted for 86 % of the newly installed capacity and this share is increasing[113]. The strong growth of renewables like wind energy and solar PV in the past decade can be explained by the implementation of supportive policies (e.g. national renewable energy targets and support schemes) and significant reductions in the cost of renewable energy technology. These cost reductions are expected to continue in the years to come.[114]

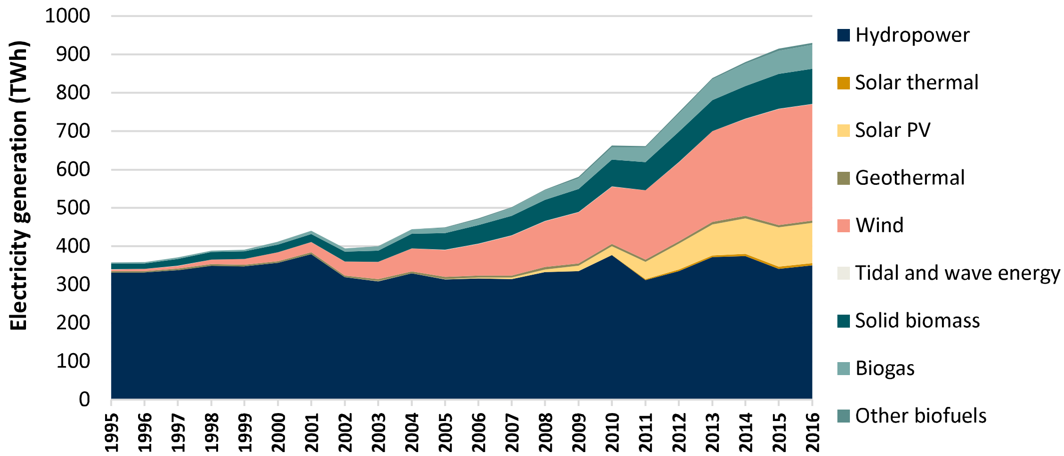
[111] In the future, hydropower output in Europe might be affected by climate change. Additionally, existing hydro dams can aggravate water scarcity in dry area such as the Mediterranean. Trinomics (2018) Study on adaptation of the energy system to climate change.

[112] EC (2017). Third report on the state of the energy union.

[113] EEA (2017) Renewable energy in Europe – 2017 Update.

[114] IRENA (2018) Renewable power generation costs in 2017.

Figure 11: Composition of the EU's renewable electricity supply



Source: Trinomics (2017) based on Eurostat[115].

Although the recent cost reductions and growth in renewable energy sources is good news for the decarbonisation of Europe, these developments also pose significant challenges to energy infrastructure. The largest challenge is that, in contrast to traditional electricity sources like thermal power plants and hydropower plants which can provide a reliable, predictable and flexible (dispatchable) electricity supply, technologies like wind energy and PV are inherently variable in their output. This so-called intermittency of renewable energy sources poses serious challenges for balancing electricity supply and demand in the grid.

In countries where wind and solar energy have a significant share in the electricity supply, short-term intermittency already generates challenges for balancing. For example, in Germany in 2017 renewables accounted for 36.2 % of the electricity supply[116], but there were days when 100 % of the electricity demand in Germany was met by renewables for a couple of hours. On such days, the combination of abundant electricity supply and limited demand can cause an excess of available electricity in the system and lead to negative electricity prices. If the excess electricity cannot be absorbed by end-users, renewable energy producers can be obliged to reduce (curtail) their injection into the grid in order to avoid the risk of a black-out.

3.3.2. Flexibility options in the energy system

There are a wide range of solutions that can provide flexibility to the energy system. The majority of the solutions fall into one of the following categories:

- Supply-side flexibility;
- Flexibility through energy transport;
- Energy storage;
- Demand-side flexibility.

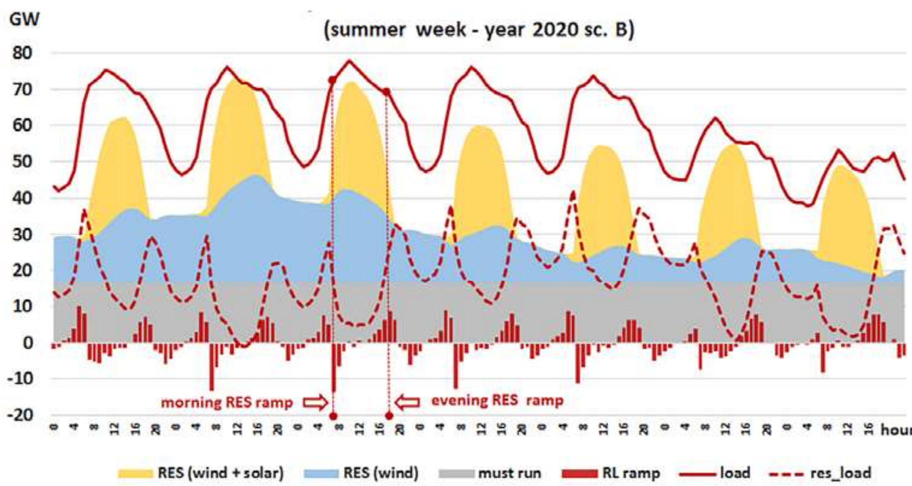
[115] Eurostat (2016) Supply, transformation and consumption of electricity - annual data (nrg_105a). Gross electricity production means electricity production at the source without correcting for energy use in the energy sector and distribution losses.

[116] BMWi (2018) Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland.

a. Flexibility in the electricity system

Variability in electricity demand generally follows, daily and weekly patterns is higher during the day than the night and higher during the week than at the weekend. There are also seasonal variations, particularly in EU Member States with a large share of electric heating (e.g. France). These variations in electricity demand are relatively easy to predict as they follow daily and weekly patterns with limited variation between different days and different weeks. A second source of variability is in electricity supply, which is caused by the variable output of conventional and especially renewable electricity sources (as explained above). This variability is more important than variations in demand, as can be seen in Figure 3-8. This figure presents the residual load (demand minus supply of renewable electricity) in Europe as forecast by the European Network of Transmission System Operators for Electricity (ENTSO-E), for a summer week in 2020. This graph shows that solar electricity supply represents a large daily variability, much greater than that of demand, and is accompanied by a variation in wind power output. As can be seen the output of renewable electricity sources is much more uncertain than electricity demand.

Figure 12: Simulation of the European power load and supply for 2020



Source: ENTSO-E, 2015[117].

The **supply-side flexibility solution** that is currently mostly used is controllable flexible electricity generation capacity, such as gas-fired power plants, which can adjust their output relatively quickly in response to imbalances. The electricity output of wind and solar energy sources cannot be increased on demand, and it is not economically efficient to reduce it in response to drops in demand. However, if all other available flexibility options (including export, storage and demand-response) are insufficient to cope with a substantial imbalance due to excess electricity supply, some of the renewable energy producers can be obliged to disconnect their installation from the grid or to curtail their injection. Although such a measure is a technically effective way to balance the system, it might have negative economic or environmental impacts and reduce the profitability of renewable energy producers. Moreover, in systems where the share of renewable energy is already high, such measures could disincentivise further investments in additional renewable energy capacity. Curtailment only offers a solution for times of excess renewable electricity, not for times of supply shortages.

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[117] ENTSO-E (2015) Introduction to the flexibility challenge.

Imbalances in electricity supply and demand can also be counteracted to a certain extent by transporting electricity from areas with excess supply to areas with less renewable energy supply at that moment. This **flexibility through electricity transport** has prevented Germany from experiencing blackouts during recent periods of high renewable electricity production and low demand, by exporting its excess electricity to neighbouring countries, primarily Switzerland, Austria and the Netherlands[118]. However, this option will not work in the longer term, as renewable energy share will increase in all Member States. As the variability in renewable energy output is strongly dependent on regional weather conditions, it is also likely that neighbouring countries will experience excess renewable electricity supply simultaneously. However, such correlations in renewable energy output are lower between regions that are located further from each other[119]. This means that transporting electricity over large distances might remain a viable flexibility solution but transporting large amounts of electricity from one European region to another would require large expansions of the electricity grid.

An alternative solution for balancing demand and supply in the short-term is **energy storage**. Energy storage technologies can be used for different purposes, including arbitrage on the energy spot and balancing markets[120], ancillary services like frequency and voltage control and the capability to provide a 'black start'[121]. Specific challenges in this respect are that it is difficult to store electricity and converting electricity to other energy carriers leads to energy losses. The dominant form of energy storage in the electricity sector is pumped hydro storage, which accounts for 97 % of all such storage capacity in Europe[122]. The advantage of pumped hydro is that it is a relatively cheap storage option with a high round-trip efficiency of between 65 % and 80 %[123]. The problem with pumped hydro is that it can only be easily achieved in a few locations in Europe. Batteries are another means to store electricity with a high round-trip efficiency, but the costs are still relatively high compared to other balancing solutions[124]. However, large-scale battery storage is increasingly being used for the provision of grid balancing services. In auctions for the reserve capacity market in the UK, 2GW of battery projects have prequalified to operate in the reserve capacity market for the 2018/2019 period, which corresponds to 13 % of the total required reserve capacity. For the delivery period 2021/2022 4.7GW of battery projects have prequalified to participate[125].

Another possibility for providing flexibility to the power system is **demand response**. This is a solution where electricity demand is adjusted in response to the cost and availability of electricity supply, which is usually monitored via the electricity spot market prices. There are two types of demand-response, implicit and explicit. With implicit demand response, grid tariff and/or electricity price incentives (or penalties) are used to influence energy consumption behaviour[126]. Explicit demand response involves the participation of (aggregated) energy-consuming loads in wholesale, balancing and/or reserve

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118 Fraunhofer Institute for Solar Energy Systems (2018) Power generation in Germany – assessment of 2017, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Stromerzeugung_2017_e.pdf.

119 Olauson & Bergkvist (2016) Correlation between wind power generation in the European countries. *Energy*[114](2016): 663-670.

120 Arbitrage is a term that is used for temporarily storing energy for trading purposes (e.g. storing electricity when it's cheap, and selling it again when electricity prices are high).

121 A black start is the provision of the initial power that is required to start up power generating equipment, mostly in conventional power plants, after a black-out.

122 EC (2017). Energy storage – the role of electricity https://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf.

123 Kougias, I., Szabó, S. (2017) Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse? *Energy* 140(1): 2017, pp. 318-329.

124 DG ENER- The future role and challenges of energy storage. https://ec.europa.eu/energy/sites/ener/files/energy_storage.pdf.

125 http://everoze.com/uk-cm/.

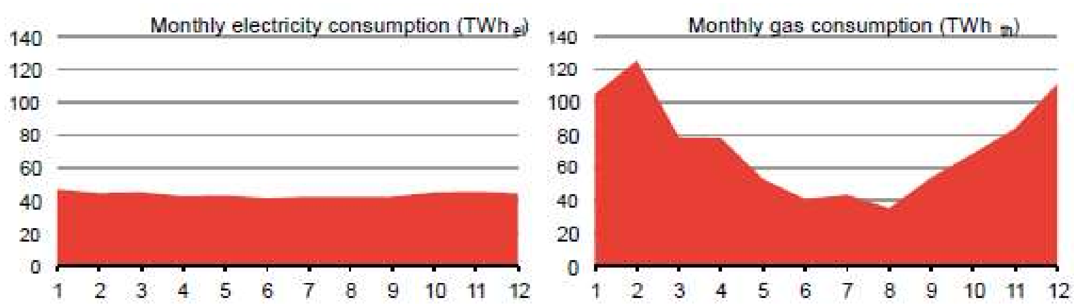
126 Smart Energy Demand Coalition (2017) Explicit demand response in Europe – Mapping the markets 2017.

capacity markets. Explicit demand response can be an attractive source of power system flexibility to ensure the adequacy and reliability of the energy system at least cost; it also contributes to reducing electricity price volatility. Participants in explicit demand response are typically large consumers like industrial companies or food retailers. For example, supermarkets usually have large cooling compressors, whose load can be reduced if sudden frequency drops in the grid occur[127]. This temporary turn down is made easier because compressors in supermarkets often only run at 30-40% of their maximum load. By installing thermal storage, cooling compressors can be operated at full load during off-peak hours and reduce their demand during peak hours, and hence lower their energy bill (by avoiding peak charges and/or being rewarded for this) while contributing to the flexibility and security of the energy system.

b. Flexibility in the gas sector

Demand variations in the gas sector are different to those in the electricity sector. Short-term variation in gas demand is lower than in electricity demand and can generally be absorbed by the network itself (flexibility available via linepack, i.e. increased pressure of gas in the system allows temporary peaks in demand to be met). While the average monthly electricity demand is rather stable across the year in most EU Member States, gas demand shows a strong seasonal pattern (figure 3-9). This pattern is driven by a large increase in gas demand during the cold months when gas is used for heating. Another difference to the electricity sector is that the level of gas supply is relatively easy to control and not dependent on the weather or the season. However, while electricity is mainly produced domestically, a large share of the gas consumption is imported from outside the EU, which creates supply risks.

Figure 13: Comparison of the annual electricity load and gas consumption pattern in Germany



Source: Frontier economics, 2017[128].

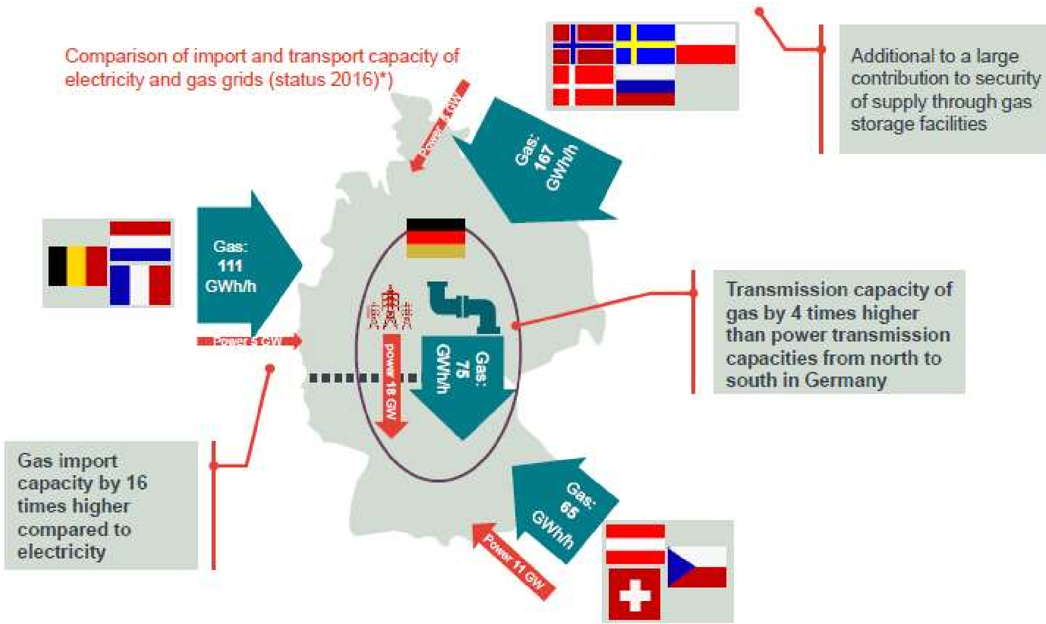
The characteristics described above mean that flexibility solutions in the gas sector, in particular gas storage, are mostly used to ensure the availability of gas in cold periods when demand for gas is high. The gas infrastructure also has to meet specific standards to ensure security of supply, in case of supply disruptions or unavailability of a large infrastructure component. **Supply side flexibility** in the gas sector can be achieved through temporarily adapting storage or domestic production levels, by changing import levels or by switching between different import routes and gas types. As most EU Member States are dependent on imports to meet their gas demand there is an extensive gas import

[127] Danfoss (2015) Supermarket Refrigeration as an important smart grid appliance http://files.danfoss.com/technicalinfo/dila/01/DKRCE.PE.000.Q1.22%20Supermarket%20Smartgrid.pdf.

[128] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

and transmission infrastructure in Europe. In comparison to the electricity transmission network, the gas transmission network has much larger capacities; a comparison of both networks for Germany is shown in figure 3-10.

Figure 14: Comparison of electricity and gas transmission capacities in Germany



Source: Frontier Economics, 2017[129].

The gas sector also has a large energy storage capacity. This storage capacity is mainly to enable sufficient supply in times of peak demand and to have reserves to ensure sustained supply in case of sudden disruptions of imports. The gas storage capacity in the EU is 112 bcm or 1 180 TWh[130], which represents 22.8 % of the annual gas demand (491 bcm or 5 173 TWh in 2017). As a comparison, although data on the current total pumped hydro storage capacity is unavailable, the total storage potential within Europe (including some non-EU countries) is estimated to be a maximum of 54 TWh[131], which is only 1.65 % of the annual electricity production in the EU (3 255 TWh in 2016). The utilisation level of gas and electricity storage is very different. Gas storage is in principle only used to absorb seasonal fluctuations in demand and to ensure security of supply, pumped hydro storage capacity is much more intensively used to respond to intra-day price fluctuations, to balance the portfolio of market operators (balance responsible parties), and to provide ancillary services to grid operators.

c. Cross-vector integration - combining flexibility in the electricity and gas sector to increase overall flexibility of the system

Although the electricity and gas sector have both their own flexibility solutions, **cross-vector integration** could increase the overall flexibility of the energy system, thereby decreasing the need for additional infrastructure to support decarbonisation and helping ensure security of energy supply.

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129 Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

130 https://www.gasinfocus.com/en/indicator/underground-storage-sites-for-natural-gas-in-europe/.

131 JRC (2013) Assessment of the European potential for pumped hydropower energy storage.

Power-to-gas technologies could be employed as a **supply-side flexibility solution** when renewable electricity is abundant while the short-term storage options available through the gas infrastructure, like linepack[132], can be used to temporarily store renewable gas[133], e.g. for later conversion back into electricity. An issue with the power-to-gas-to-power route is that the round-trip efficiency is relatively low (30-40 %[134]). This is one of the reasons why using renewable gas for flexible back-up electricity generation is less energy efficient and more expensive than also using renewable gas for final energy end-uses[135]. Applying power-to-gas technologies in periods of excess electricity supply removes the need for curtailment of renewable electricity generation or the need for additional investments in electricity transmission, distribution or storage infrastructure.

Cross-vector integration can also help to address seasonal fluctuations in energy demand in a cost-effective way. Currently, these large fluctuations in energy demand can be accommodated because heat is primarily supplied by fossil energy carriers which are easy to store. However, in a decarbonised energy system that is highly electrified (including most of the heat demand), sufficient electricity supply needs to be available to meet all the additional demand for heating during the cold periods of the year. Even with ambitious improvements in energy efficiency and extensive deployment of heat pumps (which are more energy efficient than electric boilers), very large energy storage capacities and/or additional electricity generation capacity would be needed. The existing gas storage capacity can be used for this purpose, although refurbishments will be needed to accommodate the large-scale use of hydrogen.

Adjustments would also need to be made to the gas transmission and distribution networks in order to make them fit for the transport of hydrogen. A recent Dutch study showed that the gas transmission system is in principle fit for the transport of 100 % hydrogen, although some specific adjustments will be required[136]. The pipelines need to be equipped with additional insulation, and metering equipment and compressors need to be replaced, to account for the specific characteristics of hydrogen. The study also mentions that in order to maintain integrity of the pipelines and protect them from cracks, it is important that large pressure fluctuations are avoided with hydrogen transport. This will reduce the potential to use linepacking for short-term gas storage.

Utilising the existing gas storage capacity appears to be a more cost-effective way to ensure that sufficient energy is available in winter than installing additional dedicated electricity storage infrastructure[137], or building peak electricity generation capacity. Even if stored gas is reconverted into electricity to power electric heat pumps, the costs from the energy losses resulting from the energy conversion steps do not seem to outweigh the cost reductions achieved in other parts of the energy system. However, additional research is needed to clarify the overall costs of adapting the current gas infrastructure to high hydrogen concentrations. If these costs are found to be excessive, methanation of hydrogen to synthetic methane may become an attractive option, despite the additional energy

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[132] Temporary increase of pressure in gas pipelines to increase storage capacity.

[133] According to the DNV (2017) study 'verkenning waterstofinfrastructuur, the opportunity for using linepack in hydrogen networks might be limited, due to corrosion risks.

[134] The lower end corresponds to methane-based PtGtP processes and the higher end corresponding to H2-based PtGtP routes. Source: Energy storage association website: http://energystorage.org/energy-storage/technologies/hydrogen-energy-storage.

[135] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

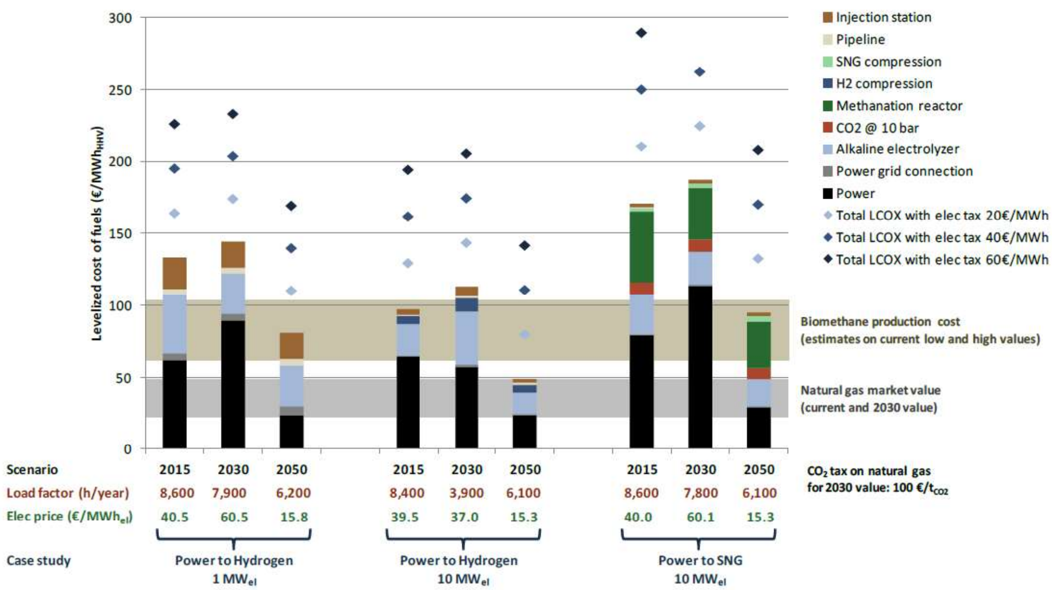
[136] DNV-GL (2017) Verkenning waterstofinfrastructuur (exploration hydrogen infrastructure) https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/DNVGL%20rapport%20verkenning%20waterstofinfrastructuur_rev2.pdf.

[137] Frontier Economics (2017) The importance of gas infrastructure for the German Energiewende.

losses. Synthetic methane has similar characteristics to natural gas, so it can be injected into the existing gas infrastructure without the need for major refurbishments.

Although power-to-gas solutions could become a valuable source of flexibility in the future energy system, it is important to realise that the implementation of power-to-gas technology will only be economically feasible if these facilities can be operated with a high load factor of, according to some studies, at least 3 000 hours a year[138] while others refer to more than 6 000 hours a year[139]. This means that only using power-to-gas solutions at times of excess electricity supply is not viable, due to the high investment costs related to electrolyser technologies. A comparison of the production costs for hydrogen and synthetic methane under different load factors (operating hours) is shown in figure 3-11. The economic feasibility of hydrogen production with renewable electricity seems to be higher than that of synthetic methane, because the latter generates additional energy losses and requires additional investments in conversion equipment[140].

Figure 15: Levelised costs of PtG plants at different load factors and electricity prices



Source: ENEA (2016)[141].

3.3.3. Possibilities for large scale renewable energy imports

The availability of energy is crucial for economies to function. It is therefore not surprising that energy policy has always focused on the availability of affordable/competitive energy and a secure supply. International conflicts such as the recent Russian annexation of Crimea and events like the oil crisis in the 1970s have shown the vulnerability of the EU economy due to its high energy import dependence.

138 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

139 ENEA (2016) The potential of power-to-gas.

140 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

141 ENEA (2016) The potential of power-to-gas.

Energy independence could be considered as an ideal to strive for; however, in some cases there can be a trade-off between reducing energy independence and cost efficiency.

Some neighbouring areas are very rich in renewable energy resources, the MENA region for example has very strong solar irradiation which makes solar energy generation in this area very competitive. This fact led to the Desertec concept being developed in 2009. Desertec planned to harness the vast solar energy potential by building large Concentrated Solar Power (CSP) plants to provide Europe with cheap, renewable and reliable (baseload[142]) electricity supply. However, because of a complex combination of techno-economic, political and social factors, the Desertec initiative has stalled (for now)[143].

One of the issues with large-scale power generation in the MENA region is that it would require the construction of high-capacity transmission lines to Europe, involving large-scale infrastructure investments in some politically unstable areas. As the costs of solar energy have come down very dramatically in recent years, a new opportunity is arising. Instead of being a large-scale electricity producer, the MENA region could become a major producer of synthetic gas and liquid fuels which could be transported to Europe via (existing) pipelines or by ship. It has been estimated that by 2050 synthetic methane could be produced in North Africa at a cost of around €100/MWh[144]. This is still about three times the predicted price for natural gas in 2050[145]. Alternatively, synthetic methane could be produced in Iceland using geothermal energy and hydropower, which might be possible at a cost of €80/MWh in 2050[146]. Similarly, synthetic liquid fuels could be produced at €100-150/MWh, which is about twice the cost of untaxed fossil gasoline or diesel[147]. Today, the first projects for international renewable hydrogen trade are being set up. Chile, Argentina and Australia are already developing roadmaps for using their high renewable energy potentials for the production and subsequent export of hydrogen[148].

Sector coupling between the electricity sector and industry will facilitate the production of hydrogen at an acceptable cost. Furthermore, the existing gas infrastructure could be adapted so that large-scale transport of hydrogen becomes possible. Further research is needed to investigate how the costs of such refurbishments compare with other decarbonisation options.

142 The plan was to combine CSP large-scale high-temperature thermal energy storage, so that a continuous electricity output can be realised 24h a day.

143 Schmitt (2017) (Why) did Desertec fail? An interim analysis of a large-scale renewable energy infrastructure project from a Social Studies of Technology perspective.

144 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

145 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

146 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

147 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

148 IRENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.

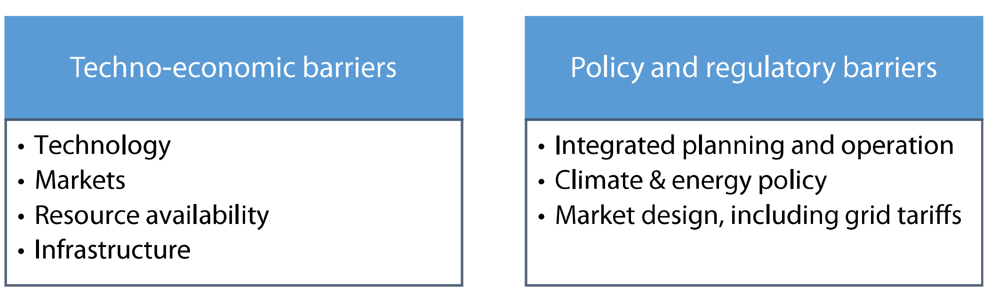
4. BARRIERS/BOTTLENECKS TO SECTOR COUPLING IN THE SHORT AND MEDIUM TERM

KEY FINDINGS

- Several sector coupling technologies are not yet competitive in terms of cost and performance.
- Market conditions such as energy end-user prices restrict the deployment of sector coupling technologies to specific applications.
- The most appropriate technological options vary by Member State depending on resource availability.
- Enabling sector coupling will require reviewed operational standards for energy infrastructure.
- Current grid charging methodologies do not provide a level playing field for all technologies and do not properly account for the positive externalities of sector coupling technologies.
- A proactive, future-focussed and integrated approach is still lacking for the planning and operation of the European energy system.
- Instability in EU climate and energy policies, and lack of adequate carbon pricing, hinder sector coupling projects from developing at large scale.
- Flawed market designs still restrict the participation of sector coupling technologies, and negatively affect their profitability.

The barriers and bottlenecks to sector coupling can be classified in both techno-economic and policy, legal and regulatory categories. As indicated in Figure 4-1, techno-economic barriers include technology (cost, performance and materials), market conditions, resource availability and infrastructure, while policy, legal and regulatory barriers are integrated energy system planning and operation, overall climate and energy policy, and market design.

Figure 16: Categorisation of barriers and bottlenecks to sector coupling



4.1. Techno-economic barriers

Arguably the most important techno-economic barrier for sector coupling is the need for further innovation in the various supply, demand, transmission, distribution and storage technologies to improve the techno-economic feasibility of the most relevant technologies. The combination of renewable electricity generation and local storage is still not competitive with other solutions in most regions and applications, despite battery prices falling by 22 % in 2017.[149] Power-to-gas solutions for transport such as hydrogen and methanol have to compete with other low-carbon alternatives, but without financial incentives they may cost up to 20 % more than fossil fuels even in 2050 (unless compared to taxed fossil fuels).[150] Similar examples can be found for other technologies such as hydrogen from nuclear power or CCS-enabled coal gasification and natural gas reforming, steel hydrogen-direct reduction, hydrogen-to-power[151], or carbon capture, utilisation and storage in industry and transformation.[152]

Innovation in sector-coupling enabling technologies will impact their cost and performance. Performance aspects such as the efficiency, durability and degradation of these technologies still represent a major barrier to their deployment. For example, the IEA indicates that priorities for hydrogen technologies R&D include the improvement in durability and degradation of fuel cell mechanisms for this reason.[152] In the same way, the potential deployment of biomass-based CCS is dependent on the efficiency of CCS technologies.[151] The development of power transmission capacity and the optimisation of its utilisation will also require further monitoring and control solutions.[153] Many of the technologies enabling sector coupling require additional standards and efficiency labels for their deployment, e.g. heat pumps.[154] The lack of standardization hampers the mass deployment of energy technologies, the interoperability between manufacturers and the insertion of the technologies in energy infrastructures such as gas grids, while the lack of efficiency labels impedes the comparison and adoption of the most efficient technologies by consumers. Finally, innovation in these technologies will also have to address material use, for example metals for hydrogen fuel cells (especially platinum) and for batteries (cobalt and lithium).[152]

Market conditions are another techno-economic barrier to sector coupling technologies. Although they are competitive in certain applications, these technologies may not be competitive in other markets. For example, power-to-heat for industry may be competitive in times of low electricity prices, but its feasibility is still very sensitive to the spread between electricity and gas prices. Similarly, the prospects of power-to-gas for grid injection are challenging due to the low market value of gas.[155] The role of hydrogen blending in the gas grid may also be limited, due to the opportunity cost of missing more efficient uses in other applications. Likewise, hydrogen production competes with other uses for biomass feedstock.[151] There are, however, uncertainties on the future level of deployment of technologies fostering decarbonisation, and hence forecasts on these technologies and their applications vary and may conflict. An example is hydrogen injection into the gas grid, which, depending on the scenarios and assumptions, may become significant in some EU Member states.[156]

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149 IEA (2018) Tracking clean energy progress.

150 ENEA (2016) The potential of power-to-gas.

151 Sgobbi et al. (2016) How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system.

152 IEA (2018) Tracking clean energy progress.

153 IEA (2018) Status of Power System Transformation 2018.

154 SETIS (2015) Heat Pumps: Technology Information Sheet.

155 ENEA (2016) The potential of power-to-gas.

156 Trinomics (2018) The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

At present, market conditions or competing applications restrict the deployment especially of resource-limited technologies such as hydrogen. Hence, in order to value sector coupling synergy potentials, INSIGHT_E recommends that 'reliable, financially predictable frameworks for new business models' are necessary given the changing market conditions.[157]

Sector coupling opportunities are also hindered by the limited availability of resources, for example, of biomass feedstock for biogas production. The consideration of the environmental impact of biomass limits the types and potential available to decarbonise the energy system.[158] Solar steam reforming for hydrogen production is also limited to high-solar radiation regions such as Southern Europe and northern Africa.[159] Another example is that of heat pumps, which are only an appropriate solution in well-insulated buildings, forming a barrier to their deployment in older buildings, as retrofitting such buildings to provide the required level of insulation is often technically or economically difficult. Air-source heat pumps are also not as effective in colder climates, while the potential for ground-source heat pumps is limited.[160] Therefore, the most effective sector-coupling technologies will vary by region and application according to local resource availability, market conditions and the comparative performance of the technologies.[161]

The need for adequate infrastructure for energy carriers such as power, conventional and renewable gases, heat or CO_2 is a major techno-economic barrier for sector coupling in Europe. This barrier arises from the need for increased capacity or the need for technical adaptations of existing infrastructure. Sector coupling may help delay investments or divestments in specific infrastructure, for example divestments in the European gas grid[156] . However, other developments will still need investments. For example, the 2018 Electricity Ten-Year Network Development Plan, of which the scenarios were jointly developed by the European electricity and gas Transmission System Operators, forecasts €114 bn in transmission investments by 2030. Additional investments will be needed for power generation, transmission and distribution, storage, conversion processes, and others. The infrastructure costs are also a barrier for renewable energy based district heating, making it uncompetitive with decentralised heating technologies such as ground- or air-source heat pumps.[162] For gas, a scenario with large scale electrification may lead to decreasing utilisation levels for gas import and transport infrastructure, but a scenario of large scale development of renewable gas will require further investment (for example for reverse flows due to biomethane injection at the distribution level or to adapt grids and storage sites for high shares of hydrogen).[163]

The lack of specific infrastructure can act as a barrier, such as for CO_2 transport for carbon capture, utilisation and storage, or heat networks. The latter will require larger investments than comparable electricity or gas infrastructures, which are already much more developed.[164] The infrastructure barrier also includes the need to adapt existing technical regulations and standards, for example to facilitate hydrogen and biomethane injections into the gas grid. National regulators will need to define clear

157 INSIGHT_E (2014) Synergies in the integration of energy networks for electricity, gas, heating and cooling.

158 Energy Transitions Commission (2018). Bioenergy and Bio-based Products in a Zero-carbon Economy.

159 Sgobbi et al. (2016) How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system.

160 SETIS (2015) Heat Pumps: Technology Information Sheet.

161 Energy Transitions Commission (2018). Electricity, hydrogen & hydrogen-based fuels in a Zero-carbon Economy.

162 IRENA (2017). Renewable Energy in District Heating and Cooling – A Sector Roadmap for REMAP.

163 Trinomics (2018) The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

164 Imperial College London (2016) Comparing the impacts and costs of transitions in heat infrastructure.

rules for admixture, infrastructure connection and access to capacity, and commercial arrangements for local gas producers.[165,166]

4.2. Policy and regulatory barriers

There are several important policy and regulatory barriers for sector coupling in the EU, mainly related to (lack of) integrated planning and operation, general climate and energy policies and market design (including grid tariffs).

An important barrier to enable sector coupling is the lack of integrated planning and operation of parts of the energy sector which present synergy potentials, such as the gas and electricity sectors. Several studies indicate that planning and operation practices currently fall short of this integrated approach.[165,166,167,168,169,170] Such an integrated approach must be proactive, addressing the long regulatory lag between regulatory changes and their effects. For example, if they are not integrated and forward-looking, UK policies to foster heat pumps, district heating networks and hydrogen admixing may lead to stranded consumer investments in appliances or leave consumers out of the heat networks.[167] Regarding trans-European gas infrastructure, the various possible scenarios (large scale development of electrification coupled with biomethane and/or hydrogen) require future-proof investment planning on the part of the European TSOs, with corresponding enabling regulations.[163]

The integrated planning and operation must cover all energy sectors, considering the whole value chain from supply to demand, all energy vectors and all levels, from the local to the European. For example, local authorities in most EU Member states have great influence on the heat sector e.g. choosing local heat solutions such as district networks, or fostering capacity-building.[167] Failing to conduct integrated planning may lead to divestments in assets which could otherwise be efficiently employed, for example in gas infrastructure.[165] This will allow also the correct assessment of the full benefits and costs of different digitisation technologies[171] which are crucial enablers for sector-coupling technologies. Integrated planning and operation will also require that security of supply strategies, including the energy system's adequacy and operational reliability, consider all parts of the energy sector and include all energy vectors, in particular electricity, heat and gas, rather than focusing on single energy vectors.[172]

In addition to the lack of an integrated planning and operation of the energy sector, climate and energy policies affect sector coupling directly by explicitly (not) addressing it, or indirectly by impacting sector-coupling enabling technologies. Hence, Eurelectric acknowledges climate policy as the first driver of electrification in Europe[173]. Analysing synergies from sector coupling, INSIGHT_E calls for clear political signals in order to allow for new business models leveraging these technologies.[172] In a similar manner, an Imperial College London study indicates that long-term clarity in the UK to develop heat infrastructures does not currently exist, even though it is necessary given the long lifetime of energy infrastructure and the duration of the energy transition.[174] Specific sector policies will also affect sector

165 DNV-GL (2018) Future Role of Gas from a Regulatory Perspective.
166 Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.
167 Imperial College London (2016) Comparing the impacts and costs of transitions in heat infrastructure.
168 IEA (2018) Status of Power System Transformation 2018.
169 VDMA (2018) Turning the power transition into an energy transition - Sector coupling.
170 Berenschot (2016) Energie-innovaties van de Topsector: Institutionele belemmeringen en oplossingsrichtingen – Integratierapportage.
171 IEA (2018) Tracking clean energy progress.
172 INSIGHT_E (2014) Synergies in the integration of energy networks for electricity, gas, heating and cooling.
173 Eurelectric (2018) EU electrification and decarbonization scenario modelling.
174 Imperial College London (2016) Comparing the impacts and costs of transitions in heat infrastructure.

coupling, for example transport policies impacting power-to-gas[175] or the reviewed article 8 in the EU building directive[176] establishing requirements for the installation of recharging points for electric vehicles in buildings.

An aspect of the EU climate and energy policy indicated in the literature as pivotal to the deployment of sector-coupling enabling technologies, is an efficient GHG emissions policy and adequate carbon pricing. The options available for this include the reform of the EU emission trading scheme (ETS) or the implementation of a carbon tax. As the ETS is already in place, its reform appears the most straightforward approach to improve carbon pricing and making sector coupling economically sustainable. By 'correctly' pricing all carbon emissions, both from ETS and non-ETS installations, a level playing field would be created for all energy technologies and vectors, providing long-term certainty for the deployment of low-carbon technologies such as hydrogen.[177] This should possibly include the expansion of GHG trading globally, otherwise risking the participation of European Member States such as Germany.[172] However, currently important emitting sectors such as fossil fuels in transport and buildings, are not a part of the ETS, and the success of the current Market Stability Reserve reform is not assured.[178] An adequate carbon pricing scheme and cost-reflective, transparent and fair fuel prices are necessary to harvest sector coupling synergies.[179]

The current market design is another important barrier to sector coupling in Europe. For gas, several studies address changes required to the current regulation of transmission, distribution and storage activities.[180,181] These indicate among other aspects, the need to adapt revenue regulation (asset valuation, depreciation, cost of capital, project-specific rules), to consider the role of network operators in storage, and to improve incentives for innovation projects (for example with innovation allowances). The Trans-European Energy Networks and Connecting Europe Facility mechanisms could also be reformed according to the new European investment priorities, such as infrastructure investments to facilitate the deployment of renewable gas and electricity, which would directly enable sector coupling technologies.[181]

The business case for energy storage also illustrates the impact of market design. This business case often depends on combining multiple value streams by providing different types of services, for instance balancing energy and reserve capacity (e.g. ancillary services provided to TSOs), as long as these services can physically be provided simultaneously. Therefore, allowing energy storage providers to participate in multiple markets can improve the economic feasibility of energy storage technologies, but some market designs still limit the participation of storage[182]. For example, in 2017 a majority of EU TSOs required symmetrical products (i.e. requiring both upward and downward regulation capacity) in electricity frequency containment reserve markets[183].

Market design barriers also exist to enabling flexibility and the provision of flexibility services for low-carbon technologies.[179,184] This constrains the business case of technologies driving, for example, end-

[175] ENEA (2016) The potential of power-to-gas.

[176] Directive (EU) 2018/844.

[177] Sgobbi et al. (2016) How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system.

[178] German National Academy of Sciences Leopoldina (2018) Coupling the different energy sectors – options for the next phase of the energy transition.

[179] Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.

[180] DNV-GL (2018) Future Role of Gas from a Regulatory Perspective.

[181] Trinomics (2018) The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

[182] EASAC (2017) Valuing dedicated storage in electricity grids.

[183] EASAC (2017) Valuing dedicated storage in electricity grids.

[184] IEA (2018) Status of Power System Transformation 2018.

use sector coupling (e.g. heat pumps and electric vehicles) or cross-vector integration (such as power-to-gas). An extensive study[185] on the barriers to energy innovation in the Netherlands identified regulatory and legal barriers as the most important ones restricting electrification and greater system flexibility, covering all four considered end-use sectors. Net-metering and the tariff structure were two of the most frequent specific barriers identified. Other market design parameters requiring adaptation include barriers in the power sector, such as must-run requirements for power plants, separate upward and downward balancing procurement and market time granularity. However, market design must always consider the characteristics of the technologies and the specific regions. For example, local heat solutions strongly depend on existing alternatives, building stock and user profiles, and urban planning and regulation.[186]

Another particular aspect of market design which can act as a barrier or facilitator for sector coupling technologies are the tariffs for grid connection and access. Depending on the national tariff methodologies and modalities, grid tariffs for energy storage or local injection of renewable electricity or gas can facilitate these technologies or penalise them. The use of capacity versus commodity-based tariffs also has an impact on the economic feasibility of sector coupling technologies.[187] Grid tariffs should be technology-neutral and cost-reflective and duly take account of the benefits that injection of (renewable) gas or electricity from local producers or storage facilities have on the grid operations. The current tariff structure is considered as one of the main barriers hindering electrification and system flexibility in the Netherlands.[188] Germany also provides a tariff reduction to energy-intensive industries achieving a high number of utilisation hours,[189] which could prove to be a barrier to the implementation of industrial demand response. Another example are grid tariff schemes for storage; if storage operators have to pay grid charges for both the charging and discharging cycles, storage becomes less competitive compared to other flexibility options. This applies to any technology including this cyclical aspect and was identified as one of the most important barriers to the business case of storage and power-to-gas technologies,[190] which are crucial to fostering sector coupling in Europe. Few Member States provide relief to the double-charging of transmission tariffs to storage, which is usually focused on pumped hydro storage.[191] More generally, while the new network code on harmonised transmission tariff structures establishes measures to address double charging for natural gas, there is no comparable measure for electricity.[192]

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185 Berenschot (2016) Energie-innovaties van de Topsector: Institutionele belemmeringen en oplossingsrichtingen – Integratierapportage.

186 Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.

187 Trinomics (2018) The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

188 Berenschot (2016) Energie-innovaties van de Topsector: Institutionele belemmeringen en oplossingsrichtingen – Integratierapportage.

189 Ispex (2018) Netzengelte. https://www.ispex.de/netzentgelte/.

190 STORE&GO (2017) Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation – D7.2 European Legislative and Regulatory Framework on Power-to-Gas.

191 ENTSO-E (2018) ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2018.

192 European Commission (2017) 2017/460 Network code on harmonised transmission tariff structures for gas.

5. CONCLUSIONS AND RECOMMENDATIONS

KEY FINDINGS

Recommendations for integrated planning and energy policies coherency

- Further progress towards integrated planning and operation of different parts of the energy system is needed.
- Planning of and financial support for new large energy infrastructure should be future-proof and consider interlinkages between electricity and gas sectors.

Targeted recommendations for specific end-uses, vectors and technologies

- IT solutions for smart energy management are key enablers for smart integration of (local) energy generation and end-uses.
- Support for development of a hydrogen market might be needed to ensure sufficient cost-reductions for hydrogen to play a significant role in the future energy system.

Recommendations for a future-proof market design

- Markets must reflect positive and negative externalities for each market participant, while barriers to participation of demand response and storage should be removed.
- Directions for improvement include: adequate pricing of emissions, reforming transport and access tariffs for infrastructure, adapting criteria for participating in flexibility markets and increasing time granularity of energy markets.

Recommendations for Research, Development and Innovation (R, D &I)

- EU R, D &I must provide guidance and funding also to the integrated planning and operation of the energy system.
- EU R, D&I funding should focus on high-risk innovations while developing venture capital financing and R&I by regulated network operators.

This report shows that **sector coupling can offer important added value in the decarbonisation process** of the EU energy system, by **contributing to the increasing flexibility needs and to the reliability of the energy system**, and by **reducing the global costs** of the energy transition. End-use sector coupling could facilitate an increase in the penetration of intermittent renewable energy sources through a combination of electrification of energy demand and strong interaction between demand and supply, which both contribute to improving the overall energy efficiency and reliability of the system. Cross-vector integration helps to decarbonise the energy supply while ensuring system security and adequacy and enhancing the potential to utilise the available renewable energy and existing energy infrastructure in the most cost-effective way.

Some sector coupling technologies are becoming familiar, such as low-temperature heat pumps or electric vehicles. However, **important techno-economic and policy and regulatory barriers hinder the deployment of several sector coupling technologies** in the European energy system. While the barriers apply to innovations with both high and low technology readiness levels, they are not all equally important to every sector coupling technology, as the characteristics (both of the technology and external) and the applications vary. The recommendations in the following sections aim to overcome these barriers; they focus on integrated planning and coherence in energy policies; targeted recommendations for specific end-uses, vectors and technologies; need for developing a future-proof market design; and guidance and funding for research and innovation.

5.1. Integrated planning and coherent long-term energy and sustainable development strategy

This study demonstrates that there is a strong interaction between the different parts of the energy system. Sector coupling is all about optimising these interactions to achieve an efficient and cost-effective energy transition. However, in order to cost-efficiently achieve far-reaching integration of the different parts of the energy system, **forward-looking integrated planning and operation of the energy system is needed**, not only at the European and national levels but also at the local level. In this way lock-ins to undesirable technologies, sub-optimal planning and operation in sub-sectors and conflicts between well-intended policies can be prevented. The Governance of the Energy Union[193] intends to address this issue at the European level. EU Member States, regions and municipalities also need to guarantee the coordination of their policies across energy sectors and other relevant levels.

Appropriate initiatives by European, national and local authorities are necessary to carefully plan and evaluate the **further development of energy infrastructure. This planning should look at the energy system as a whole** so that new developments contribute to facilitating a least-cost transition to a carbon-neutral system. This means that, for example, the need for extensions or reinforcements of (international) electricity transmission lines should not be evaluated only within the context of the electricity system, but the required transport and balancing capacity should be assessed within the energy system as a whole.

Considering the ongoing transition to a low carbon energy system, projects for **new fossil fuel-based energy infrastructure should be thoroughly assessed** in order to limit the risks of stranded assets, and to make investments in new or existing gas assets future-proof, i.e. also suitable for renewable or carbon-neutral gas. The requirements for possible refurbishment of gas infrastructure (transport, distribution and storage) to make it suitable for higher volumes of hydrogen need to be investigated. Further analysis is also needed to assess how the costs of such refurbishments compare with additional costs associated with conversion of hydrogen to methane. Such comparisons can help in developing cost-efficient strategies for decarbonising the energy supply and setting technical standards for the admixing of hydrogen in the gas infrastructure.[194]

EU funding for energy infrastructure through EU instruments, in particular Connecting Europe Facility and the European Investment Bank, should prioritise investments that are in line with the integrated planning approach described above. Also, **priority should be given to investments that facilitate the uptake of low-carbon technologies and flexibility solutions**. The latter is a particular area of interest as most of the ongoing Projects of Common Interest focus on electricity and gas networks and LNG terminals, with only a few on energy storage and other flexibility solutions. By restructuring European Funds in this way, the limited financial resources available can be optimally used to facilitate innovation and the risk of stranded assets can be reduced.

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193 Provisional agreement resulting from interinstitutional negotiations on COM(2016)0759 – C8-0497/2016 – 2016/0375(COD) http://www.europarl.europa.eu/RegData/commissions/envi/inag/2018/06-29/CJ10_AG(2018)625412_EN.pdf.

194 Trinomics (2018) The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

5.2. Targeted recommendations for specific end-uses, vectors and technologies

The challenge for EU energy policy is to balance **an integrated approach to the energy system maintaining technology neutrality, while supporting high-potential specific innovative energy technologies.** Technology support is indispensable in order to ensure that sufficient technological progress is made so that long-term benefits are safeguarded and that uncertainty for potential investors is reduced. However, with this kind of specific support it is important that impacts on the energy system overall are taken into consideration and that negative impacts on specific parts of the energy system are prevented as much as possible. The development of other high-potential technologies that are possibly essential to the decarbonisation of the European energy system, should also not locked out.

In some cases, demand pull, or market push can be an effective tool to support the development of a market for innovative technologies. For example, specific support for PV in Germany via feed-in-tariffs has been very effective in creating a market for PV, which has significantly contributed to the maturing and cost reductions achieved in PV technology. Similarly, availability of adequate charging/refuelling infrastructure lowers the barrier for consumers to switch to alternative fuel vehicles. Such initiatives are already taking place, e.g. through the Alternative fuels infrastructure directive[195] and the H2 initiative in Germany.[196]

As many studies indicate that renewable gases and specifically hydrogen produced via electrolysis can play an important role in reducing the overall costs of the energy transition, it may be appropriate to **support market development for more widespread hydrogen use in order to promote technological learning and achieve the cost reductions** that are required for large-scale deployment[197]. This market development can start by focusing on large users like industries or large fuelling stations, e.g. for ships or trucks, to create opportunities for high-scale hydrogen production which reduces costs[198]. Allowing for long-term purchasing contracts can also provide investors with sufficient certainty to invest in this type of project. Enabling power-to-gas facilities to provide flexibility services to grid operators in addition to hydrogen sales, would also improve the business case of such projects. Together these support measures can facilitate the development of hydrogen for industrial (feedstock and high-temperature heat) and transport applications that are hard to decarbonise otherwise and for seasonal energy storage purposes.

Smart energy system management based on state-of-the-art IT infrastructure is a central enabler for the coordination of decentralised actors with sector-coupling and/or flexible technologies in the energy sector. It is necessary to foster such IT infrastructure, which will increase the transparency of the energy system operation while guaranteeing data security and privacy. This is especially relevant at the distribution level[199] where new actors, such as aggregators, storage operators and self-producers (prosumers) are appearing and where the role of traditional actors is changing. System balancing will need intelligent management through a smart grid that goes beyond smart meters, and standards will have to be developed on data exchange and cyber security protocols in order to allow that smart management becomes a reality.

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195 Directive 2014/94/EU of 22 October 2014 (Published in OJ on 28 October 2014).

196 H2 MOBILITY Deutschland (2018) Full steam ahead.

197 IRENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.

198 IRENA (2018) Hydrogen from renewable power – technology outlook for the energy transition.

199 INSIGHT_E (2014) Synergies in the integration of energy networks for electricity, gas, heating and cooling.

Low-temperature electric heat pumps are already established solutions to provide heat and cooling in buildings, but despite advances, their uptake in the European building stock is still limited. Policies are therefore necessary to **develop standards and energy efficiency labels for heat pumps and facilitate access to funding** to overcome the high investments costs. **High infrastructure costs** also form a barrier to the development of the other main alternative for low-temperature heat supply, namely district heating. Even though district heating systems and local conditions vary significantly, there can be a role for EU and national institutions **to help project developers by providing system design and operation benchmarks and contractual guidance**.[200]

Care must be taken to **avoid the cannibalisation of policies** fostering solutions such as building insulation, district heating or hydrogen admixing in gas networks. Integrated and coordinated policies can lead to synergies (such as in the connection of heat pumps to local heat networks) and value the additional benefits such as increased system flexibility these technologies provide.

Regarding **high-temperature heat pumps**, beyond focused R&D efforts, specific policy must improve the risk-aversion and extremely short payback periods required in industry, the sharing of knowledge in the form of best practices and consider the plant-wide benefits of such investments. This is essential to develop a technology central for the hard-to-decarbonise high-temperature heat needs of industry (in combination with the development of green hydrogen).

5.3. Developing a future-proof energy market design

Many of the changes needed in the energy system to achieve rapid and cost-effective decarbonisation can be stimulated by improving the design of the energy markets and their regulatory framework. Areas with significant potential for improvement include: cost-reflective energy prices, proper market rules to facilitate a level-playing field for different flexibility solutions, adequate carbon pricing and future-proof energy grid tariffs.

Adequate and cost-reflective energy price signals for market operators and end-users are necessary. End-user prices of energy are not currently integrating all external costs, and hence do not incentivise the most effective energy use and investment choices. End-user prices for electricity are still regulated in several MSs and do not reflect wholesale prices; moreover, they include, next to grid charges, several fees (e.g. renewable energy contribution) and taxes,[201] while for fossil fuels, the surcharges included in the energy bill are in general lower or these fuels even enjoy significant subsidies.[202] This discrepancy creates a market bottleneck for electricity-based solutions that offer economic and environmental benefits compared to fossil fuel based solutions, e.g. electric heat pumps. Energy retail prices should not be fixed by authorities but should rather reflect wholesale prices, and surcharges or subsidies may not lead to competition distortion amongst energy vectors or technologies and must be based on addressing positive or negative externalities and policy objectives.

An essential means to make energy prices more cost-reflective and to reduce market and competition distortions, is an EU wide implementation of an **adequate pricing of carbon emissions for all energy vectors and installations.** The EU Emissions Trading Scheme (EU ETS) only currently covers large conventional power plants and industrial installations, while the heating/cooling and mobility sectors are not included. Several EU Member States have introduced carbon pricing for the non-ETS sectors, but in some other Member States there is not yet a level playing field for all energy carriers in terms of

[200] JRC (2016) Efficient district heating and cooling systems in the EU.

[201] Trinomics (2018). Study on Energy Prices, Costs and Subsidies and their Impact on Industry and Households.

[202] Overseas Development Institute and CAN Europe (2017) Phase-out 2020: monitoring Europe's fossil fuel subsidies.

CO_2 emissions. A more coordinated approach, based on a similar CO_2 levy on all energy vectors and installations, should allow reaching the climate targets at a lower cost while avoiding distortions.

The increasing share of intermittent (PV and wind energy) electricity generation is making the management of the electricity system and its balancing much more complex. Sector coupling is expected to provide, in particular via power-to-gas technologies and storage, additional flexibility. All flexibility potential should be optimally exploited in order to ensure that the required reserve capacity and balancing energy is available at reasonable cost; demand response (load shifting based on technical or price signals), storage (pumped hydro, heat, batteries, gas) and flexible operation of conventional or renewable power generation, will further gain importance in the future energy system. **Appropriate rules and liquid markets with adequate time granularity** should be put in place for reserve capacity and balancing energy (preferably at supra-national level) in order to create a level playing field for different flexibility solutions to participate in these market segments. Smart metering and real-time pricing of electricity for end-users, should be more widely implemented in order to enable demand-response solutions.

Connection and access tariffs for electricity and gas networks can, depending on the tariff methodologies and modalities, act as a barrier or facilitator for sector coupling technologies. In order to facilitate their deployment, grid tariffs for energy storage or local injection of renewable electricity or gas should be structured in such a way that the right price signals are offered to create a fair distribution of costs between energy producers, users and energy storage service providers to incentivise the availability of balancing services and the deployment of renewable energy. Such adjustments in grid tariffs could for example increase the economic feasibility of injection of biomethane/hydrogen into the grid versus local use/storage of biogas/hydrogen in end-use sectors or for power generation.

5.4. Providing guidance and funding for research and innovation

EU institutions play an important role in guiding and funding sector coupling R&I. Guidance is at present offered via among others the Framework Programmes priorities and specific calls, the Strategic Energy Technology Plan (SET-Plan) and the R&I roadmap developed by the ETIP Smart Networks for Energy Transition (SNET). Financing is provided via multiple instruments, such as the Framework Programmes (and the InnovFin program) and the European Fund for Strategic Investments.

The R&I roadmap of the ETIP SNET[203] addresses research needs for the integration of the power, gas and heat sectors in all the steps of the value chain, estimating the R&I funding needs at €1.1 bn for electricity transmission and €1.5 bn for distribution and noting that EU funds can only cover part of these needs. The EU therefore needs to provide guidance and leverage funding in order to maximise R&I investments in technologies that facilitate integrated planning and operation of energy systems. The ETIP SNET vision indicates that **EU funding must focus on high-risk innovations** not covered by private finance, while simultaneously **developing venture capital financing** for this segment. This should be combined with **shared European research, demonstration and validation infrastructures** in order to accelerate the deployment of R&I project results. [204]

This approach is in line with the new European Innovation Council[205] under Horizon Europe, which aims to **help high-risk, high-investment innovations scale-up** and bridge the so called 'valley of death'. It

[203] ETIP SNET (2016) Final 10-year ETIP SNET R&I roadmap covering 2017-26.

[204] ETIP SNET (2018) Vision 2050 - Integrating Smart Networks for the Energy Transition: Serving Society and Protecting the Environment.

[205] EC (2018) Funding - Awareness - Scale - Talent (FAST) - Europe is back: Accelerating breakthrough innovation.

would be appropriate that this new initiative also properly contributes to stimulating relevant sector coupling technologies, such as high-temperature heat pumps and hydrogen, CO_2 or heat pilot installations and networks. Also, **R&I by network operators should be incentivised by the national regulatory frameworks**, which is currently not always the case. For example, in the electricity sector R&I investments from TSOs are often classified as operational expenses and subject to efficiency mechanisms which may unintentionally disincentivise R&I efforts.[206]

Focused efforts in R&I addressing the specific technology barriers indicated in section 4 (including initiating and stimulating pilot projects) are necessary in order to improve the techno-economic feasibility (cost, performance and infrastructure) of relevant technologies such as fuel cells and high-temperature heat pumps, as indicated in section 3. R&D should also focus on the potential use of methanation. As in a decarbonised energy system, CO_2 availability might become challenging, the source of CO_2 for use in methanation processes should be carefully chosen so that no net CO_2 emissions are created. To clarify this issue, specific R&D in CO_2 direct air capture might be required.[207]

Research is also needed to **develop models which facilitate integrated planning and operation of energy infrastructure**.[208] This will enable accounting for the end-use sector coupling, cross-vector integration and flexibility benefits of different technologies, with practical steps already being taken in the gas and electricity sectors (collaboration between ENTSO-E and ENTSOG[209]). This priority is already reflected in the Horizon 2020 framework programme, supporting modelling research for the better representation of energy systems.[210]

The next **European Framework Programme Horizon Europe** includes objectives to reinforce the link between R&I and other EU policies and to strengthen interdisciplinary research in the cluster of climate, energy and mobility. The high-level R&I strategy of Horizon Europe acknowledges the importance of energy R&I for Europe but still has to address sector coupling explicitly.[211] In this context, the European institutions should properly address not only the policy and investment needs of sector coupling technologies, but also support R&I in these technologies and in the integrated modelling, planning and operation of the European energy system. Horizon Europe should also improve knowledge towards empowering consumers as active participant in the energy market in order to enable sector coupling.[212]

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206 ENTSO-E (2017) R&I Implementation Plan 2017-2019.

207 Frontier Economics (2018) The future cost of electricity-based synthetic fuels.

208 Imperial College London (2018). Unlocking the Potential of Energy Systems Integration.

209 ENTSO-E and ENTSOG (2018) TYNDP 2018 Scenario Report, as of 29.03.2018.

210 European Commission (2018) H2020 call LC-SC3-CC-2-2018 - Modelling in support to the transition to a Low-Carbon Energy System in Europe.

211 DG RTD (2018) A New Horizon for Europe - Impact Assessment of the 9th EU Framework Programme for Research and Innovation.

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Sector coupling involves the increased integration of energy end-use and supply sectors with one another. This can improve the efficiency and flexibility of the energy system as well as its reliability and adequacy. Additionally, sector coupling can reduce the costs of decarbonisation. To foster the full potential of sector coupling in several end-use and supply applications, it is important that existing techno-economic, policy and regulatory barriers are removed. Furthermore, a more integrated approach to energy systems planning is needed. This document was provided by Policy Department A at the request of the Committee on Industry, Research and Energy.

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