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Energy integration across electricity, heating & cooling and the transport sector – Sector coupling

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Content

1 Introduction

The EU plans to cut Greenhouse-Gas (GHG)-emissions to 80% below 1990-levels by 2050 and to 40% by 2030. In the frame of the European Green Deal the European Commission in 2020 announced a comprehensive plan to increase the European Union's emissions reduction target for 2030, from 40 % towards 55 %, (see European Commission (2019)). In order to achieve climate targets, renewable energy sources (RES) are required to replace fossil fuels. This includes the substitution of fossil fuels with RES not only in the power sector, but also in other sectors and applications such as heating, industry or transport. However, the current use of RES in certain industry branches, heating & cooling as well as in the transport sectors is rather limited. In addition, potentials for the direct use of RES e.g. in the transport sector are limited or its development is not desirable for certain reasons. In case of the transport sector, a further development of first generation biofuels made from food crops and grown at arable land (e.g. bioethanol, biodiesel) is considered critically due to several concerns such as sustainability issues and the "food vs. fuel" debate. Instead, electric cars using renewables-based electricity (RES-E) are one alternative decarbonisation option for the transport sector. Generally speaking, new technologies and applications using renewables-based electricity can contribute to decarbonising sectors or applications with a low GHG-reduction potential.

In addition to the GHG-reduction potential, the increased use of electricity in other sectors has an impact on system operation in particular in systems with a high share of variable RES-E. Depending on the load pattern electricity-using technologies, such as electric cars or heat pumps, may contribute to increasing the flexibility of the power system and avoid RES-E curtailment by using excess power generation. So far, energy sectors (power, heat, transport, industry, agriculture) have been using different energy carriers and have been dealt with mainly separately. However, there is an increasing relevance of joint and integrated consideration of all energy sectors.

For example, retail prices of gas and electricity have an impact on the profitability of different heating systems, such as a gas-fired condensing boiler and heat pumps using electricity as input fuel. At the same time, the regulatory framework including taxes, levies and charges has a strong influence on the profitability of new heating systems. Depending on the scheme with respect to regulatory price components in each EU Member State, there may be distortions of competition. This is for example the case in Germany, where charges on electricity are higher than charges on gas. The stronger inter-relationship between sectors may pose important challenges for policy-making and require detailed analysis. Coupling, joint planning and organising the sectors of electricity, heating & cooling and transport therefore becomes crucial for a successful energy transition.

With the beginning of investigations in the integration of large-scale, variable wind power in future renewable energy systems, a first mention of the term *sector coupling* or *integrated energy* in peer reviewed literature can be found (see Schaber et al. (2013), Schaber (2013), Richts et al. (2015)). Moving deeper into the actions towards the energy transition, in 2017 several German ministries and international energy agencies developed thorough guidelines and information on sector coubling (see BMWi (2016), BMUB 2016, BDEW (2017), IRENA et al. (2018)). In 2020 the European Commission presented a comprehensive EU Strategy for energy system integration (European Commission (2020)). Despite the growing research on sector coupling applications in all end-consumption sectors, the meaning and scope of the concept still has to be clarified consistently.

It is the objective of this paper to define "integrated energy" or "sector coupling", to identify the relevant technologies, to explain the impact on the energy system and infrastructure and to draw first conclusion of the different sector coupling options.

In the next chapter we discuss the terminology and the role of integrated energy or sector coupling. Chapter 3 has a focus on the technologies and solutions/options connecting the energy sectors. Next chapter 4 focuses on the impact of sector coupling on the energy system and the infrastructure. In chapter 5 we discuss the impact of taxes, levies and fees on the profitability of sector coupling technologies. Comparing different pathways towards a stronger integration across energy sectors is the issue of chapter 6. The final chapter provides a summary and conclusions.

2 Terminology and the role of "Integrated Energy" or "Sector Coupling"

Although the terms "sector coupling" or "integrated energy" are frequently used in the energy policy debate today, it is often not used clearly and uniformly (Scorza et al., 2018). Therefore, we first consider the definition of the "energy integration across sectors" or "sector coupling" based on a definition used in the context of the low-carbon energy transition in Germany.

We regard sector coupling as the "*substitution of fossil fuels in conventional technologies with alternative energy carriers (e.g. renewables including wind, solar, biomass, geothermal) in new applications or technologies. This can be done either by directly using electricity (in Power-to-Heat PtH and Power-to-Move PtM), by converting electricity into synthetic fuels (Power-to-Gas PtG and Power-to-Liquid PtL), or the use of heating networks* (Wietschel et al. 2017). Although the given definition is rather comprehensive and includes in principle all energy carriers that may substitute "commonly used" fuels, we focus on the use of predominantly renewable-based electricity in other sectors or applications, e.g. to generate heat or produce hydrogen or synthetic fuels. These electricity-based technologies can be subsumed as Power-to-X (PtX) technologies.

In addition, we focus on the use of new or alternative technologies and not on classical power consumers such as night storage heating, electric trains and trams.

The objective of the "energy integration across sectors" are the following:

(1) Contribution to emission reductions

Sector coupling pursues the objective to reduce greenhouse gas (GHG) emissions in sectors with low GHG-reduction potentials by using e.g. renewables-based electricity (RES). Whilst RES have already developed well in the electricity sector, their deployment in the heating & cooling sector is lagging behind expectations and sustainability issues have hampered the development of RES in the transport sector. Thus, the use of RES-based electricity may contribute to achieving climate targets in sectors with a low GHG-reduction potential.

The actual decarbonisation effect of sector coupling measures depends on the power mix. Due to the current power mix, there is typically less contribution to reducing GHG-emissions at present than in the future, i.e. renewable energy shares are below 100% in most power systems. This means, that we do not limit our definition of sector coupling to the use of renewables-based electricity, but also consider sector coupling using power partly generated with fossil fuels.

(2) Contribution to flexibility of the power system

Furthermore, the integration across energy sectors may contribute to increasing the flexibility of a power system with a high share of RES. Thus, additional electricity demand from new sector coupling applications can make use of excess electricity generation due to high renewables feed-in (see Kirchner et al. 2016).

Although excess electricity from renewables in the EU is still limited, sector coupling is more relevant for the future power system with increased shares of variable RES (wind, solar).

(3) Contribution to energy efficiency

Sector coupling technologies are characterised by efficiencies, which are different from classical applications. New technologies may either contribute to improving energy efficiency, but not all technologies do use electricity or biomass more efficiently than classical applications.

The next chapter provides a brief overview on the new technologies that contribute to energy integration across sectors.

3 What are the technologies and solutions/options connecting the energy sectors?

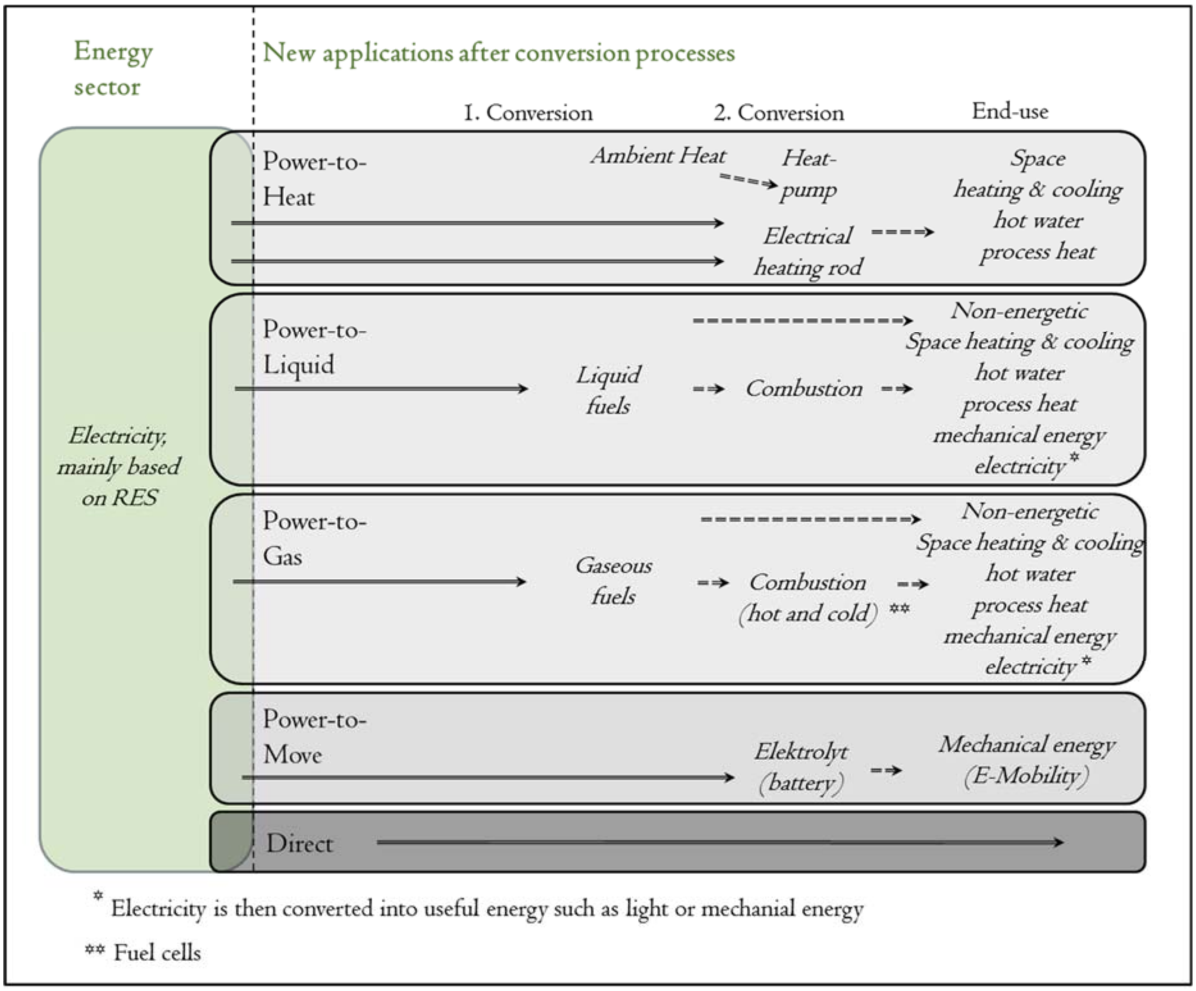
New applications using electricity can be classified according to the end-use purpose and according to the conversion process (see Figure 1).

Power-to-Heat

Thus, electricity can be used in the heating sector to produce space heating & cooling, hot water or process heat (Power-to-Heat). Potential conversion technologies are a direct electrical heating rod or heat pumps using ambient heat either of the ground (geothermal heat pump) or the air (air heat pump). Using ambient heat increases efficiency and heat pumps can substitute gas-using condensing boiler, whilst the direct use of electricity for heating in an electrical heating rod is less efficient and only makes sense as a flexibility measure with low utilisation and used in times of excess electricity generation and low or negative electricity prices. In the industry sector, an increased substitution of blast furnace with electric furnace for steel production is another sector coupling option, characterised as PtH.

Power-to-Move

The direct use of electricity in the transport sector, stored e.g. temporarily in a battery, and converted into mechanical energy in an electric motor to drive vehicles or the electrification of buses or lorries via trolley wires is another sector coupling option (Power-to-Move or e-mobility).



Source: Wietschel et al. 2015

Figure 1: Overview of different sector coupling options according to the conversion processes

Power-to-Gas

Hydrogen can be produced via electrolysis by using electricity and then either be used directly or be converted into synthetic natural gas in a subsequent methanation process. These gaseous fuels can then be used for energetic purposes and be fed into the gas network. Alternatively, the produced gases may be used for non-energetic purposes such as ammonium production. According to Stolzenburg et al. (2014) und Michaelis et al. (2017) converting electricity into hydrogen involves capital-intensive facilities, which in turn require high utilisation rates.

Power-to-Liquid

Hydrogen, produced as in the case of PtG based on electrolysis, is transformed using e.g. Fischer-Tropsch synthesis and a subsequent refining process into liquid fuels (kerosene, diesel, petroleum). These liquid fuels are characterised by a high energy density, are easily storable and transportable and may use the existing infrastructure.

Alternatively, methanol can be produced using methanol synthesis. In contrast to hydrogen, methanol is liquid under standard conditions and does not need to be liquefied for storage or transport. The major disadvantage of methanol is the low efficiency of the overall process chain (ca. 15%-20% if RES-based electricity is used). In addition, the energy density is about half of the level of gasoline and part of the infrastructure would need to be adapted due to corrosion problems. However, the efficiency of methanol combustion engines can be about 40% higher than the efficiency of an Otto engine (Brusstar et al. 2002).

Instead of directly using methanol, it can be synthesised to gasoline, diesel or kerosene (see Albrecht et al. 2013). Overall efficiencies are lower than in case of methanol, but investment in adapting the infrastructure can be saved.

In general, the efficiency of the overall process chain reduces from PtG-hydrogen towards PtG-methane and PtL with increasing processes required.

Table 1: Examples of sector coupling technologies in several application areas/ demand sectors

Energy conversion	Household & Services Sectors	Heating Networks	Transport	Industry
Power-to-Heat (PtH)	Heat pumps, direct electrical heating	Large heat pumps, electrode boiler		Process heat generation from electrode boilers, heating rod, electric arc furnace, etc.
Power-to-Gas (PtG)	Combustion in heating boilers and CHP-plants; Fuel cells	Combustion in heating boilers and CHP-plants; Fuel cells	Fuel cell, combustion engine, gas turbine	Process heat generation, chemical feedstocks (ammonium, methanol, ...)
Power-to-Liquid (PtL)	Combustion in heating boilers		Combustion engine, gas turbine	Chemical feedstocks
Power-to-Move or direct electric drive			Electric car, trolleytruck, trolleybus, electrification of trains	
Electricity-based new processes				New processes (Plasma, etc.)

Source: based on Wietschel et al. 2015 and BMWi 2016

4 What is the impact of sector coupling on the energy system and the infrastructure

The increased use of electricity in other sectors has an impact on system operation in particular in systems with a high share of variable RES-E. Depending on the load pattern electricity-using technologies, such as electric cars or heat pumps, may contribute to increasing the flexibility of the power system and avoid RES-E curtailment by using excess power generation. So far, energy sectors (power, heat, transport, industry, agriculture) have been using different energy carriers and have been dealt with mainly separately. However, there is an increasing relevance of joint and integrated consideration of all final energy sectors.

Using electricity for heating & cooling or transport purposes requires the integrated consideration of all involved sectors. The increasing interconnection between electricity, heating & cooling, transport and industrial processes poses additional challenges for planning and managing the energy system and may require adaptations in the existing infrastructure. One main topic here is the future role of gas and gas infrastructure. With a share of 23.8% in Germany today (2017) (AGEB 2018), natural gas is the second most important primary energy source after mineral oils. Natural gas is also used as a final energy source in almost every sector. Only in the transport sector is it less relevant with minor market shares of natural gas-powered passenger cars. However, there is a growing focus on alternatives, especially in buildings (households and service sector). For example, heat pumps are increasingly used to supply heat to highly insulated buildings, and are being installed in heat networks (district heating).

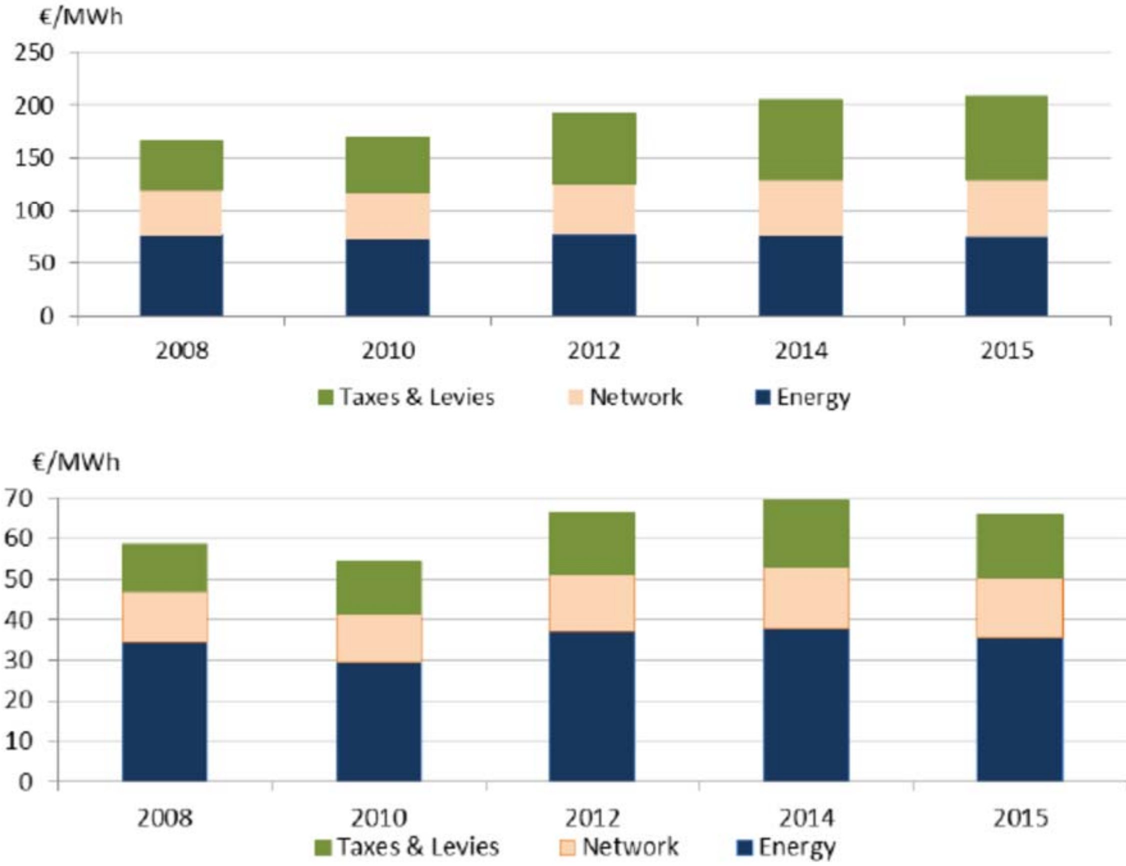
Various studies, investigating a significant GHG-reduction of 95% until 2050 compared to 1990, indicate a clear decline in the demand for natural gas by 2050 (dena 2018; BCG and prognos 2018; Öko-Institut and Fraunhofer ISI 2015; IEA 2019). Especially in buildings, these studies point to a switch from heat generation based predominantly on natural gas to electricity-based heat by 2050. Such a strong drop in the demand for natural gas in a gas distribution network, assuming its length remains unchanged, results in a sharp rise in the specific operating costs (Wachsmuth et al. 2019) and casts doubt on the economic efficiency of a natural gas distribution network for supplying heat to buildings. See Oberle et al. 2020.

The higher complexity coming along with sector coupling requires improved data management strategies and implies the need for an improved digitalisation, e.g. to use flexibility potentials in terms of demand side management measures. Thus, smart energy concepts (smart technologies for power generation, storage, transmission and consumption) may contribute to facilitating an integrated energy transition. In addition, increasing electricity consumption due to new consumers in other sectors and change in maximum load may require adaptations and extensions of the existing grid infrastructure. Finally, sector-coupling technologies may contribute additional flexibility for managing the increasing share of RES-E, whilst other technologies are less flexible in times of use and cannot be used as a flexibility option for the power sector.

5 What is the impact of taxes, levies and fees on the profitability of sector coupling technologies?

In the EU, the development of RES has been stronger in the power sector than in heating & cooling and in the transport sector. Provided that financing of additional costs arising from RES-support is predominantly financed via levies on top of the electricity price, the burden on electricity (weighted EU-average) has been increasing between 2008 and 2015 (see Figure 2, upper figure), leading to higher burden for electricity compared to gas. This leads to high fuel prices for heat pumps, whilst a gas boiler profits from gas prices with lower regulatory price components. We observe an increasing relevance of regulatory and non-market based price components in particular in case of electricity (see Figure 2, upper figure). Whilst the higher burden for electricity has not been a problem for competition in two separate and mainly independent markets, differences in charges can lead to distortions of competition, if electricity competes as a fuel with gas. Another effect of the increased relevance of regulatory price components is that price signals from the market do not reach the final consumers in an undistorted manner and may set wrong incentives. Thus, industrial load management may lead to higher grid fees if the maximum load increases due to the implemented measures (see Agora Energiewende, 2017). Self-produced electricity which is often (partially) exempted from charges or fees may not cease production in times of excess electricity supply or electricity prices amounting to zero (see Agora Energiewende, 2017).

To summarise, we can say that a high burden for electricity can hamper an efficient and undistorted energy transition and integration across sectors. Possible solutions are a stronger alignment of charges for all fuels including electricity, gas and transport fuels either per unit of final energy or per ton of CO_2 emitted.



Source: European Commission (2016)

Figure 2: Components of weighted average EU household retail prices for electricity (upper figure) and gas (lower figure)

6 Comparing different pathways towards a stronger integration across energy sectors

Based on the described technologies in chapter 3, we have identified three main pathways or tendencies of sector coupling for the future. This includes a strong focus on electricity as the first pathway, a focus on hydrogen as the second pathway and the transformation of hydrogen in liquid or other gaseous fuels as a third pathway. Table 2 shows a short evaluation of the different sector coupling options. It shows that the direct use of electricity is the most efficient option from an economic and technical perspective, whilst the PtG and PtL options are characterised by very low technical efficiencies and comparatively high costs. Hydrogen production via electrolysis shows medium technical efficiencies, but requires building a new and cost-intensive infrastructure.

Table 2: Short evaluation of different sector coupling options

	Direct use of electricity	**Hydrogen (Electrolysis)**	**Electricity-based hydrocarbons (PtL, PtG)**
Chances	Most technically efficient pathway In many cases the most cost-efficient solution	More technically efficient than hydrocarbons Easy to store Flexibility option to integrate variable RES-E	Infrastructure partially exists Applicable in various sectors and applications Existing storage can be used
Risks	Grid and storage infrastructure extension is required Need for additional flexibility measures in case of high RES-E shares Not always technically feasible (e.g. low storage density)	Requires building a new and cost-intensive infrastructure High path depency Higher losses than in case of direct electricity use Public acceptance due to high RES-E shares required	Requires CO_2-Input Potentials for GHG-emissions is limited Low economic efficiency Lowest technical efficiency Public acceptance due to high RES-E shares required
Efficiency Production (Basis: RES-Eletricity)	95 %	60-75 %	50-60 %
Efficiency of overall process	60-85 %	30-50 %	10-30 %

Source: based on Wietschel et al. 2017 and Pfluger et al. 2017

7 Summary and conclusions

A stronger integration across energy sectors can **contribute to achieving climate targets**, provided that fossil fuels are substituted by renewable energy sources. One analysis for the German energy market estimates the potential GHG-emission savings due to sector coupling to 50 Mio t of CO_2 emissions by 2030 (see Wietschel et al. 2017). A high potential to reduce GHG-emissions in the short and medium term is provided by direct electrification options: e-mobility, heat pumps and electric blast furnace. In the longer term, trolley trucks may also contribute to GHG-emission reductions, but the technology is not yet mature and it will depend on the achievable technology and cost development. There are also options in the industry sector, including methanol, ammonium or refineries, but these options are still far from being economically efficient.

Producing electricity mainly based on RES is crucial for exploiting the GHG-emission reduction potential of sector coupling technologies. However, we believe that a timely market entry of sector coupling technologies is required in order to exploit potentials on a longer term. The current electricity mix still shows considerable shares of fossil fuels, but a further increase of the RES-E share is a precondition for exploiting the GHG-emission reduction potential of sector coupling technologies. Wietschel et al. (2017) suggest using options with high efficiencies and a high GHG-emission reduction potential in the early phase of the transformation mainly for reasons of public and social acceptance.

Sector coupling technologies may also contribute to **increasing energy efficiency** (e.g. e-mobility, electric steel) and thus reduce GHG-emissions due to efficiency improvements. For example, heat pumps make use of the ambient heat and can therefore improve efficiencies. Wietschel et al. (2017) have estimated for Germany that final energy consumption can be reduced by 180 TWh due to the efficiency effect by 2030, whilst electricity demand of new applications would increase by 50 TWh.

Finally, sector-coupling technologies can increase the flexibility of the power system, which can be particularly relevant for systems with high shares of variable RES-E. However, the flexibility potential of different options and technologies strongly differs. According to Wietschel et al. (2017) there are high potentials for e-mobility and electrode boilers in heating networks.

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