

# The coupling of energy sectors – a promising strategy to a decarbonized world?

Katja Purr, Max Werlein, Oliver Seel and Uwe Leprich  
German Environment Agency

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## 1. Introduction

Climate change is already under way. The United Nations Framework Convention on Climate Change, including all members of the international community, are collaborating to prevent serious disruptions to the climate system and its uncontrollable consequences. The main question to answer is, how to avoid the unmanageable and manage the unavoidable climate changes and its adverse effects. In order to achieve this, the global mean temperature shall not exceed 2°C temperature increase compared to pre-industrial times. The Paris Agreement also pursues efforts to limit the temperature increase at 1.5 °C above pre-industrial levels (cf. UNFCCC, 2016). This internationally agreed climate target can only be met if all countries reduce their greenhouse gases (GHG) emissions significantly and establish a climate neutral society.

As one of the wealthiest industrialized countries, Germany is willing to play a leading role and to take responsibility with regard to the global challenges concerning climate protection. At present the German government aims for a total greenhouse gas emissions reduction of 80–95% by 2050, compared to 1990 levels (cf. Bundesregierung, 2010).

In general, the energy sector including the industry and transport sector is assumed to deliver the highest share in GHG reductions. However, to achieve a high ambition level of greenhouse gas reduction (95%) the energy supply must become completely CO<sub>2</sub> neutral while other sectors such as agriculture and certain industrial processes cannot eliminate their GHG emissions completely (cf. UBA, 2014a).

For the energy sector, the established and essential measures necessary are an extensive exploitation of energy efficiency potentials and an increased use of renewable sources of energy on the supply side, combined with a successive withdrawal of fossil fuels (cf. UBA, 2014a).

Due to the attributes of electricity as being convertible into every other form of energy and easily transportable, combined with the break-through of clean electricity production through wind and PV, the recognition of an extended renewable supply with direct and indirect use of electricity-based energy sources and resources in all fields of application, as additional core component for a CO<sub>2</sub> neutral energy system, has asserted itself.

Sector coupling with Power to X (PtX) technologies offers the opportunity to supply all fields of application with energy from renewable sources and thus, to virtually eliminate energy-related greenhouse gas emissions and considerably reduce process-related greenhouse gas emissions.

However, a large number of factors determine the extent of sector coupling, for example:

- The overall greenhouse gas reduction target: PtX options will play a significant role for a reduction of greenhouse gas emissions, mainly above 80 % compared to 1990.<sup>1</sup>
- The successful exploitation of energy efficiency potentials.
- The degree to which other low carbon alternatives substituting fossil fuels, combustibles and raw materials can be unlocked - particularly the availability and acceptance for using crop-based bioenergy (cf. UBA, 2013) as well as technical measures to tie carbon. In our opinion, crop-based bioenergy and CCS do not belong to a sustainable energy system, due to irreversible impacts on land usage, limited potential and technological risks.

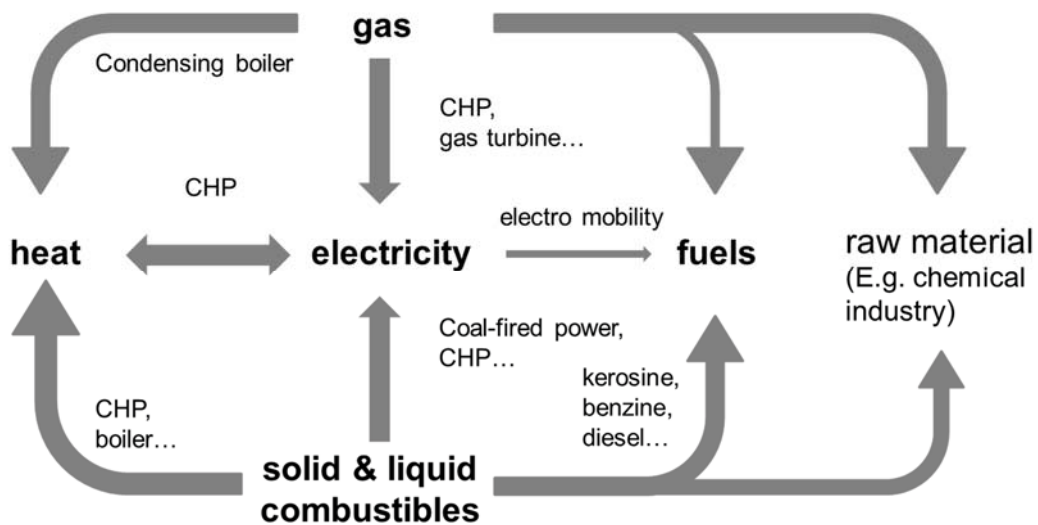
• This paper seeks to give a short overview about the changing role, challenges, and prospects of sector coupling.

## **2. Changes to sector coupling for a decarbonized energy system**

Sector coupling is not new. Links between the various sectors have been in place for a long time, e.g. electrical heating or railway transportation. Nevertheless, today the vast amount of electricity supply, heat, fuel and raw materials are based on direct usage of fossil fuels. (See Figure 1: Conventional links between fuels, combustibles and resources

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<sup>1</sup> Shown in many studies, for example: (Nitsch, 2016; Gerhard, et al., 2015; Öko-Institut, 2015a; UBA, 2014a)



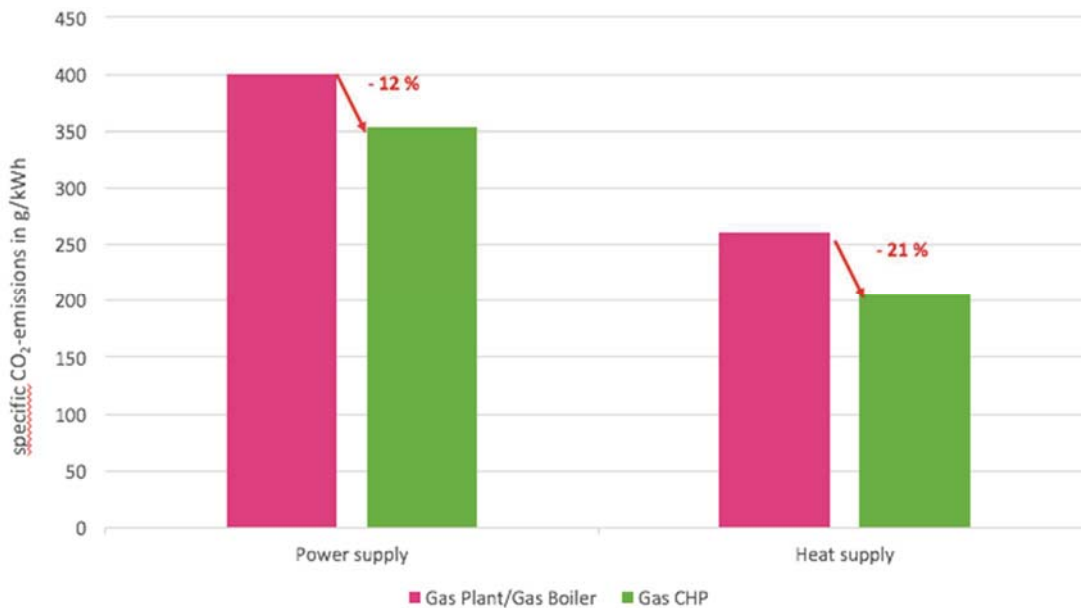
**Figure 1: Conventional links between fuels, combustibles and resources** (cf. Purr, 2016)

In the above outlined conventional system, combined heat and power (CHP) generation technologies are the central components for linking the sectors.

In comparison to conventional power plants CHP plants provide, in addition to power, an amount of usable heat. The emerging heat is mostly used in district heating systems, for industrial processes or other commercial facilities. Common CHP technologies like gas motors or reciprocating engines usually operate to cover a baseload demand of heat. On the other hand, the operator has an economic interest to produce power when the power prices are high. Therefore, the operator optimizes the heat and power production of the plant to generate highest revenues.

Due to the fact that heat and power are used in combination, the application of CHP technologies ensures a highly efficient energy supply (cf. U.K. Department of Energy and Climate Change, 2008). CHP plants achieve efficiency ranges from 80 % - 90 %. Combined cycle gas turbine power plants, for example, achieve a generating efficiency of about 50 %. The fuel use efficiency in CHP plants is hence very high. This has a positive effect by lowering the input of fossil fuels.

When it comes to the ecological benefits of an application of CHP plants, it always has to be considered which power plant or heat station will be replaced by a CHP plant. Figure 2 shows the CO<sub>2</sub> savings of a gas-fired CHP when separate power plants and heat stations are replaced. This case example assumes a central provision of power by a standard gas plant and a heat provision by a gas boiler feeding in a district heating system.



**Figure 2: Specific CO<sub>2</sub> emission reductions when replacing separate power and heat generation by a CHP station. (Data source: (cf. Öko-Institut, 2015b; UBA, 2014b)) .**

The replacement of a gas plant by a gas-fired CHP plant results in specific CO<sub>2</sub> emission reductions of 12 % with respect to power generation. A replacement of a gas-fired boiler, which covers mainly the district heating demand, results in specific CO<sub>2</sub> reductions of 21 %. When CHP plants with lower carbon fuels, e.g. natural gas substitutes, separate coal-fired power and heat technologies, the CO<sub>2</sub> reductions are even higher (cf. U.S. Department of Energy; U.S. Environmental Protection Agency, 2012).

Therefore, many countries have recognized the advantages of a highly efficient, clean and low carbon energy supply by CHP plants and intensify their installation. Countries with very high or high CHP shares of electricity generation are Denmark (> 50 %), Finland (about 40 %), Russia (30 %) and Germany (17 %) (cf. International Energy Agency, 2009).

When decarbonizing the electricity sector in these countries, the integration of high shares of variable renewable energy sources (RES) will be a main challenge which should be flanked by flexibility options like the establishment of a high share of CHP plants. Hence, CHP technologies would be able to react flexibly and to counterbalance the feed-in of variable RES and thus cover the so called residual load. On the other hand, CHP plants are facing other challenges in the heating sector: When efficiency in buildings and industrial processes increase, the heat demand will decrease, and additionally renewable heat production will increase covering a growing part of the heat supply. Therefore, CHP technologies should become more

flexible to cover the heat demand in periods when renewable heat is not available. One possible solution for both of these challenges is to decouple the heat and power supply with CHP by the installment of heat storages. Another option is to use the heat storage capacity of a district heating system as it can buffer the coproduced CHP-heat when there is an economic opportunity to produce power.

The mentioned components for a flexible CHP operation are already used today in existing energy systems, e.g. in Denmark. The Gram district heating system (see Figure 3) for example combines a gas CHP plant (5.5 MW<sub>el</sub>) and a gas boiler (5.5 MW<sub>th</sub>) with a heat pump (950 kW<sub>th</sub>), a solar collector field (44.800 m<sup>2</sup>), industrial heat (2 MW<sub>th</sub>), an electric boiler (10 MW<sub>el</sub>), a thermal pit storage (122000 m<sup>3</sup>) and a storage tank (2300 m<sup>3</sup>). These various energy technologies allow a flexible operation of the heating system especially when energy costs are low.

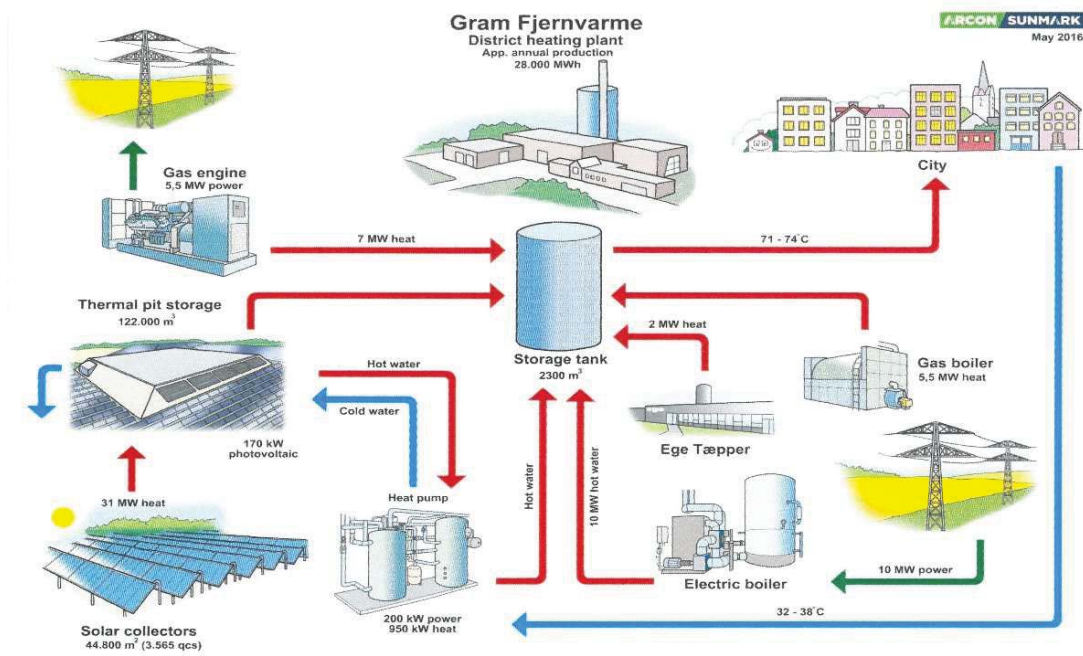
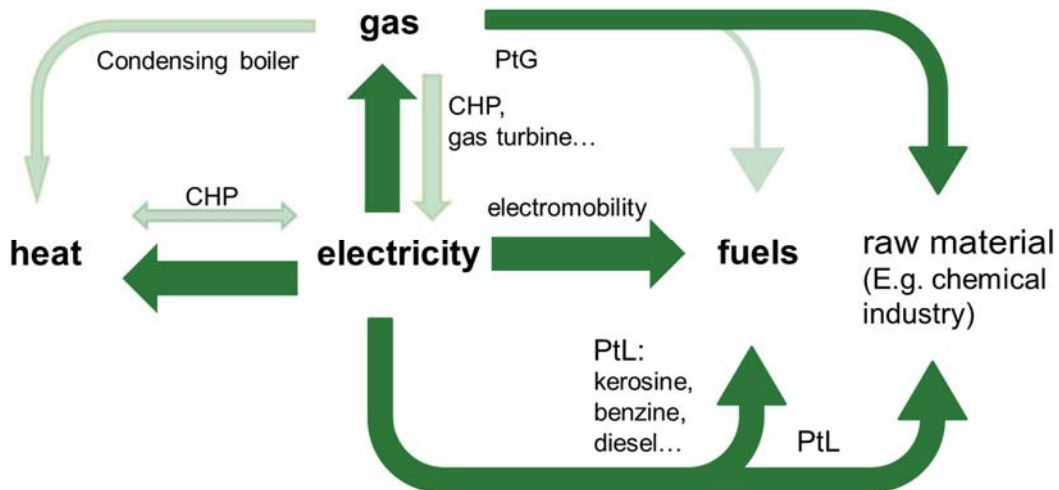


Figure 3: Gram district heating system. Source: (Arcon Sunmark, 2016)

However, with an increasing awareness on climate change, and the Energiewende gaining momentum, the way and significance of linking the sectors is already changing. Beyond CHP more and more Power to X (PtX) technologies will be integrated. The initial point of this new approach of sector coupling is that renewable electricity is offering a full range of options (see Figure 7). These are namely Power to Heat (PtH), Power to Gas (PtG) as well as Power to Liquids (PtL). Power to heat includes all technologies for electricity-based heat supply, such as direct electric heaters (e.g. electric boilers in district heating networks, electric smelting furnaces, electric heating for process heat in manufacturing processes) or indirect heating with heat pumps. PtG is the production of hydrogen and methane, and PtL is the

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production of liquid fuels both from using renewable electricity. PtG und PtL can be used in various sectors, can substitute fossil fuels vastly maintaining the traditional infrastructures (eg. gas pipes) and make it possible to supply renewable energy for all applications (such as in the chemical industry) (cf. UBA, 2016).



**Figure 4: Future links between fuels, combustibles and resources under a strong penetration of PtX.** (cf. Purr, 2016)

Thus, the shorter the usage chain for electricity based applications, the lower are the efficiency losses (see Figure 9 for details).

In a renewable heating sector, both building and process heating will shift towards electricity based processes and especially focus on efficient technologies such as heat pumps wherever possible. And renewable gas as fuel will supply combustion processes, whenever a carbon source is required.

The most energy-efficient option for using renewable electricity in the transport sector is the direct use in electric vehicles. Electric cars play a key role in individual mobility, for light commercial vehicles as well as for buses and short-distance traffic. Today, a high share of road traffic is short distance transport which can be replaced by electric cars. Electrification is not feasible for all applications, i.e. for long range vehicles an additional renewably based liquid or gaseous fuel (such as with plug-in hybrids) is necessary (cf. UBA, 2016). Especially for aviation (cf. LBST, 2016; UBA, 2016) and for shipping, PtL is needed as a GHG-neutral energy supply.

Last but not least: in the long run PtG and PtL could play a major role in supplying renewable based raw materials and thus, contribute to GHG reduction in the chemical industry.

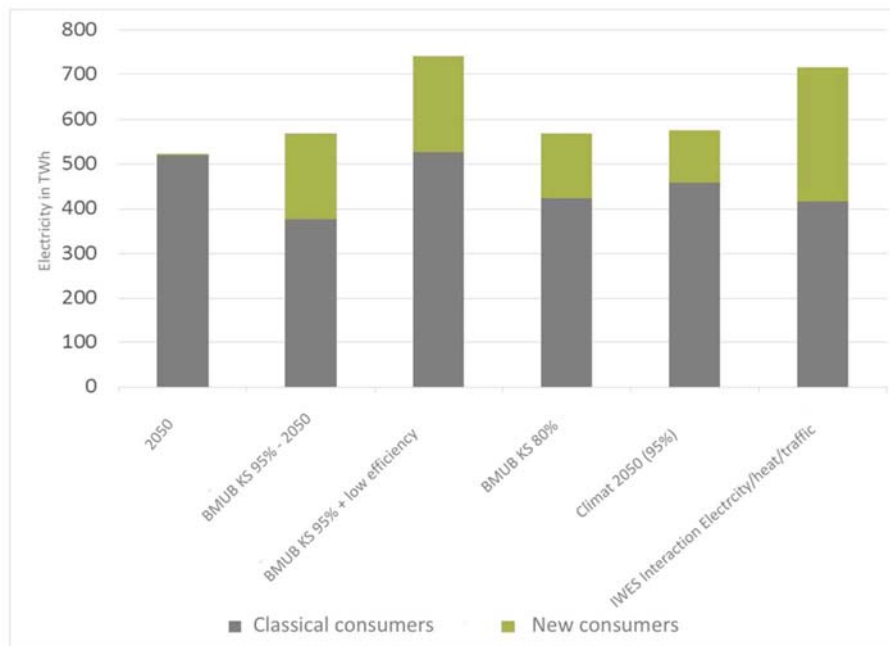
The argumentation above shows the variety and importance of sector coupling in general and the probable application in all sectors, but also points out that PtX offers solutions to decarbonize beyond the electric sector, if the electricity is produced from renewable energy sources.



### 3. System challenges

The usage of sector coupling, especially for an entirely decarbonized energy system, needs an extended electricity production based mainly on solar and wind energy. As mentioned before, especially the degree of targeted emission reduction and the degree of implementation of efficiency measures determine the amount of RES electricity needed.

As mentioned in the introduction, several scenarios for the development of the electricity sector exist, each of which includes sensitivities such as lacking efficiency measures or different reduction targets. These developments can be observed for example in the ‘BMUB Klimaschutz Scenarios’ for 80%, 95% and 95% GHG reduction until 2050 without efficiency measures<sup>2</sup>. The lower reduction level of 80 % mainly corresponds to a higher consumption level of electricity for classical applications (see Figure 5).



**Figure 5: Conventional and new electricity end uses (consumers) in different scenarios.<sup>3</sup> (cf.**

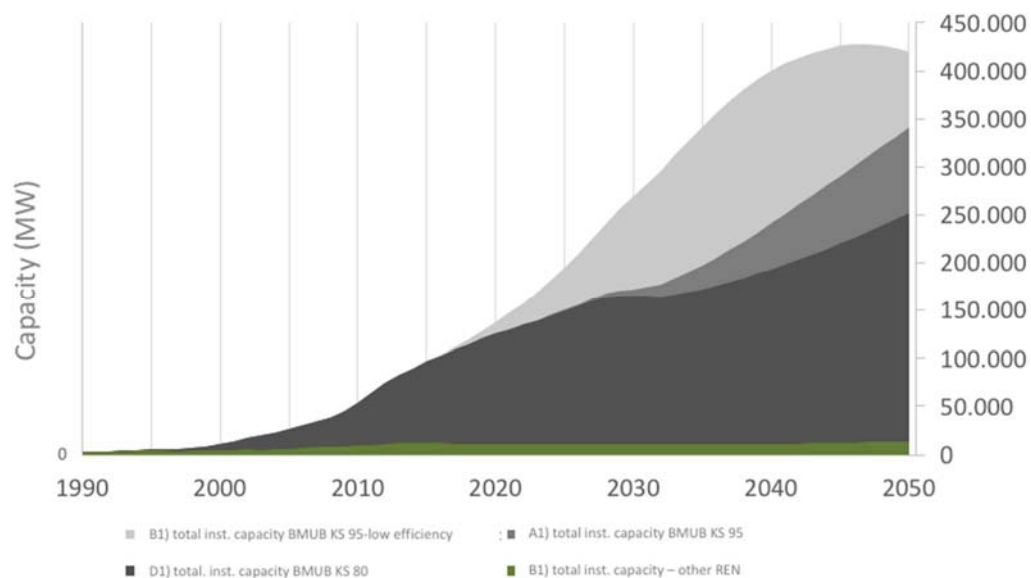
<sup>2</sup> The datasets 2, 4, 5 in figure 5.

<sup>3</sup> The results of the lacking efficiency implementation scenario are driven by the assumption that the consumption due to the classical applications stay on the 2015 level, but that the same overall reduction in emission reduction is achieved. This hence implies that the additional consumption, comparatively speaking has to be provided through RES. Shown in the scenario “BMUB KS95% + efficiency” based on “BMUB KS95%”.

*Nitsch, 2016*)<sup>4</sup>, (cf. *Gerhard, et al., 2015*)<sup>5</sup>

For the further analysis concerning the determination of the amount of RES necessary, an isolated German view is presumed<sup>6</sup>. The resulting effects upon the total installed RES capacity are shown in Figure 6.

For each scenario, the amount of controllable RES capacity such as hydro or biomass is the same and comparable to the current levels<sup>7</sup>. The variable RES electricity generation combines the generation technologies PV and wind on- and offshore.<sup>8</sup> In 2050 they would have a combined installation capacity of about 240 GW for the less ambitious 80% scenario, whereas the 95 % reduction would require 330 GW. If the ambitious efficiency targets cannot be met, an additional 100 GW of capacity will be needed for compensation.



**Figure 6: Development of RES capacity in Germany based on BMUB KS Scenarios** (cf. *Öko-Institut, 2015a*)

<sup>4</sup> For the scenario “Klima 2050” look at Nitsch (2016): “Die Energiewende nach COP21 – Aktuelle Szenarien der deutschen Energieversorgung”.

<sup>5</sup> For the scenario “IWES Interaktion Strom/Wärme/Verkehr” look at Gerhardt (2015): Interaktion EE-Strom, Wärme und Verkehr.

<sup>6</sup> The degree of renewable electricity imports in large quantities affect the amount of RES generation in Germany needed.

<sup>7</sup> Due to limited potentials.

<sup>8</sup> PV and wind onshore are the two dominant technologies capacity wise, due to less limited potential and lower cost.

*Insertion: Germany in 2050 – it can be a greenhouse gas-neutral country*

In order to meet climate protection goals, Germany will not only need to switch to a GHG-neutral electricity supply in the long term, but to a completely GHG-neutral energy supply, including heating and motor fuel. This kind of restructuring of the energy supply system is technically possible, as a recent study by the German Environment Agency showed<sup>9</sup>. Primarily, it will be based on electricity generated from wind and solar energy.

Due to the need for sector coupling, final energy demand for electricity in absolute terms cannot be reduced significantly in the long term. This is the case even if we assume considerable efficiency gains. The main reason for this is the shift towards electricity-based technologies like heat pumps for heating and towards electricity-based industrial processes.

An energy efficient sector coupling is a central pillar of climate and resource protection in addition to the expansion of renewable energies and the exploitation of existing energy efficiency potentials. Retaining today's techniques such as internal combustion engines, and a "one-to-one" substitution of fossil energy carriers by renewable energy carriers (PtG/PtL) would lead to significantly higher electricity demands and raw material use. (cf. UBA, 2017c)

A key part of GHG-neutral energy supply is the conversion of renewable electricity into chemical energy sources. Figure 7 illustrates the basic energy flow.

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<sup>9</sup> (UBA, 2014a)

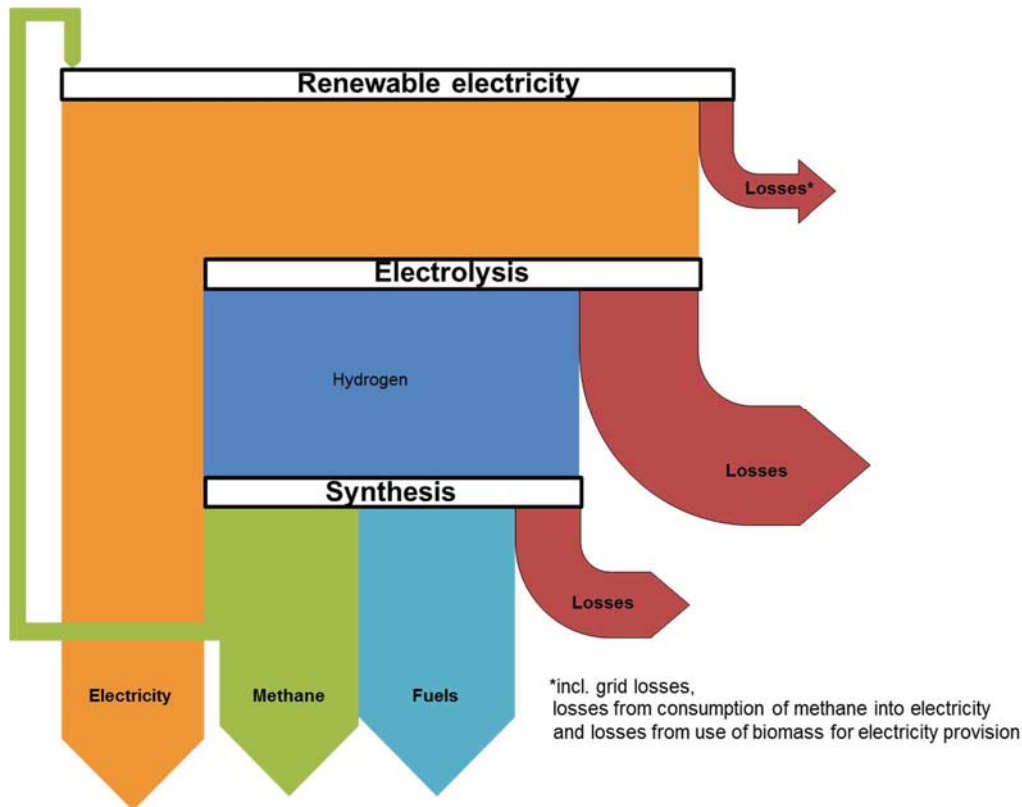


Figure 7: Qualitative final energy flow representation in a GHG neutral scenario

This power-to-gas technology uses water electrolysis to produce renewable hydrogen, which can in turn be used in a catalytic reaction to produce renewable methane. Renewable liquid fuels can also be provided (power-to-liquid technology). The importance of power-to-gas technology is not limited to its role in electricity supply. In the long term it will be a key component of a virtually GHG-neutral energy supply system. Additionally, in the long term, this technology can be used to provide GHG-neutral raw materials for the industry, and with that also helps lowering GHG emissions in this sector. A basic condition for this technology is the availability of water and a GHG-neutral source of carbon (usually in the form of CO<sub>2</sub>). Besides the industrial-scale implementation of the technology, its further development will depend largely on the availability of the inputs, or on the amount of energy that will be needed to supply them. This is what will determine the potential contribution of a power-to-gas technology in the energy system. Hydrogen technology should also play a part in a system based on renewables, because the hydrogen production process is more energy efficient and has the advantage of not needing a carbon source.

The production of renewable heating with methan, motor fuels and raw material for the chemical industry is associated with considerable losses compared to the existing fossil fuel system. Because of these losses, e.g. transport losses, the net electricity

generation required will be 3.000 TWh p.a. roughly estimated. To realize this, another capacity of renewables are needed in addition to the domestic capacity in Germany (shown in figure 6). It might be possible to meet the demand for electricity from a domestic potential. But it is likely that in an international energy network, renewable electricity will be generated at low-cost locations in other countries and then converted into hydrogen, and possibly also into motor fuels and methane, on site or nearby. It is therefore likely that most of Germany's heating and motor fuel requirements will continue to be met by imports. It is realistic to assume that the import ratio will remain at today's levels.

*End of insertion*

The switch to fully generate electricity from renewable sources is of central importance for the transformation process in Germany. In 2016, the peak share of renewable sources of electricity supply in Germany was 68 % (cf. Fraunhofer ISE, 2017) and averaged 31.7 % (cf. UBA, 2017b). Thus the electricity system will face significant challenges with an increasing share of RES.

Due to delayed grid expansion, and conventional fossil power plants unable to reduce their electricity generation capacity ("must-run"), situations occur in which the increasing additional power generation from wind power and PV-plants feeding into distribution grids cannot be transmitted to the upstream transmission grids. This results in serious and increasing bottlenecks limiting the transmission of power from northern Germany to the industrial centers in the south. These constraints sometimes make post market measures (redispatch) necessary in order to keep the system stable. Renewables are then curtailed in the north while conventional power plants in the south are fired up although their actual production costs lie above the market clearing price. The frequency of these measures will increase in times when a lot of RES electricity is produced. Besides phasing out the most inflexible fossil fuel power plants, another option to overcome this problem in a short term, would be to reduce the CHP power generation while using the high availability of RES electricity for substitution of both heat and electricity likewise delivered by CHP in northern Germany.

In the medium term (2030) flexibilization of conventional generation capacity and realization of already planned grid extension and reinforcements could effectively remediate the problems (cf. Übertragungsnetzbetreiber, 2017).

However, in an energy system based on a high share of renewable energy sources, situations, in which the generation capacity of RES exceeds the total load, will occur frequently. Here we will observe a negative residual load. In Figure 8 this is shown for an ambitious scenario with a share of 80% of renewable generation for the year 2030.

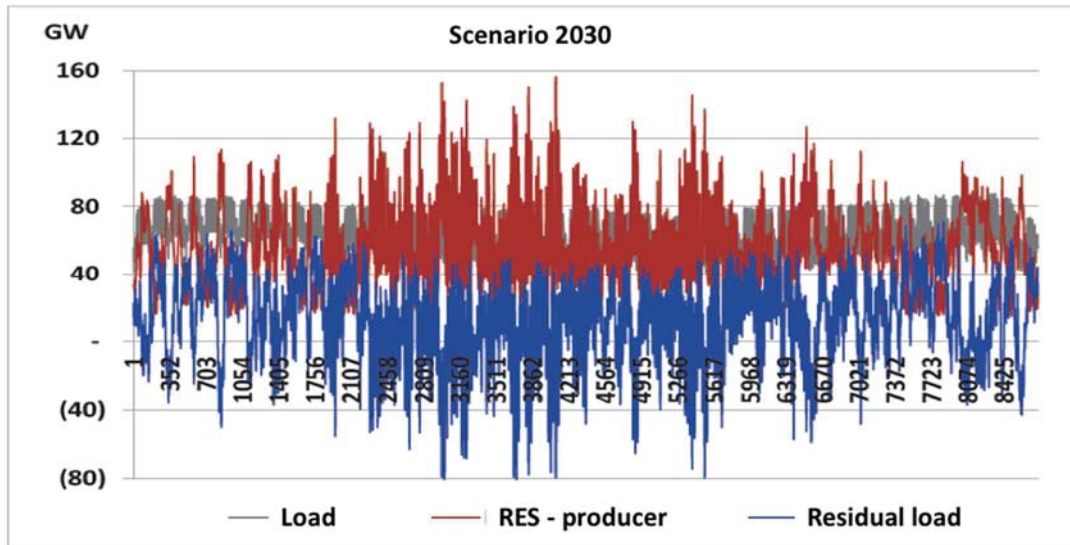


Figure 8: RES generation, load and residual load for an ambitious scenario 2030. Source: (BET, 2013)

Hence it is important to predominantly follow the principle of using the clean energy produced instead of curtailing it. Thus, an efficient trans-sectorial interaction between consumers and generators has to be implemented. Next to reduction of conventional fossil “must-run” capacities and load management, these new “prosumers”<sup>10</sup> increase the flexibility in the electricity system and can therefore, support the integration of variable power supply from renewable sources in the long term (cf. Pape, et al., 2014; Schraber, Steinke, & Hamacher, 2013).

## 4. Recommendations for the new approach of sector-coupling

The integration of additional consumers (PtX) should be in line with GHG mitigation considerations and follow an energetically efficient and economically viable logic for the use of technologies. The emissions reduction contribution of the PtX options is highly dependent on the CO<sub>2</sub>-content in the actual source power mix. The substitution effect of the new electricity consumers based on renewable electricity is shown in Figure 9.

<sup>10</sup> This is a combination of producers and consumers.

regenerative supply			fossil reduction			Substitution ratio	Costs
Input	Technology	Supplied end-/use energy	Technology	Input			
1 kWh regen. power	PtH Heat pump	3,3 kWh (thermal)	3,3 kWh (thermal)	Condensing boiler (105%)	3,14 kWh natural gas	3,14	medium
1 kWh regen. power	e-car (80%)	4,6 km	4,6 km	combustion engine (28%)	2,6 kWh liquid fuel	2,6	medium
1 kWh regen. power	PtH Direct electric	0,95 kWh (thermal)	0,95 kWh (thermal)	Condensing boiler (105%)	0,91 kWh natural gas	0,91	low
1 kWh regen. power	PtG – H2 material	0,74 kWh (hydrogen)	0,74 kWh (hydrogen)	Steam reforming (85,2%)	0,87 kWh natural gas	0,87	high
1 kWh regen. power	PtG – CH4	0,58 kWh (methane)	0,58 kWh (methane)		0,58 kWh natural gas	0,58	Very high
1 kWh regen. power	PtL	0,5 kWh (liquid fuel)	0,5 kWh (liquid fuel)		0,5 kWh liquid fuel	0,5	Very high

Figure 9: Substitution effect by Power to X-technologies (cf. UBA, 2016)

In the short- and medium-term, priority should be set on the energetically more efficient technologies which offer a high substitution effect with regard to fossil fuels and thus, result in significant GHG reductions. Obviously, the use of the technology options with the highest substitution factors such as power to heat with heat pumps and electric vehicles will already under today’s conditions reduce the GHG emissions. Since these technologies are already available, their share should be increased, due to their high CO<sub>2</sub> reductions per kWh of final energy.

One example for effectively reducing GHG emissions is the direct use of electricity via an electric boiler in district heating networks, if electricity generation from RES exceeds demand. This cost effective option can be used for making use of temporary surpluses of RES and it can thus substitute fossil energy supply and with that reduce GHG-emissions. (cf. Agora, 2014)

Since sources of CO<sub>2</sub> are needed for synthesizing renewable methane, methanol and higher hydrocarbons the provision of carbon is a particular challenge. Possible sources are:

- Biogenic CO<sub>2</sub> from renewable processes, e.g. by directly connecting biogas plants,
- CO<sub>2</sub> from fossil carbon combustion processes or manufacturing processes<sup>11</sup> and
- CO<sub>2</sub> from the atmosphere.<sup>12</sup> (cf. UBA, 2016)

<sup>11</sup> This is not a greenhouse gas neutral solution. CO<sub>2</sub> will just be used twice before being released to the atmosphere.

<sup>12</sup> Needed high energy for its extraction.

An alternative for some applications is the direct use of hydrogen as an energy carrier. No CO<sub>2</sub> source is needed therefore, and the power requirements for the production of hydrogen are much lower. However, this requires a new infrastructure (hydrogen gas grid). This is a classic chicken-and-egg problem, because if there are no users of hydrogen in place, there is no need for gas distribution. But up to 15% <sup>13</sup> (cf. DVGW, 2011; Bundesanstalt, 2016), hydrogen could also be fed into the conventional gas grid.

## 5. Conclusions

Sector coupling is not a new issue. Links between the various sectors have been in place for a long time. But when the decarbonization of the energy gets continuously implemented the shape of this linking is changing significantly. Additional new electricity consumers (e. g. PtX technologies) will gain importance.

In the short- and medium-term, priority should be focused on PtX potentials based on energetically more efficient processes (e. g. Power to Heat with heat pumps) which offer a high substitution effect with regard to fossil fuels as well as a significant GHG reduction contribution. But in the long-term especially Power to Gas and Power to Liquid could become key technologies for an energy supply based solely on renewable sources without using non-sustainable biomass production.

Without sufficient RES electricity generation, the large potential for mitigation of GHG by sector coupling could not be unleashed. Therefore, the RES capacity needs to be adjusted to accommodate the new additional electricity needs, and consistent regulatory frameworks should be developed to address the large role which sector coupling should have in a renewable energy system. This would pave the way to a completely decarbonized energy system.

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<sup>13</sup> Currently in Europe, a maximum of 5% hydrogen. In the medium term a 10% to 15% hydrogen concentration in the natural gas system appears realistic.



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