WISO DISKURS

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Thomas Bruckner, Hendrik Kondziella

SECTOR COUPLING
The Next Stage of the Energiewende

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PREFACE

With its recommendation to phase out coal-fired power generation in Germany by 2038, the Commission on Growth, Structural Change and Employment has cleared the way for the next stage of the Energiewende (the "energy transition"). The termination of coal-fired power plants also heralds the advent of the post-fossil age, which visualises the abandonment of fossil fuels by 2080. This step also makes an important contribution to achieving the Paris climate goals. For the energy transition, this decision means not only that the expansion of renewable energy generation capacities must move forward, but also that other sectors need to make a contribution of their own to CO_2 reduction and that there have to be sufficient opportunities to use green electricity.

In this context, the concept of sector coupling is increasingly attracting political and public interest. Particularly in view of the long-term climate protection goals, both globally and nationally, technological approaches in which the electricity, heating and transport sectors can be linked up in a particular efficient manner are currently under discussion. The hope is to be able to achieve the climate goals more quickly and more effectively through synergy effects. Sector coupling is also linked to the goal of storing electricity from renewable sources in the form of hydrogen or methane in order to then use it as a source of energy and heat. But sector coupling can do even more. PtX processes can be used to produce synthetic fuels, lubricants, composites and carbons that can be used in industrial and chemical production as well as in the mobility and construction sectors. No wonder, then, that many experts see sector coupling as a key technology, not only to realise the transition to a largely CO_2-neutral energy supply in the long term, but also as an opportunity for industrial production and employment in the post-fossil age.

But what is the best way to shape this next stage of the energy transition? In this publication, Thomas Bruckner and Hendrik Kondziella from the University of Leipzig summarise the current state of the art and knowledge on sector coupling in a generally understandable way while providing a comprehensive explanation of the various terms. In addition, the authors discuss current technological constraints on sector coupling and explore the economic costs. Nevertheless, in their view, sector coupling has the potential to move us closer to the goal of a decarbonised economy, also in terms of economic costs. The crucial factor, however, will be establishing the right price incentives, for example through a CO_2 price. By the same token, underlying conditions must be shaped politically in such a way that a sufficient demand for these technologies is generated and investment is channelled into these technologies and their application. The authors therefore conclude with recommendations for political action that can help on the one hand to break down existing barriers to a stronger coupling of sectors and, on the other, to promote sector coupling processes in a targeted manner - to make sure that the next stage of the Energiewende is a success.

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1

SUMMARY

The parties to the Paris Climate Agreement agreed to pursue the objective of limiting the increase in global mean temperature to 1.5°C. In the context of Germany's Energiewende targets (Bundesregierung 2010), this means working to reduce greenhouse gas emissions by at least 95 percent by 2050. Given the levels of unavoidable emissions in other sectors, this implies an electricity supply based entirely on renewables.

Sector coupling represents a key technology for realising such an energy supply, and thus for successful realisation of the Energiewende as a whole. A comprehensive evaluation of sector coupling at the infrastructure level must take cumulative CO_2 emissions into account, because an earlier shift from fossil fuels to renewable energy sources in all sectors is good for the CO_2 budget. In the medium term, fossil natural gas can serve as a bridge, which would then be successively substituted in the longer term by green gases (biogas, or hydrogen/methane generated using renewable electricity).

The use of renewable electricity for an ambitious decarbonisation of all sectors and emission types will demand extensive coupling of multiple infrastructures through the application of so-called power-to-X technologies: power-to-heat (use of renewable energy for heating, short-term), power-to-mobility (electromobility, medium-term), power-to-gas (green gases, medium-term) and power-to-liquid (synthetic fuels, long-term). This will enable the use of renewable electricity in the heating sector and (via electromobility) in the transport sector.

It will be impossible to achieve an entirely renewable energy supply in all sectors as long as energy storage systems required to bridge unpredictable "dark and windless" events (weather situations with little wind or sunshine) are lacking. Power-to-gas offers one practicable route to secure the required long-term storage, using the existing gas distribution infrastructure with its storage facilities and pipeline networks in connection with an appropriate reserve of gas-fired power stations. As such the gas distribution infrastructure can guarantee security of the electricity and heat supply throughout dark and windless periods, even in a situation where the Energiewende reduces the guaranteed capacity of nuclear and coal-fired power stations and/or shortages occur in the European electricity market.

Public opposition to the expansion of transmission networks represents a threat to further expansion of renewable energy. Power-to-gas (PtG) can offer an alternative, offering significant network-serving potential once renewables reach 80 percent of electricity demand. PtG can bridge delays in transmission network expansion by using existing gas infrastructure (pipelines and storage facilities). Coupling the electricity and gas networks and operating the infrastructures in parallel also enhances the resilience of the power supply.

If ambitious and cost-effective climate action is to be pursued, the incremental introduction of power-to-X technologies must begin today, aiming to allow for a market penetration in the medium term, because achieving the macro-economic dimensions required by 2050 will involve significant lead times.

The central elements of macro-economically appropriate promotion of sector coupling technologies include:

(1) CO_2 pricing covering all sectors, at a steadily increasing level consistent with ambitious climate targets;
(2) Creation of a level playing field concerning state surcharges on electricity use;
(3) Promotion of research;
(4) Technology-specific promotion of market entry of innovative sector coupling technologies;
(5) Avoidance of unnecessary restrictions on technological openness (for example in connection with the discussion of all-electric approaches or the utility of multiple infrastructures in the electricity, gas and heating sectors).

2

INTRODUCTION

In the longer term, implementation of the German government's Energy Concept (Bundesregierung 2010) will mean transitioning to a largely CO_2-neutral power supply. The core long-term goals laid out in the document therefore include reducing CO_2 emissions by 80 to 95 percent, through measures including increasing the share of renewables in electricity production to 80 percent and reducing primary energy consumption by 50 percent (all to be achieved by 2050). Nuclear power is to be phased out by 2022. Important contributions to achieving these targets are expected from increasing energy efficiency, and associated reductions in electricity demand and primary energy consumption.

The Paris Climate Agreement proposes: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." Whereas an 80 percent reduction in German greenhouse gas emissions by 2050 is fairly compatible with the long-standing 2 degree target, the new 1.5 degree target demands significantly more ambitious action – with accelerated decarbonisation largely completed by 2050. Since the Paris Climate Conference the focus of the climate debate in Germany has therefore shifted to a reduction in national greenhouse gas emissions orientated on the upper end of the Energiewende targets for 2050 (i.e. 95 percent).

As the German government's monitoring reports on implementation of the Energiewende show, the targets for the share of renewable energy in the electricity supply will be met or even exceeded in the medium term. But deficits exist in relation to emissions targets. Greenhouse gas emissions have to date only been reduced by 27 percent in relation to the reference year 1990. Despite a multitude of additional measures – as laid out in Aktionsprogramm Klimaschutz 2020 – it must therefore be assumed that the target of a 40 percent reduction by 2020 will be missed. This applies especially to the transport and heating sectors: The original targets for emissions reduction and renovation of existing buildings will not be met.

Supplementing the request for adjusting the regulatory framework , there is increasing discussion of technological sector coupling approaches, especially in connection with the long-term climate targets. The idea is that closer linkage of the electricity, heating and transport sectors can generate synergy effects in the overall economic implementation of the Energiewende. The benefits achievable through closer coupling of sectors include: (1) the use of renewable electricity as a contribution to accelerated decarbonisation in the heating and transport sectors; (2) integration of fluctuating surplus electricity from wind and photovoltaic that would otherwise be subject to curtailment (i.e. wasted); (3) storage of renewable green gas to safeguard security of supply in an energy supply system that includes ever fewer fossil power stations as a result of the Energiewende; (4) in terms of industrial policy, to become an international technological leader in this innovative field.

From a systemic perspective, sector coupling opens up new opportunities to improve the cost-effectiveness of climate action. The extent to which coupling is desirable and the extent to which it will be necessary to provide targeted support (for example for innovative processes such as generating synthetic methane) or modify the legal framework has yet to be fully clarified. However, a consensus is emerging that it will not be possible to achieve the long-term target of reducing CO_2 emissions by 95 percent without sector coupling (for example through increasing electrification of transport and the application of renewable electricity for heating and generating synthetic gases).

The present study seeks to lay out the state of the art in the field of sector coupling in an accessible manner. Chapter 3 begins by describing the context, while Chapter 4 defines the key terms (such as sector coupling, power-to-heat, power-to-gas, power-to-liquid, power-to-X) and outlines the associated concepts and technological possibilities. Chapter 5 summarises and contextualises the findings of existing publications concerning economic and policy aspects and identifies the significance of sector coupling for successful implementation of the Energiewende. Chapter 6 concludes with a discussion of policy recommendations that could help to remove barriers to the growth of sector coupling, as well as situations where it would appear sensible to subsidise sector coupling developments.

3

THE ENERGY AND CLIMATE CONTEXT

Growing public and political interest in sector coupling is fuelled by the urgency of global and national energy and climate targets. This technological approach has already chalked up successes, but existing deficits must also be noted. In the following we present a global overview and outline the national situation, as the context for the different methods of sector coupling.

3.1. THE GLOBAL CLIMATE CONTEXT

The signatories to the Paris Climate Agreement (COP 21) have agreed to pursue the objective of: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." As climate modelling demonstrates, this target can only be achieved if the CO_2 concentration in the earth's atmosphere can be stabilised and future cumulative emissions of the greenhouse gas CO_2 restricted to a budget compatible with the temperature targets (IPCC 2014, 10). By 2011 the "residual budget" of global CO_2 emissions had shrunk to about 1,000 $GtCO_2$ (for 2 degrees) and 400 $GtCO_2$ (for 1.5 degrees). Current global emissions are close to 40 $GtCO_2$ per annum (IPCC 2014a). In other words, more than half the remaining budget for the 1.5 degree target has already been used up. It is thus very clear that postponing climate action until after 2030 will make it harder to transition to a decarbonisation path and significantly narrow the range of available options. At the same time the following are all increasing: (1) the costs of climate protection, (2) the necessity to actively remove CO_2 from the atmosphere, and (3) the risk that it will no longer be possible to achieve the Paris climate targets (IPCC 2014a). According to calculations using integrated assessment models (IPCC 2014b; IPCC 2018), a climate protection target of 2 degrees can be achieved if global CO_2 emissions are reduced to zero in the course of the second half of the century; the 1.5 degree target, by contrast, requires net emissions to reach zero by around year 2050 (see Figure 1).

From a technological perspective there are essentially three possibilities for achieving the desired reduction in emissions without risking the security of energy services: (1) reducing final energy demand through efficiency measures (for example in buildings, industry and transport); (2) provision of low-CO_2 energy supply (for example renewable energy); and (3) removing CO_2 from the atmosphere (so-called negative emissions). The latter can be realised for example by combining the use of bioenergy with CCS (carbon capture and sequestration) to remove the CO_2 released when biomass is burned. Which of these options is realised on what scale will depend – alongside technological practicability – crucially on economic and acceptance aspects that often differ between countries (Bruckner et al. 2014).

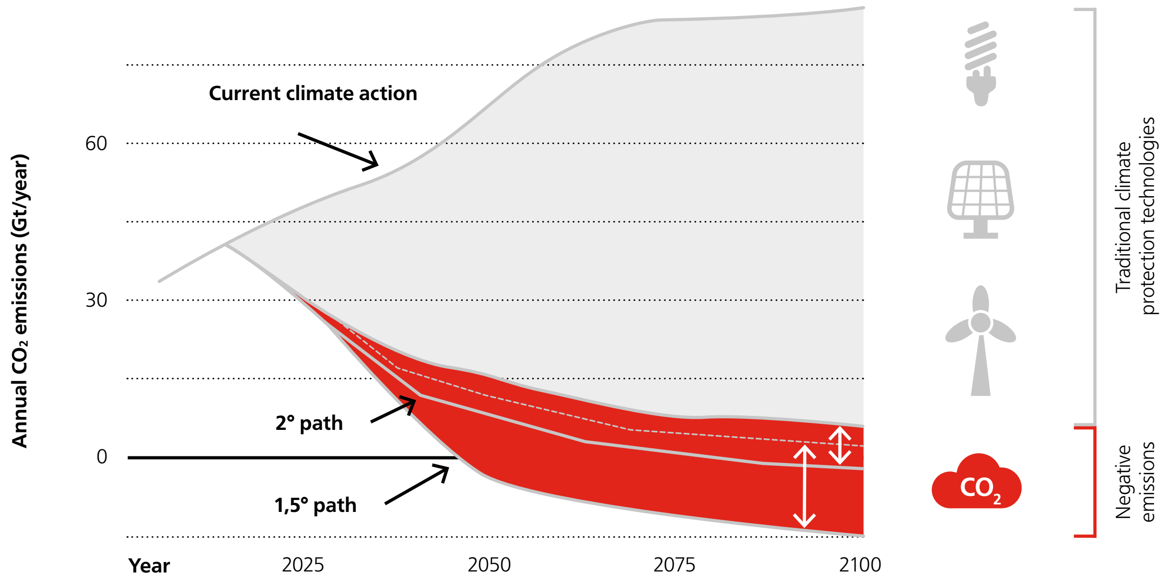
3.2. NATIONAL ENERGY CONTEXT

The German government's Energiewende decisions of 2010 set a series of quantitative targets for Germany's contribution to containing global climate change and protecting finite resources (BMWi 2016c, see Table 1) in the context of European energy and climate policy (BMWi 2016a; BMWi 2016b, BMUB 2017).)

Most of the aforementioned targets of the Energiewende were already laid out in the German government's Energy Concept published in 2010 (Bundesregierung 2010). Concrete implementation is occurring in an ongoing legislative process involving the reform of a multitude of energy-related laws and instruments (BMWi 2016d). The German Federal Ministry of Economics (BMWi) publishes regular progress reports (BMWi 2016c). Since the Energy Concept was originally published in 2010 there has been a substantial change in the political objectives: Following the nuclear disaster at Fukushima the German government reversed its decision to extend the working lives of the country's nuclear reactors. The fundamental political objectives of the Energiewende now include phasing out nuclear power by 2022, alongside climate protection, safeguarding competitiveness and upholding security of supply (BMWi 2016d; BMWi 2015: 8).

As Figure 1 shows, the upper target for reducing greenhouse gas emissions (GHGs) in the German government's Energy Concept (95 percent in 2050 vis-à-vis 1990) would

Figure 1
Paths for anthropogenic CO_2 emissions



Source: MCC 2016. See also IPCC 2018.

Table 1
Quantitative targets of the Energiewende

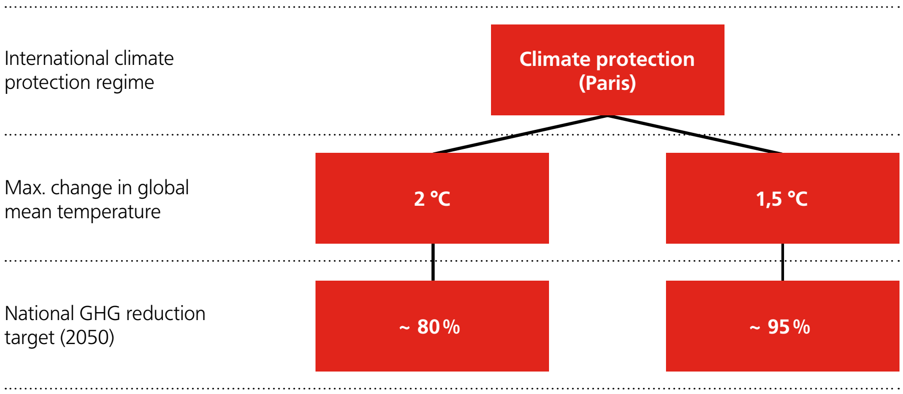
Year	2020	2030	2050
GHG EMISSIONS			
Greenhouse gas emissions (reduction compared to 1990*	40%	55%	80–95%
RENEWABLE ENERGY			
Share of gross final energy consumption	18%	30%	60%
Share of gross electricity consumption	35%	50%	80%
EFFICIENCY AND CONSUMPTION			
Primary energy consumption (reduction compared to 2008)	20%		50%
Gross electricity consumption (reduction compared to 2008)	10%		25%
Primary energy demand, buildings (reduction compared to 2008)			80%
Heat demand, buildings (reduction compared to 2008)	20%		
Final energy consumption, mobility (reduction compared to 2005)	10%		40%

* In the cases highlighted in red, the targets are not currently expected to be met.
Source: Targets: BMWi 2016c: 4; expectation of achievement of targets after Expertenkommission 2017.

represent an appropriate German contribution to meeting the global 1.5 degree target (see Figure 2). The lower target of an 80 percent reduction in GHG emissions corresponds – as Figure 1 shows – more closely to the objective of meeting the 2 degree target. At this juncture it is already worth emphasising that the difference between the two targets addressed here (80 percent and 95 percent) plays an outstanding role in the subsequent assessment of the sector coupling techniques considered in this study.

According to the German government's Climate Action Plan 2050 (Klimaschutzplan 2050, BMUB 2016a; BMUB 2016b): " Germany's long-term goal is to become extensively greenhouse gas–neutral by 2050.". Assuming adherence 'to the Paris Climate Agreement – as Figure 1 shows – this means that Germany cannot simply stop at 80 or 95 percent reduction in GHG emissions after 2050. It is obvious that in particular the figure of 80 percent by 2050 (and even a value of 95 percent) can only be understood as a transitional step

Figure 2
Global climate targets and national reduction targets für greenhouse gas emissions (GHGs)



Source: Authors.

on a climate protection path leading to a complete decarbonisation of the economy in the course of the second half of the century. In the present study the twin climate targets (95 percent/1.5 degrees) thus imply an attempt (or in fact a necessity) to permanently avoid greenhouse gas emissions wherever this is technologically possible.

The German government's climate protection targets identify a target corridor for greenhouse gas reductions by 2050. As described in Chapter 3.1. for the global context, the international community has a residual budget of CO_2 emissions that is compatible with meeting the respective temperature targets. At the same time, integrated assessment modelling makes it clear that a rapid reduction in emissions is required if the emissions reduction path is to be economically viable (IPCC 2014a; UNFCCC 2015).

Assuming a linear reduction path from 2015 to the respective targets in 2050, Germany will emit approx. 20.85 $GtCO_2eq$ in the 80 percent scenario. If the 95 percent scenario is chosen today, the cumulative CO_2 emissions will be less, at approx. 17.5 $GtCO_2eq$. This would save the global GHG budget approx. 3.4 $GtCO_2eq$ (Figure 3).

As well as repercussions for expected emissions in 2050 (max. 250 Mt for 80 percent path compared to 67 Mt for 95 percent path), the choice of GHG emissions target (80 percent versus 95 percent) also affects the cumulative budget: the less ambitious path leads to roughly 20 percent higher consumption over the period as a whole. Alongside the expansion of wind and solar, a faster cross-sectoral fuel switch from coal and oil to gas (in the short term to natural gas and in the medium to long term to renewable power-to-gas or biogas) can thus contribute to preserving the remaining CO_2 budget.

If we are seeking cost-effective climate protection, analysts at the global level (IPCC 2014a) and in the national sphere (Frontier Economics 2017) show that the available emissions budget is not evenly distributed among all sectors. Because there are practically unavoidable emissions in industry and agriculture, an overall GHG reduction target of 95 percent implies almost complete decarbonisation of the electricity and heating sectors, and in the long term also mobility. Given the phasing out of nuclear power and the caution observed to date in the public opinion in relation to CCS, a 95 percent GHG reduction target will require almost 100 percent of the electricity supply to be renewable.

Progress to date in implementing the Energiewende can be summarised as follows (see Figure 4) (Agora Energiewende 2018, UBA 2018):

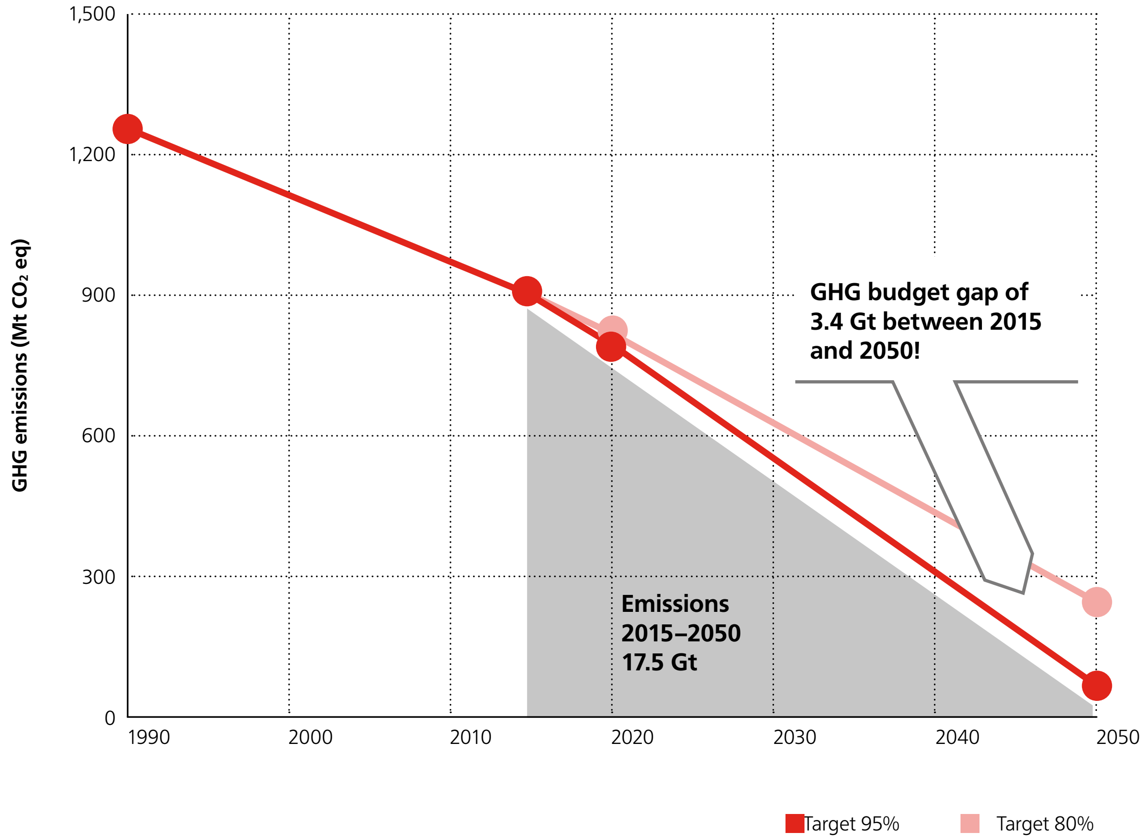
- The proportion of electricity demand supplied by renewables rose in 2017 to more than 36 percent. The Energiewende objective for 2020 (35 percent) has thus already been met. But the share of renewable energy is stagnating in heating and falling in the mobility sector (UBA 2018).
- Primary energy consumption in 2017 was 5.9 percent lower than in the reference year (2008). The trend is thus far from meeting the target (20 percent by 2020) (Expertenkommission 2017).
- Greenhouse gas emissions in 2017 were 27.6 percent lower than in the reference year 1990. Again, the trend is thus far from meeting the target (40 percent by 2020) (Expertenkommission 2017).

3.3. DECARBONISATION OF THE HEATING AND TRANSPORT SECTORS USING RENEWABLE ELECTRICITY

Consideration of the energy and climate goals and the progress made to date leads to the following interim conclusion: While the targets of the Energiewende that relate to phasing out nuclear power and expanding the use of renewable energy in the electricity sector will in all likelihood be achieved, considerable deficits remain in relation to efficiency targets. But the biggest challenge is in relation to the uppermost objective of the Energiewende, that of reducing greenhouse gas emissions (Expertenkommission 2017).

In view of those findings, it would be tempting to compensate the deficits in improving overall energy efficiency

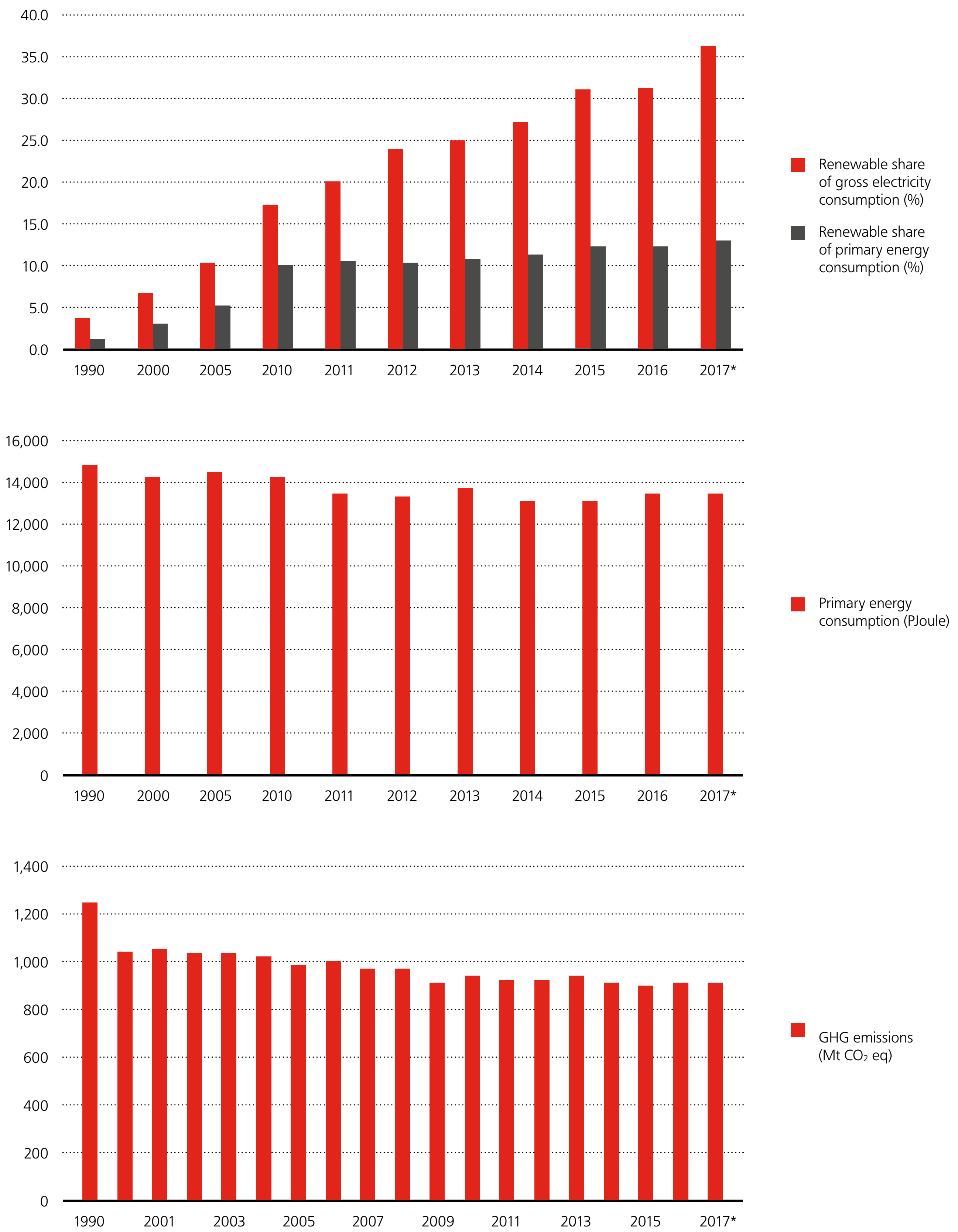
Figure 3
GHG emissions in Germany (2015)



Source: Authors, data from BMUB 2016b.

and increasing the use of renewable energy in the heating and transport sectors by using renewable electricity not only in the electricity sector itself, but increasingly also to drive decarbonisation in other sectors. This approach – known as sector coupling – can potentially harness the very impressive development of renewable energy in the electricity sector to benefit other sectors. Many actors see sector coupling as a central approach that can make a significant contribution to the necessary future reductions in national greenhouse gas emissions. To what extent and under what preconditions sector coupling can fulfil those desires is discussed in greater detail in the following. First of all the technological principles are examined, followed by an analysis of the economic efficiency. The contribution concludes with recommendations for energy and climate policy.

Figure 4
Achievement of concrete Energiewende targets



* Figures for 2017 are provisional.
Source: AGEB 2018, Agora 2018.

Table 2
Likelihood of achieving Energiewende 2020 targets

DIMENSION	INDICATOR	LIKELIHOOD OF MEETING TARGET
Main aims of energiewende	Reduction in greenhouse gas emissions	unlikely
	Phasing out of nuclear power	likely
Renewable energy	Increase share of renewable energy in gross final energy consumption	likely
	Increase share of renewable energy in gross electricity consumption	likely
Efficiency and consumption	Reduction in primary energy consumption	unlikely

Source: Authors, based on statements of Expertenkommission zur Bewertung der Energiewende (Expertenkommission 2017).

4

THE ENERGY AND CLIMATE CONTEXT

Sector coupling methods offer the potential to move towards the target of a decarbonised energy sector in a manner that is also economically optimal. The question of economic efficiency is addressed in Chapter 5. First, the different technological paths are presented here and their energy efficiency compared.

4.1. SECTOR COUPLING TECHNIQUES

The brief outline of the technologies relevant to sector coupling is based on the definitions in DVGW/VDE (2016). More detailed technological descriptions are found in Sterner/Stadler (2017). In all cases a contribution to comprehensive decarbonisation only arises if the electricity used is increasingly supplied from renewable sources. This can be (but is not necessarily) surplus renewable electricity that would otherwise be subject to curtailment. The most important sector coupling techniques are:

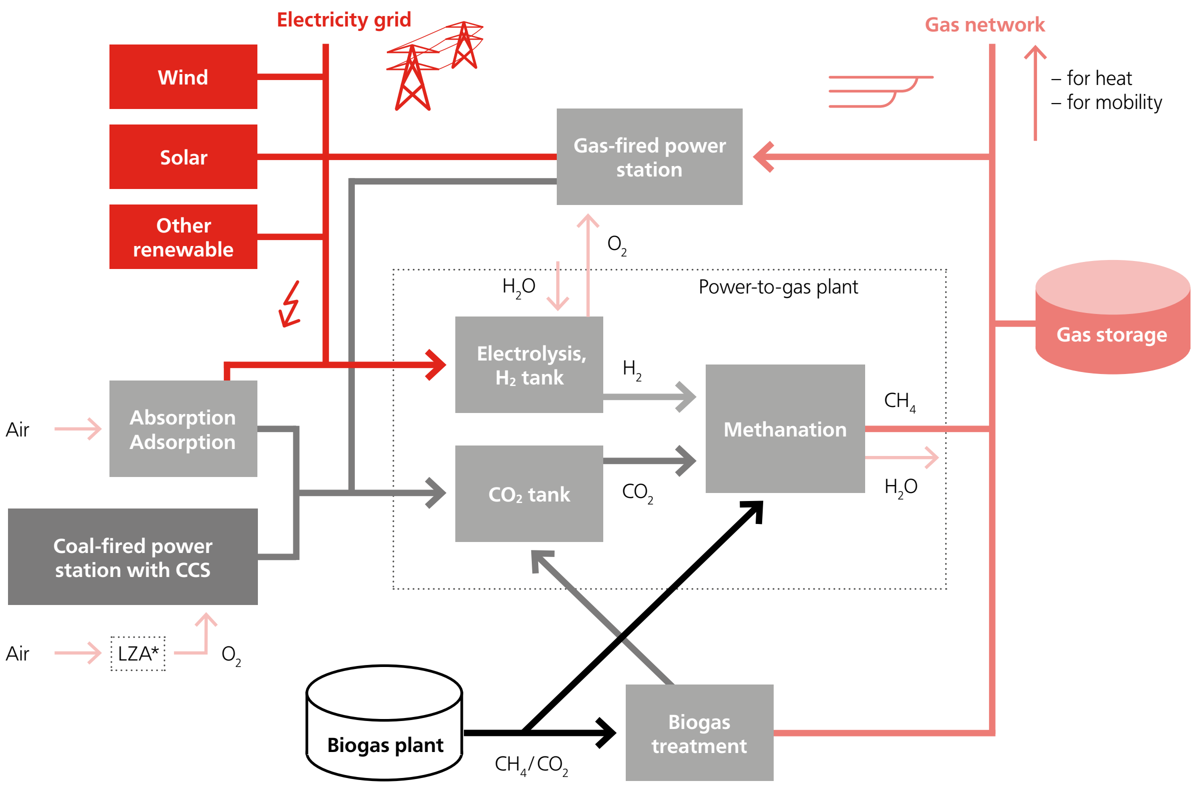
– Power-to-heat (PtH, P2H): Use of electricity for heating, for example by fitting simple heating elements (electric boiler) in district heating systems or use of electrically powered heat pumps.

– Power-to-gas (PtG, P2G): Generation of combustible gas (for example hydrogen or methane) by electrolysis of water – splitting water molecules into hydrogen (H_2) and oxygen. In a subsequent step (known as methanation, see Figure 6) the hydrogen can be converted into synthetic methane (CH_4) by combining it with carbon. The standard source of carbon would be CO_2 for example (1) sourced from biogas processing, (2) captured from the emissions of fossil-fired power stations (analogous to CCS) or (3) captured directly from the air (direct air capture). If renewable electricity is used, we speak of renewable natural gas, as natural gas is largely composed of CH_4. The term "green gases" comprises renewable natural gas and biogas.
– Power-to-liquid (PtL, P2L): Processes generating synthetic liquid fuels using electricity. Hydrogen generated through electrolysis is combined with carbon in subsequent chemical processes to produce synthetic hydrocarbons (methanol, dimethylester, kerosene, etc.). The term "power-to-fuel" comprises both power-to-liquid and power-to-gas, where the gases generated (H_2 and CH_4) are used in mobility applications .
– Power-to-chemicals: Use of electricity to produce chemicals. In a broader sense this also includes the products produced by power-to-gas and power-to-liquid. In a narrower sense it is understood as meaning the use of electricity to produce feedstock for the chemicals industry (for example in the context of "green" chemicals).
– Power-to-mobility: Covers all (direct and indirect) uses of electricity in the transport sector. As well as battery-powered road vehicles, this also includes electric trains, trolleybuses and (in the future potentially) trolley-trucks. Alternatively the hydrogen or methane from power-to-gas processes can be used in vehicles powered by fuel cells, CNG or LNG. The latter would also contribute to decarbonisation in the mobility sector.
– Power-to-battery: Use of electricity to charge electric vehicle batteries. In theory the mobile battery in the car can also be used to store electricity, feeding electrical energy back into the grid as needed (vehicle-to-grid approach).
– Power-to-power: (Intermediate) storage of electricity in batteries or other systems (for example pump storage or compressed air storage).
– Power-to-X (PtX, P2X): Umbrella term for all possibilities to use (renewable) electricity outside the conventional electricity sector via power-to-heat, power-to-gas, power-to-liquid, power-to-chemicals, power-to-battery (or power-to-mobility).

4.2. SECTOR COUPLING AND POWER-TO-X

The historically observed expansion of renewable energy has led to a marked fall in costs. The prices offered in bidding processes for new photovoltaic and wind power installations at good locations have in the meantime fallen below 6 ct/kWh in Germany, with the globally price at approx. 3 ct/kWh

Figure 5
Power-to-gas (power-to-methane)



* LZA: Luftzerlegungsanlage

Source: Sterner/Stadler 2017.

(Thomaßen/Deutsch 2017; REN21 2017). Today wind and solar electricity under favourable conditions are already competitive in terms of full costs against conventionally generated electricity from fossil and nuclear sources. If wind and solar electricity are to be used in other sectors as their price falls, it will be necessary to convert and store the energy in other forms.

The technologies of power-to-heat, power-to-gas, power-to-liquid, power-to-chemicals and power-to-mobility (referred to collectively in the following as power-to-X) make it possible to couple the electricity grids with heating, gas and mobility infrastructure so that (1) the renewable electricity can contribute to decarbonisation of other sectors (see Figure 7) and (2) further cross-sectoral synergy effects can be tapped (DVGW/VDE, 2016).

The concept of energy sector coupling is also understood to encompass integration of the electricity, heating and gas distribution networks and the mobility sector (see Figure 7). This expands the options available for cost-effective implementation of the Energiewende.

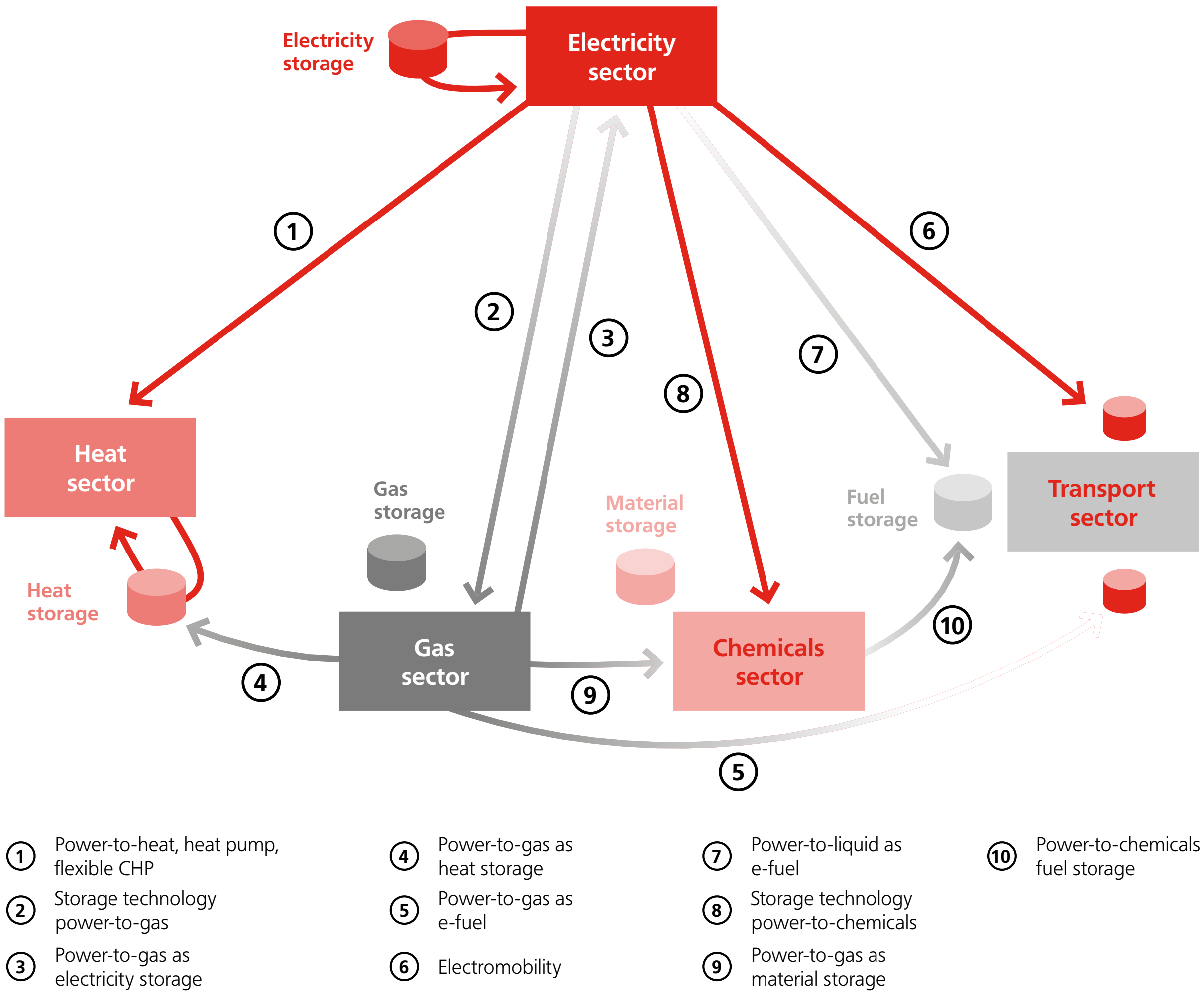
4.3. TECHNICAL EFFICIENCY OF SECTOR COUPLING OPTIONS

From a purely technological perspective, the paths described above open up multiple, diverse possibilities to utilise renewable electricity in different sectors of the economy. As described in Chapter 3, the expansion of renewables in the electricity sector has proceeded faster than expected. At the same time the heating and transport sectors exhibit major deficits in relation to the goals of the Energiewende. It is therefore unsurprising that sector coupling is often treated as a cure-all in the energy debate (Energate 2016).

Yet just because a method is technologically possible does not mean that it is macro-economically sensible. The contribution that power-to-X technologies can actually make to cost-effective realisation of the Energiewende depends in particular on (1) the technical efficiency with which they convert electricity into heat and movement, and (2) the investment and operating costs associated with their application. Because the latter are highly dependent on energy and climate policy and can be influenced by subsidy programmes, we first turn our attention to the technical efficiency of the conversion technologies.

When electrical energy is stored in pump storage systems or batteries, losses occur in particular in association with charging and discharging. Despite these losses, batteries and pump storage systems achieve technical efficiencies exceeding 80 percent (Sterner/Stadler 2017). When electricity is converted into heat (power-to-heat) in an electrode boiler, technical efficiency of almost 100 percent is achieved (Böttger et al. 2015). In the case of heat pumps, which draw heat from their surroundings, technical efficiency averaged over the year (in

Figure 6
Sector coupling with power-to-X and energy storage



Quelle: Sterner/Stadler 2017.

the case of heat pumps this is referred to as the annual performance factor) can exceed 100 percent of the electrical energy consumed (annual performance factor exceeding 1). The efficiency of heat pumps depends strongly on the temperature of heat to be supplied and in particular on the type of heat supply. Typical annual coefficients of performance (COP) factors for air source heat pumps in combination with radiators for heating buildings are around 2; ground-source heat pumps with underfloor heating can achieve annual performance factors exceeding 4 (Fraunhofer IWES/IBP 2017).

The technical efficiency of power-to-gas-on the other hand is significantly lower than 100 percent: the figure for hydrogen production using electrolysis is today in the region of 75 percent (see Figure 8), with further losses for methanation. The technical efficiency of converting hydrogen to methane is generally given as 80 percent (see Figure 8). The technical efficiency of the combined-cycle power plant used to convert gas (back) into electricity is about 60 percent, while the technical efficiency of ordinary gas turbines is significantly less. In the case of power-to-gas the overall technical efficiency is only 36 percent if the entire chain through to power generation is taken into consideration (even assuming of the very efficient variant of combined-cycle power plant). If ordinary gas turbines are used for power generation the overall efficiency falls below 25 percent.[1]

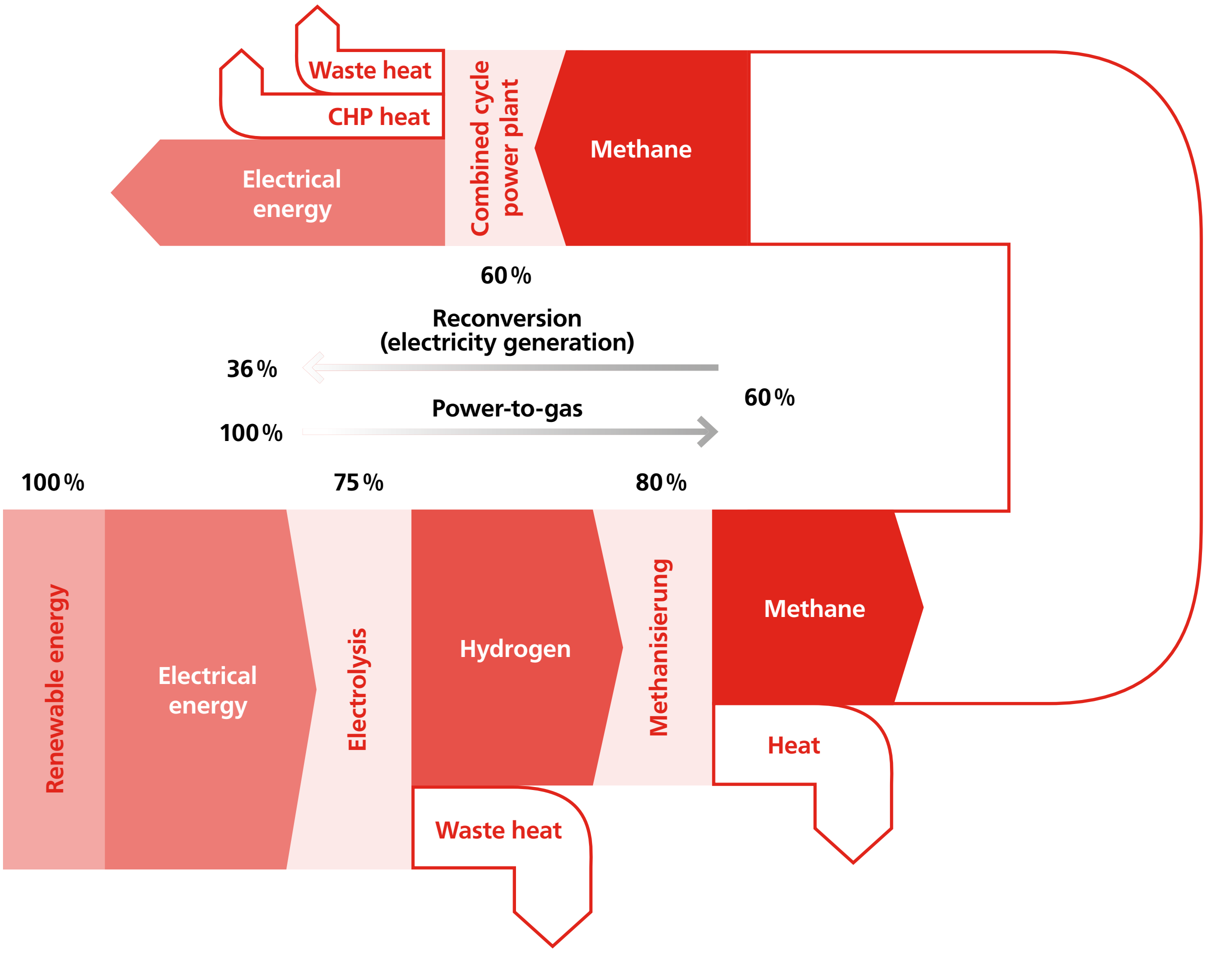
In other words, if one attempts to "save" 1 kWh of surplus electricity from curtailment through power-to-gas using ordinary gas turbines, only one quarter of the energy is actually fed back into the system; 75 percent is lost. Nevertheless, in a comprehensive systemic approach to challenges associated with the Energiewende, at high levels of decarbonisation there are good reasons to use power-to-gas despite its relatively low technical efficiency. These are laid out in detail in Chapter 5.

If we consider the efficiency of different heating technologies (see Figure 9a) (BMWi 2017), it is apparent that heat pumps enjoy a clear advantage over direct electrical heating

1 Although the technical efficiency of conversion to hydrogen is comparable to that of batteries (80 percent), methanation of hydrogen is only one step in the power-to-gas process. The process as a whole is: electrical energy –> hydrogen (75 percent) –> hydrogen to methane (80 percent) –> methane used to generate –> electrical energy (60 percent). The efficiency calculation is 0.75 x 0.8 x 0.6 = 0.36 (36 percent); that is well below the technical efficiency of 80 percent achieved by battery storage.

Figure 7

Figure 8: Technical efficiency of power-to-gas conversion steps



Source: Sterner 2009.

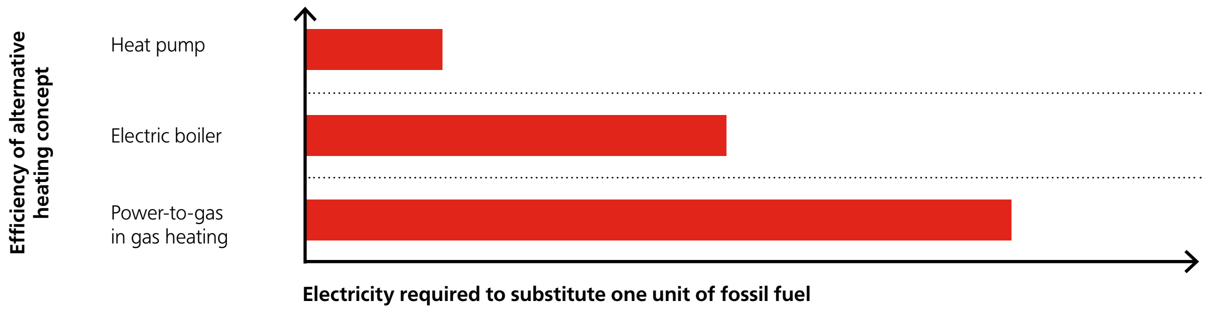
with electric boilers, and even more so over the use of synthetic gas produced using electricity (PtG). This is easy to understand if we remember that heat pumps draw heat from their surroundings, in addition to the electrical energy employed. Electric boilers in turn provide better outcomes than heating using gas produced using electrical energy, because they avoid the conversion losses involved in electrolysis (and methanation).

The findings are similar to those which are obtained for different vehicle propulsion concepts (Figure 9b). If the electricity is used directly to charge batteries (or still better via overhead wires), this is significantly more efficient than the loss-incurring production of hydrogen to use (for example) in fuel cell vehicles, which has a technical efficiency of about 60 percent (Ausfelder et al. 2017). The balance is even worse if methane or liquid fuel – produced with losses via PtG/PtL – are used in vehicles with combustion engines. Here the relatively poor technical efficiency of the conventional combustion engine compounds the losses incurred in the electricity-based production of the fuels (BMWi 2017). Whereas the technical efficiency of electric motors is over 90 percent, the technical efficiency of combustion engines is generally less than 50 percent (Ausfelder et al. 2017).

4.4. TECHNICALLY FEASIBLE – ECONOMICALLY VIABLE

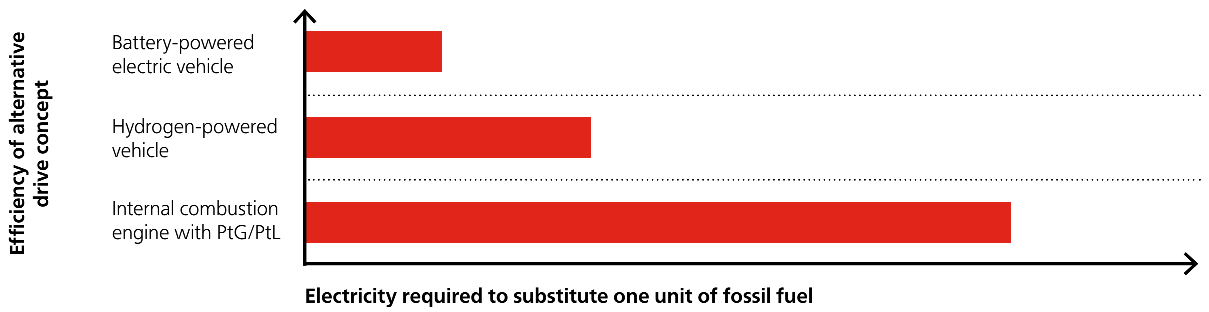
From a purely technological perspective the paths presented here create a multitude of possibilities for sector coupling. But a comprehensive evaluation of their usefulness must not be restricted to the technological perspective. Apart from technical efficiency the breadth of technologically possible applications plays a crucial role, even more so the question of cost-effectiveness. Thus, despite the obvious efficiency advantages of electricity-based sector coupling methods (for example electric heat pumps and electric vehicles) over techniques using PtG or PtL (see Figure 9a and 9b), it would be premature to conclude that all heating and mobility applications should be exclusively electric (the so-called all-electric approach). A comprehensive and systemic perspective on the challenges associated with the Energiewende shows that despite its relatively low technical efficiency, there are good grounds to use power-to-gas in clearly defined areas of application. It is that question to which we now turn in the following.

Figure 8a
Efficiency of sector coupling technologies for decarbonising the heating sector



Source: Authors, on basis of BMWi 2017: 17, Abbildung 2a.

Figure 8b
Efficiency of sector coupling technologies for decarbonising the mobility sector



Source: Authors, on basis of BMWi 2017: 17, Abbildung 2b.

The significance of sector coupling is often downplayed in the energy debate. For example, it is often discussed solely in relation to the use of surplus electricity that would otherwise be subject to curtailment. As will be shown in the following, an integrated techno-economic and systemic perspective reveals multiple important aspects that speak for greater coupling of sectors using power-to-X technologies.

5

INTEGRATED ASSESSMENT OF SECTOR COUPLING APPROACHES

5.1. SECTOR COUPLING TO COMPENSATE TEMPORAL VARIABILITY OF RENEWABLE ENERGIES

The proportion of renewable energy in the electricity supply has risen to more than 35 percent (see Figure 4). Most renewable electricity production (measured in kWh) is generated by wind and solar power, both of which fluctuate with the weather. As Figure 10 shows, the installed generating capacity for renewable electricity in 2017 was almost 120 GW. That is 50 percent more than maximum electricity demand (80 GW). The challenges this creates are discussed in the following.

Given the objective restrictions on expansion of electricity production using hydro-power, bioenergy and geothermal, it should be assumed that electricity production in 2050 will remain largely dependent on fluctuating wind power and photovoltaic. In light of the German government's target of increasing the proportion of renewable electricity to more than 80 percent by 2050 (which inevitably means a corresponding expansion of installed capacity), the number of hours where possible infeed from the renewable sector exceeds demand at that time can be expected to increase. Today residual load (defined as momentary demand minus possible infeed from the renewable sector) is generally positive. In other words, renewable energy sources are unable to satisfy 100 percent of demand and the deficit must be made up using conventional capacity.

In future the frequency of negative residual load periods can be expected to increase, because the installed capacity of fluctuating wind power and photovoltaic will greatly exceed the maximum demand. Surplus renewable electricity during such phases will then have to be curtailed, stored or directed to flexible additional loads (for example in the form of power-to-X installations). As electricity production from renewable sources approaches 100 percent of load, the two annual averages converge. When plotted on an hourly basis (see Figure 11) the residual load fluctuates around the zero line (ETG 2012).

Guaranteeing a stable electricity supply with a high proportion of renewable energy means ensuring that infeed from (conventional and renewable) generating plant and storage always corresponds to demand (including electricity being fed into storage). When this is the case, the amount of electricity entering the grid is the same as the amount leaving it. The grid is in equilibrium, as indicated by a stable network frequency (in Europe 50 Hz) across the system.

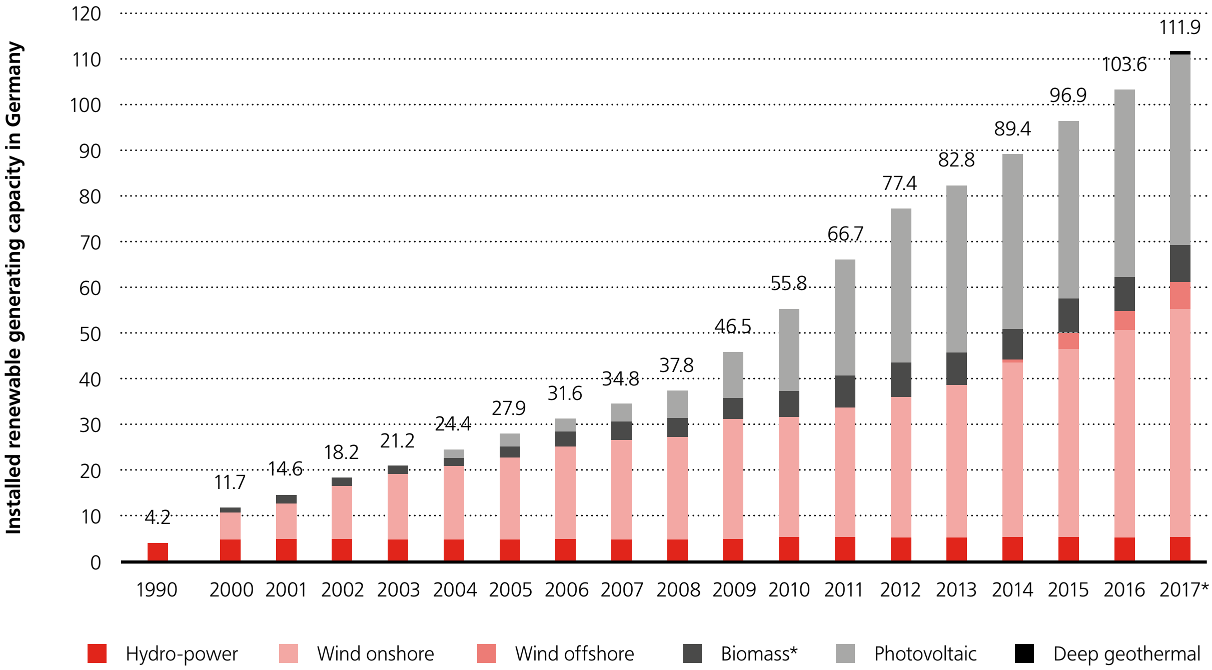
Fluctuations in the electricity supply can be balanced using the following technologies, or flexibility options:

a) Balancing through central, conventional (back-up) power stations (for example gas turbines);
b) Decentralised balancing through flexible back-up technologies ("virtual power plants");
c) Balancing via the national or European network;
d) Curtailment of renewable electricity supply (generation management);
e) Demand-response measures (load management);
f) Use of energy storage systems (pump storage, compressed air, battery storage);
g) Power-to-X (PtH, PtG, PtL, etc.).

As the diversity of options suggests, temporally variable infeed from the renewable sector alone does not create a systemic necessity to employ energy storage systems or power-to-X technologies. Surplus electricity can be avoided through generation management (e. g. curtailment of renewable energy). In periods where renewable infeed is insufficient to cover load, the shortfall can be made up in the medium term, for example by existing conventional power stations or in future by new-build gas-fired power stations (ETG 2012). Where this involves fossil fuel–fired plant, their compatibility with tightening climate targets must verisfied (see Chapter 5.2).

A comprehensive evaluation of the usefulness (or even necessity) of energy storage systems and power-to-X technologies must not be restricted purely to the question of technical feasibility (as unfortunately occurs too often in the public discourse). The very different levels of technical efficiency must also be taken into account, along with the resulting operating costs and the sometimes considerable investment costs.

Figure 9
Historical expansion of renewables in the electricity supply



*Including solid and liquid biomass, biogas (including biomethane, landfill gas, sewage gas, without biogenic share of waste). BMWi on basis of Arbeitsgruppe Erneuerbare Energie-Statistik (AGEE-Stat). As of February 2018, figures provisional.
Source: BMWi 2018.

As laid out in Chapter 4.3, long-term storage of electricity using power-to-gas and the reconversion in gas turbines is associated with especially large losses. If 1 kWh of surplus electricity is "saved" from curtailment using power-to-gas and reconverted in ordinary gas turbines, only about one quarter of the original energy can actually be fed back into the system, while 75 percent is lost. A more energy-efficient alternative in periods of renewable energy surplus (i.e. negative residual loads) is to generate heat, as long as it can be used in bivalent heating systems (BMWi 2017; Böttger et al. 2014; Böttger/Bruckner 2017; Fraunhofer IWES/IBP 2017). Bivalent systems enable the use of electricity during periods where this is economically attractive (for example when there is a surplus of renewable electricity), and switch to other sources of heat when that is not the case. They include district heating systems with power-to-heat and CHP as well as gas-fired peak-load boilers and bivalent heat pumps for individual buildings .

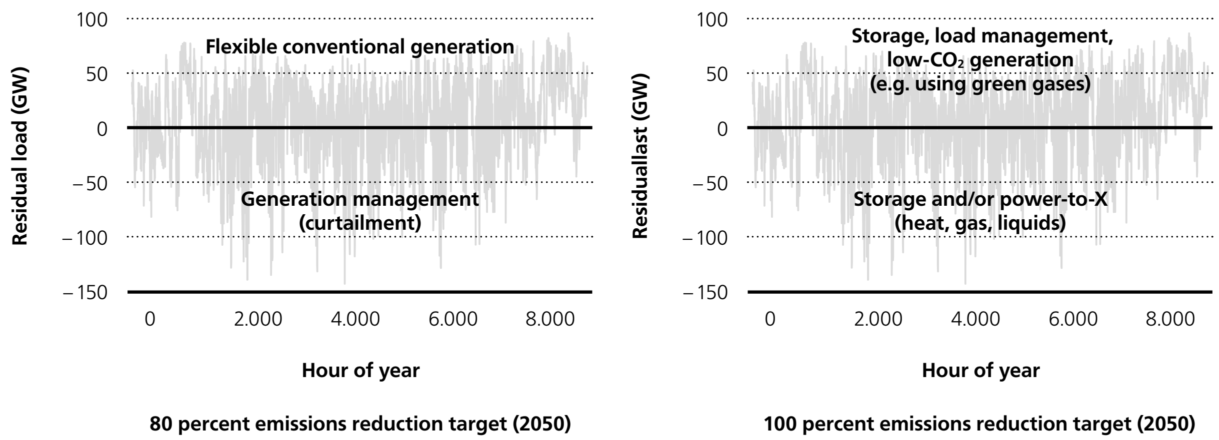
As their investment costs fall (Agora Energiewende 2017a) battery storage could also play a role in balancing short-term fluctuations in the supply of renewable energy (Schill et al. 2015). The same applies to pump storage, and to batteries in electric vehicles – if the latter are operated in so-called vehicle-to-grid mode, where electricity from the battery can be fed back into the grid (Hanemann et al. 2017).

Interim conclusion: Power-to-X can make a contribution to balancing the fluctuations in renewable electricity production. In economic terms, the possibility of temporarily storing surplus renewable energy or converting it into other forms of energy via power-to-X methods must be weighed against the costs (for example for investment in plant). Consequently, the use of these technologies is not always sensible in overall economic terms. Given the especially high investment costs of power-to-gas and power-to-liquid installations, it does not make sense to regard these exclusively as an option for using surplus renewable electricity (Agora Verkehrswende/Agora Energiewende 2018). As the current economic difficulties of many pump storage schemes demonstrate (Schill et al. 2015), there is no automatic connection between the expansion of fluctuating renewable energy and the need for storage. Cost aspects must be included in the evaluation and the systemic cross-sectoral interactions must be considered in the context of given climate protection targets.

5.2. POWER-TO-GAS TO SAFEGUARD SECURITY OF SUPPLY DURING DARK AND WINDLESS PERIODS

Unless excluded by the underlying climate protection targets, all flexibility options applied in the case of positive residual load (i.e. undersupply of renewable energy) must be measured against the benchmark of flexible use of the conventional power stations still in the system. In the longer term, increasing use will need to be made of fossil-fired low carbon alternatives to safeguard security of supply "when the sun doesn't shine and the wind doesn't blow". As its costs continue to fall (Agora Energiewende 2017a), battery storage

Figure 10
Market-serving potential for power-to-X in relation to climate target



Source: Authors' compilation on basis of acatech et al. 2015: 15, Abbildung 2; ETG 2012. The extent to which short-term storage will play a prominent role with GHG reduction less than 80 percent will depend on the extent to which storage costs fall.

will increasingly be employed to cover the frequent short-term fluctuations in wind power and photovoltaic (for example the day/night rhythm of solar). But, like pump storage, batteries are not economically viable in the case of rare but longer-lasting dark and windless periods, which do not occur often enough to recoup their high investment costs. Assuming one wishes to avoid relying on imported electricity from other European countries to cover dark and windless periods, the current state of technology offers only gas-fired power stations to fill the gap (alongside bioenergy and geothermal). (Fossil) natural gas is a fuel option in the medium term, but once the GHG emissions reduction target exceeds 80 percent – and in particular where a 100 percent renewable energy supply is sought – the only alternatives for fueling them are biogas and synthetic gas generated in PtG installations.

Under conditions of negative residual load (i.e. renewable electricity surpluses) the costs of curtailment (also known as generation management) define the economic benchmark. The findings of studies for the electricity sector that take into account the necessity for comprehensive techno-economic and systemic analysis (acatech et al. 2015, ETG 2012), are summarised below (see Figure 11).

For a share of variable renewable energy of up to 80 percent of electricity demand and an emissions reduction target of 80 percent (both in relation to 2050), generation management and flexible fossil fuel–fired power stations (for example operating with natural gas) define the economic benchmark case. As the share of variable renewable energy approaches or exceeds 100 percent of electricity demand, the use of storage and power-to-X technologies increasingly becomes a systemic necessity. These technologies also become attractive in macro-economic terms where the share lies between 80 and 100 percent, if network congestion is left out of the equation (so-called market-serving potential of PtX).

The BMWi project on convergence of energy networks reaches similar findings: in the 80 percent GHG reduction scenario, 5 GW of PtG capacity with 1,650 full load hours can integrate approx. 5.4 TWh of additional renewable electricity in the market; in the 100 percent scenario the figure is 38 GW with 4,000 full load hours. Here the demand for long-term PtG storage is 48 TWh of electricity, which requires 70 TWh of green gas (Hüttenrauch et al. 2017). Thus a relatively small expansion of power-to-gas capacity is indicated for a share of 80 percent renewable electricity supply, but PtG demand increases significantly if 100 percent renewable electricity is the objective. The reason for this is the necessity in the latter scenario to provide (renewable) electricity even when the wind does not blow and the sun does not shine in dark and windless periods. Such periods do not occur every year, and when they do, they do not normally last more than two or three weeks. During these rare events it can make sense (despite the poor overall technical efficiency) to generate electricity using gas turbines or fuel cells fired with hydrogen or synthetic gas produced using surplus renewable electricity in PtG installations.

In an electricity system that seeks to cover 100 percent of demand from renewables, 60–70 GW of guaranteed capacity remain necessary, for example through PtG with gas-fired power stations (Sterner et al. 2015). In the event of a dark and windless period lasting two weeks – as observed for example from 23 January to 6 February 2006 with 72.8 GW average residual load (Energy Brainpool 2017) – 23 TWh of secured capacity would be needed. Given that dark and windless periods can last longer than two weeks, the resulting residual load cannot be covered by short- or medium-term flexibility options (such as batteries and/or load management measures).

The meteorological outliers that create the typical multi-week dark and windless event can be expected to occur roughly every two years in similar dimensions. While European balancing via the interconnectors reduces the need for flexibility options in normal operation, it can make only a small contribution to dealing with dark and windless events which – as in 2006 – can affect the whole of continental Europe.

A comparison of the electrical energy required during a typical dark and windless period (25 TWh) with the amount of energy stored in existing gas storage facilities (260 TWh of chemical energy, corresponding to about 155 TWh of electrical energy if converted in combined cycle power plants) reveals that existing gas storage in Germany can already store enough natural gas (and later green gases) to comfortably bridge such a dark and windless period. The existing pump storage capacity of 0.04 TWh, on the other hand, is several orders of magnitude too small (Frontier Economics 2017).

Sector coupling of electricity, heating, mobility and non-energy applications (see 5.4) can further increase the capacity and energy required during dark and windless events (Energy Brainpool 2017) on account of increasing electrification (heat pumps, electric vehicles, etc.) and increasing use of electricity-based fuels (for example hydrogen in the basic chemicals sector) (see Chapters 4.2 and 5.4). This increases the annual maximum load in the German energy system and the necessary share of renewables, primarily fluctuating wind and solar electricity. The additional storage supplied by sector coupling (heat stores, batteries in electric vehicles, etc.) can provide short-term balancing, but is not suited for bridging longer dark and windless periods.

Interim conclusion: In realistic scenarios that seek to avoid importing electricity, storage of green gases will be the only way to safeguard security of supply during dark and windless events in an energy supply system that strives for maximum decarbonisation and maximum renewables. The latest studies (ewi Energy Research & Scenarios 2018) point out that synthetic gases (for example H_2 and methane) used in gas-fired power stations to bridge dark and windless events need not necessarily be produced in Germany, but may be imported and stored until needed. This could significantly reduce the expansion of renewable energy and the volume of PtG/PtL electrolysis capacity required in Germany.

5.3. SECTOR COUPLING TO BALANCE THE SPATIAL VARIABILITY OF RENEWABLE ENERGY

Given the growing acceptance problems affecting transmission network expansion, it is worth considering whether sector coupling technologies – especially power-to-gas – can help to balance spatial discrepancies between renewable energy supply and electricity demand. This is a very promising approach, because the expansion of onshore and offshore wind power will be concentrated in northern and eastern Germany, while the phasing out of nuclear power can be expected to cause an undersupply of electricity in southern and western Germany. In order to address this, the national network development plan proposes expanding transmission capacity (BNetzA 2017).

If acceptance problems lead to delays in transmission network expansion, power-to-gas and the natural gas infrastructure could be used to transport the renewable energy generated in the north and east to the south and west, where it could be converted back into electricity using gas turbines. The required gas pipelines are already in place (FNB 2016). The concentration of existing gas storage in north-eastern Germany is also favourable. As Frontier Economics (2017: 10) points out: "The use of existing gas transport infrastructure offers an alternative to the expansion of transmission networks. Given that the gas networks are underground and already exist, they can make a significant contribution to the acceptance of the Energiewende."

The potential and the timing of power-to-gas for long-term storage in the electricity sector depend crucially on the assumptions made in the scenarios. This applies in particular to the assumptions concerning expansion of transmission networks, generation mix, export and import options for European balancing, and use of alternative flexibility options such as curtailment and short-term storage. While the network development plan (Netzentwicklungsplan Strom 2035) secures a firm place for PtG, it also foresees the continuing use of many fossil fuel power stations – which from today's perspective is hard to reconcile with the consequences of the Paris Climate Agreement. Aside from the CO_2 budget, the core assumption is the speed of expansion of transmission networks: If full expansion of transmission networks is assumed, market-serving application of PtG is unlikely before 2035 (see Chapter 5.2). If it is assumed that expansion of transmission networks will be delayed – as would appear realistic today – between 5 and 30 GW of installed network-serving PtG capacity will be required (Moser 2017).

"Network-serving" here refers to the creation and operation of power-to-gas installations to overcome network congestion with the objective of avoiding or reducing the need to curtail renewable electricity generation. "Network-serving potential" indicates the installed PtG capacity found to be macro-economically cost-efficient in calculations with coupled electricity market and electricity network models. Coordinated planning of electricity and gas networks makes sense from the network perspective, using the gas infrastructure to compensate weaknesses in the electricity network infrastructure (lack of transport and long-term storage capacities) and thus complement the expansion of transmission networks and make the Energiewende more robust and resilient.

Interim conclusion: Opposition to transmission network expansion and resulting network congestion can significantly increase the macro-economically attractive scope of PtG technology.

5.4. SECTOR COUPLING TO DECARBONISE THE HEATING AND TRANSPORT SECTORS

As demonstrated by the monitoring reports on the implementation of the Energiewende (BMWi 2016c), the Energiewende targets for renewable electricity will be reached or exceeded in the medium-term. This does not, however, apply to efficiency targets (see Chapter 3.2). To date greenhouse gas emissions have been reduced only by 27 percent in relation to reference year 1990. Despite a multitude of additional measures in the German government's Climate Action Programme 2020 (BMUB 2014), the objective of a 40 percent reduction by 2020 is unlikely to be achieved. Especially in the mobility and heating sectors, the original targets for emissions reduction and building renovation will not be achieved.

In the meantime, alongside adjustments to the regulatory framework (for example reforming emissions trading) there is an increasing discussion of technological approaches that create synergy effects in the integration of renewables through stronger linkage of the electricity, heating and transport sectors, especially in relation to the long-term climate protection targets. Increased use of renewable electricity in heating and mobility can enable those sectors to contribute to decarbonisation.

Under the heading " Sector coupling as a means to achieve climate targets." the Concluding Paper: Electricity 2030 notes "A cost-efficient climate-saving policy should first of all significantly increase energy efficiency in all sectors ("efficiency first"). Then renewable energy is used directly in the respective sectors without converting it to electricity given this is reasonable from an ecologic [sic] and economic point of view (e.g. solar thermal installations in buildings or biofuels in the transport sector). To achieve the climate goals, the remaining energy demand is covered by carbon-free electricity. This is what is known as sector coupling. To limit the need for renewable installations and the grid infrastructure, the most efficient technologies possible are used" (BMWi 2017: 19, italics added).

Especially the figures on the efficiency of different power-to-X technologies reproduced in the Concluding Paper (Figures 2a and 2b in BMWi 2017: 17; see Figures 9a and 9b in the present study) have led many actors to assume that sector coupling should essentially pursue an all-electric approach in which power-to-gas technologies and the entire natural gas infrastructure are largely superfluous, even with ambitious climate targets. Diverse studies (Agora Verkehrswende/Agora Energiewende 2018, Energy Brainpool 2017, Enervis 2017, Enervis 2018, ewi Energy Research & Scenarios 2018, Frontier Economics 2017, acatech et al. 2015, Prognos/DBFZ/UMSICHT 2018) that examine the role of power-to-gas and power-to-liquid in a largely decarbonised world more closely come to more differentiated conclusions , as we report below.

Despite the obvious efficiency advantages of direct use of electrical energy in heating and mobility, a comprehensive evaluation of sector coupling must not neglect the quality of energy required and the temporal and spatial profile of renewable energy supply and demand (and the associated questions of energy storage and available energy transport options). These include the demand for energy services that are difficult or impossible to supply using electricity (for example high-temperature heat in the chemical industry or fuel for ships and aircraft), questions of security of supply, in particular in relation to dark and windless events (see Chapter 5.2) and consequences for the required expansion of electricity transmission networks (see Chapter 5.3).

The economic evaluation of gas- and electricity-based processes for low-emission heat supply depend on the application (and in particular on the required temperature level) and the progress of decarbonisation in the electricity sector (Enervis 2017, Enervis 2018). In the heating sector the scenarios seeking to reduce greenhouse gas emissions by 80 percent are consistent: In high-temperature applications (fossil) natural gas dominates, in other areas the electric heat pump and district heating play important roles. With emissions reductions targets exceeding 90 percent synthetic gas dominates the high-temperature applications (especially in industry), while electricity-based applications and district heating dominate in the low-temperature applications (Enervis 2018). Bringing the various strands together: from a systemic perspective there is no macro-economic advantage to full electrification of the heating sector, as underlined by the findings of a recent meta-study on sector coupling (Enervis 2018).

If a significant proportion of heating and mobility services were also to be based on electricity in a hypothetical all-electric world, that would be associated with a significant increase in demand for electrical energy. This in turn would require a marked expansion of the renewable electricity supply and of the electricity transmission networks. The pronounced seasonality of the resulting electricity demand – especially in association with electrification of heating – and the dependency of wind and solar power on prevailing conditions create enormous challenges for a future energy system based largely on renewable electricity, especially in relation to security of supply during dark and windless periods. Electricity storage options like pump storage and batteries can only store enough energy for hours or a few days.

According to Enervis (2017) and Energy Brainpool (2017), an all-electric system without gas storage for seasonal balancing and bridging cold dark and windless events by generating electricity from stored gases would be unrealistic or prohibitively expensive (in a completely decarbonised economy). New analyses on cost-efficient structures for future energy markets demonstrate that in an integrated perspective on the electricity and heating sectors the role of gas extends beyond being stored (potentially centrally) and used to generate electricity (for example to bridge cold dark and windless events). Broader use of the existing gas distribution network to distribute green gases nationwide also appears advantageous. In this connection it is emphasised that "the continuing use of gas transport and distribution networks to supply customers with green gas offers considerable cost advantages" (translated from Frontier Economics 2017).

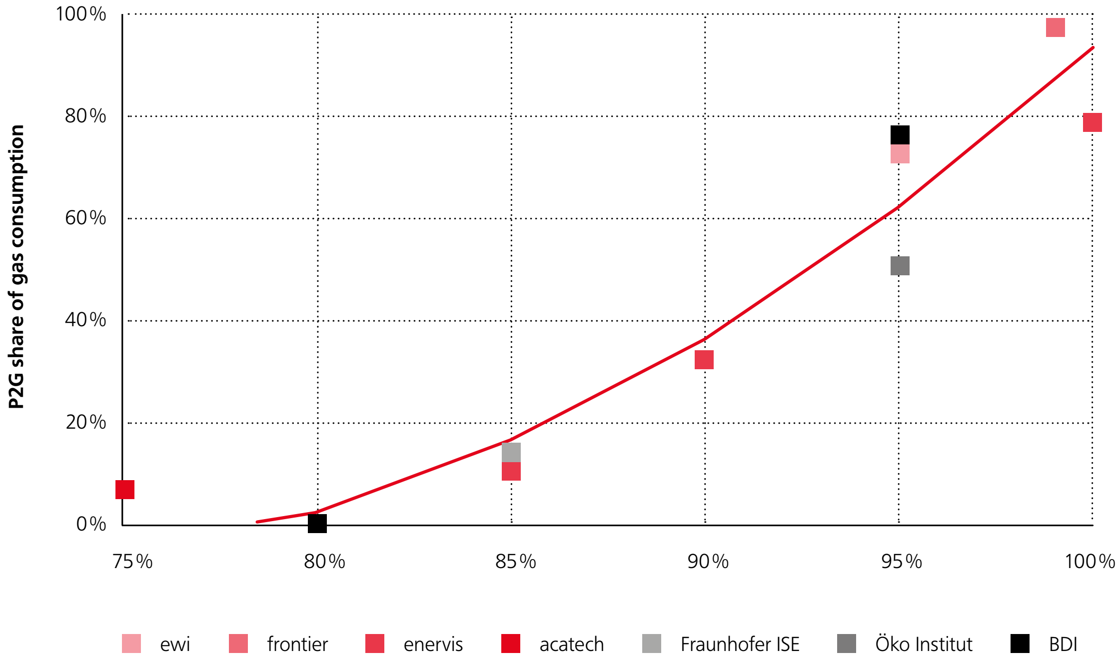
With respect to cross-sectoral electrification and the role of (conventional and) synthetic gases in the context of a growing and cost-efficient decarbonisation of the economy, the following robust statements can be made on the basis of system studies:

- In the short-term efficiency measures and the fuel to switch natural gas make it possible to harvest the "low hanging fruit" in the electricity, heating and transport sectors and make a rapid contribution to preserving the global GHG budget (Agora Verkehrswende/Agora Energiewende 2018, ewi Energy Research & Scenarios/EF. RUHR 2018).
- In the medium-term successive decarbonisation of the electricity sector will allow electricity-based technologies in the heating sector (for example heat pumps) and in the mobility sector (for example electric vehicles) to make significant contributions to deeper emissions reductions.
- In the long term, with GHG reductions exceeding 80 percent, the share of power-to-gas in total gas consumption increases significantly (Enervis 2018, cf. Figure 11). The meta-study by Kirchner et al. (2016) reaches similar conclusions.

Synthetic fuels play an important role in the period 2030 to 2050, according to many integrated system studies investigating routes to achieving climate targets. The greater the level of climate policy ambition, the more PtG and PtL will be required. The central reason for the importance of PtG/PtL is that "there is not enough sustainably produced biomass to substitute coal, oil and gas with wood, biogas or biofuel in all cases where combustion processes play a role" (translated from Agora Verkehrswende/Agora Energiewende 2018: 10). The most recent studies (Agora Verkehrswende et al. 2018, ewi Energy Research & Scenarios 2018, Prognos et al. 2018, ewi Energy Research & Scenarios/EF.RUHR 2018) point out that synthetic gases and fuels do not necessarily have to be produced in Germany, but could also be imported. That would allow a smaller expansion of renewable energy and significantly reduce the volume of PtG/PtL electrolysis capacity that needs to be created in Germany. As long as the respective PtG and PtL installations are located at sites with favourable preconditions for solar and wind power (i.e. sunny and windy), this could potentially generate further cost savings.

Interim conclusion: The use of renewable electricity for ambitious decarbonisation of all sectors and emissions sources demands comprehensive coupling of multiple infrastructures through the application of power-to-X methods: power-to-heat (short-term), power-to-mobility (electromobility, medium-term) and power-to-gas and power-to-liquid (long-term). Table 3 summarises the different areas of application of the various power-to-X methods on the basis of a techno-economic strength/weakness analysis under the premise of the objective of an economy functioning largely without fossil fuels (Agora Verkehrswende/Agora Energiewende 2018).

Figure 11
Cost-efficient power-to-gas share in 2050 in relation to level of decarbonisation



Source: Enervis 2018. Cost-efficient power-to-gas share of total gas consumption in 2050.

Table 3
Techno-economically advantageous sector coupling options in a decarbonised economy

Power-to-X	Power-to-power	Power-to-heat	Power-to-mobility	Power-to-gas / Power-to-liquid
Technologies	**Stationary batteries, pump storage**	**Heat pumps, direct electrical Direkheating**	**Direct use via power lines, indirect via (mobile) batteries**	**H_2/methane and synthetic liquid fuels generated using renewable electricity**
Heat		Low-temperature heat with heat pumps in adequately insulated buildings; high-temperature process heat with direct electrical methods in industry		CHP in existing buildings with significant insulation restrictions and hybrid heating systems with booster boilers for peak demand; high-temperature process heat for applications where electrification is problematic
Mobility			Trains, trams; buses and trucks over shorter distances; trolley-trucks and trolley-buses over shorter distances, cars, motorbikes, barges (depending on application)	Air transport and ocean-going ships, long-distance trucks and buses outside range of overhead wires, barges (depending on application)
Electricity	Short-term storage			Long-term storage and reconversion in gas turbines, combustion engines, fuel cells

Source: Authors, based on Agora Verkehrswende/Agora Energiewende 2018: 15, Tabelle 1.

5.5. SECTOR COUPLING FROM THE INDUSTRIAL POLICY PERSPECTIVE

A national climate protection strategy orientated on the Paris climate targets must aim for long-term decarbonisation of the German economy.[2] So it makes no sense to treat the figure of an 80 percent reduction in national GHG emissions – which is at the lower end of the corridor of Energiewende targets for 2050 – as a ceiling that will not be exceeded even in the long term. It is – like 90 or 95 percent – just an interim goal on the path to full decarbonisation.

For that reason, the PtG and PtL sector coupling technologies (although today still very expensive) will be of great importance in a climate protection strategy consistent with the Paris climate targets, regardless of interim goals and specific dynamics. In the context of the given policy framework in Germany (no nuclear power and lack of national engagement for CCS) and the simultaneous desire to safeguard the national electricity supply even in dark and windless periods, their role is tantamount to a systemic necessity – at least if the accustomed intensity of energy services supplied in the electricity, heating and transport sectors is not to be called into question.

In view of the path dependency of expansion of the required infrastructures, long-term decarbonisation must be prioritised at an early stage. The generation of methane or synthetic fuels need not necessarily be located in Germany, as the latest studies show. But even if synthetic gases and fuels are imported in future, other (non-electric) transport networks will play a significant role for security of supply (especially the gas infrastructure). One important caveat here is that fugitive (methane) emissions during gas transport be kept to a minimum or actively reduced (IPCC 2014b).

If the costs of producing methane (or H_2) in PtG installations are compared with the costs of fossil natural gas (or hydrogen produced by conventional methods from natural gas), the production costs for PtG are many times higher on account of their low efficiency and still high investment costs (Hüttenrauch et al. 2017, Ausfelder et al. 2017).

However, in particular in relation to H_2 electrolysis and methanation, researchers believe that considerable cost-savings can be expected through so-called technological learning (as observed in recent years in renewable energy and battery storage) (DBI 2017, ewi Energy Research & Scenarios/EF.RUHR 2018). Agora Verkehrswende/Agora Energiewende underline for example that: "Synthetic methane and oil initially cost about 20 to 30 [euro] cents per kilowatt-hour in Europe. The cost can be reduced to about 10 [euro] cents per kilowatt-hour by 2050 if the global installed PtG/PtL capacity increases to about 100 GW" (translated from 2018: 19).

The preconditions for "running down" the learning curve include incentivising – through suitable policy instruments – the expansion of total installed PtG and PtL capacity, technological progress in relation to technical efficiency, and falling production costs through mass production. In relation to the required lead times for creating a desired volume of PtG and PtL capacity, alongside the pure technological development up to market launch and the promotion of market entry, the temporal and financial resources for establishing personnel capacities for routine operation and marketing must also be figured into the calculations.

When estimating the future expected market potential and the question of how today's R&D expenses and promotion of market entry can potentially be recovered, export markets should also be integrated into the analysis because the trend and necessity for decarbonisation of economies plays out on the global scale. Here Germany can establish itself as a system supplier of technologies for implementing full decarbonisation, and – in the event of success – position itself as a technology leader.

Relevant experience with the promotion of renewable energy can teach us a great deal about the combination of measures required to enable technological progress through research funding and demonstration projects (so-called technology push) and at the same time promote the transition to mass production by creating artificial markets (so-called market pull) (IEA 2011, IPCC 2011, IPCC 2014a, IEA 2016). For a summary of the lessons learnt see Figure 13.

The recognised core elements of appropriate energy policy support for the market establishment of innovative emissions-reducing technologies in the energy sector include (IEA 2016):

a) CO_2 pricing (carbon pricing at a level matching the climate protection target);
b) Dismantling of obstacles to the implementation of options that could already contribute to better integration of renewable energy today (and an associated reduction in GHGs) and would at the same time be economically beneficial;
c) Technology-specific promotion of innovative "learning" technologies with the aim of reducing costs through technological learning.

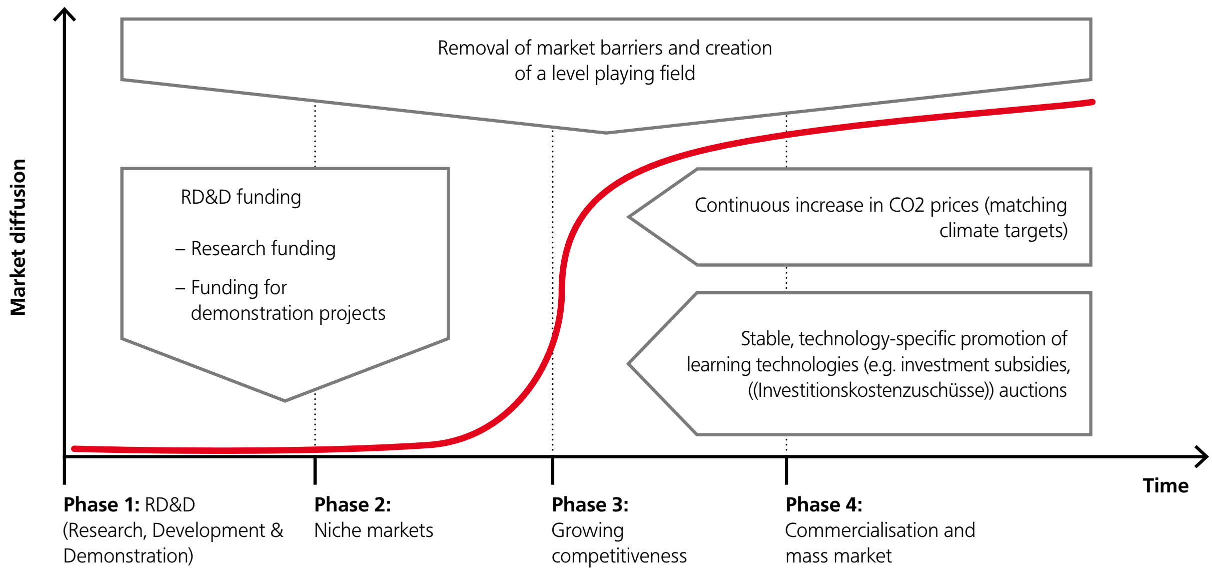
5.6. INTERIM CONCLUSION: COMPARATIVE ASSESSMENT OF SECTOR COUPLING APPROACHES

The findings of this study can be summarised in the following theses:

- The parties to the Paris Climate Agreement agreed to pursue efforts to limit the increase in global mean temperature to 1.5°C. In relation to the national sphere this means focussing on the upper range of the Energiewende targets (i.e. seeking a reduction in greenhouse gas emissions of 95 percent by 2050). Because certain GHG emissions in agriculture and industry are hard to avoid (and impossible without CCS), the target for the electricity sector must be 100 percent renewables.
- A comprehensive evaluation of infrastructural sector coupling must take account of cumulative CO_2 emissions,

2 Ausfelder et al. (2017) point out that the term "decarbonisation" – in the sense of reducing (net) greenhouse gas emissions to zero – can be misleading in the context of sector coupling, because the PtG and PtL can source the CO_2 required for methanation from the atmosphere (for example through direct air capture). This route produces synthetic fuels that contain carbon, but are renewable, sustainable and climate-neutral.

Figure 12
Appropriate promotion of innovative technologies in the energy sector



Source: Authors, on basis of IEA 2016.

where an earlier fuel switch in all sectors facilitates to observe the given CO_2 budget. In the medium term this can be achieved through the use of natural gas, in the longer term successively substituted by green gases (i.e. H_2 or CH_4 synthetically produced using renewable electricity, or biogas).

- The use of renewable electricity for ambitious decarbonisation of all sectors and emissions sources requires comprehensive coupling of multiple infrastructures through the application of power-to-X technologies: power-to-heat (short-term), power-to-mobility (electromobility, medium-term) and power-to-gas and power-to-liquid (long-term).
- The macro-economic benefits that can be realised through the application of power-to-gas technologies depend strongly on the climate policy context and the level of public acceptance of further expansion of electricity networks. For ambitious climate protection targets – above a share of 80 percent for renewable electricity – there is a considerable market-serving potential for power-to-gas. Where acceptance problems affect expansion of transmission networks there is a significant network-serving potential for PtG in connection with considerably lower targets. Via the gas infrastructure PtG can compensate for delays in transmission network expansion.
- Increasing electrification of heat, mobility and non-energy applications exacerbates the dark and windless issue. A 100 percent renewable energy supply in all sectors will therefore require long-term storage options. In technical terms the existing gas distribution infrastructure is already capable of providing the required long-term storage via power-to-gas. The gas distribution infrastructure guarantees security of supply of electricity and heat during dark and windless periods – even if the Energiewende decisions reduce the guaranteed capacity from nuclear power and coal-fired power stations and shortfalls arise in the European electricity market.
- Although power-to-gas/liquid technologies are still prohibitively expensive, ambitious, cost-effective climate protection demands that their gradual introduction and medium-term market-penetration begin today. Long lead times must be taken into account if the economically desired volume for 2050 is to be achieved.

6

THE ENERGY AND CLIMATE CONTEXT

In the energy policy debate of recent years (Energate 2016) sector coupling has frequently been treated as a cure-all capable of solving almost all the problems associated with the Energiewende: balancing variable renewable infeed (for example, Vehicle-to-Grid using the batteries in electric vehicles); avoiding generation management (curtailment), where local network congestion occurs (through sensible use of surplus renewable electricity) and an associated lowering of redispatching costs; reducing the necessity to expand the electricity network (by using gas networks, enabled by power-to-gas), and in association with this reducing the acceptance problems associated with expansion of transmission networks; compensating inadequate building renovation rates (through power-to-heat); compensating inadequate GHG reductions in the mobility sector (through electric vehicles in the scope of power-to-mobility); and thus altogether reducing the shortfall in relation to the national climate protection targets. Because not all power-to-X technologies currently find profitable business models in practice – despite the obvious benefits of sector coupling – there were soon calls to adjust the regulatory framework to reward flexibility and the priciple of "use before curtailment" (see the meta-analysis of recommendations in DBI 2017).

But in many cases a string of important restrictions were overlooked:

– There are differences – in some cases considerable – in energy efficiency between different sector coupling methods (BMWi 2017, Agora Verkehrswende/Agora Energiewende 2018).
– Certain power-to-X methods (for example in particular PtG and PtL) are associated with considerable investment costs. Economic operation therefore requires high capacity utilisation (full load hours) alongside cheap renewable electricity. These processes are therefore not suited to rely exclusively on surplus renewable electricity (Agora Verkehrswende/Agora Energiewende 2018),
– As yet, renewable energy supplies only 36 percent of electricity demand. In the event of rapid expansion of sector coupling a considerable proportion of the electricity (for example for power-to-heat) would come from CO_2-emitting power stations and/or nuclear power (Ausfelder et al. 2017).
– The renewable electricity needed to help the heating and transport sectors to achieve the required GHG emissions reductions through sector coupling would considerably increase electricity demand (BMWi 2017). This in turn would increase the necessity to expand onshore and offshore wind power and (in an all-electric world) also require a correspondingly larger expansion of the electricity networks.

In view of the current energy market situation, undifferentiated promotion of power-to-X installations makes neither energy nor climate policy sense. At the same time, the study presented here, in line with the scientific literature, has outlined how centrally important sector coupling is (alongside efficiency measures and an expansion of renewable energy in all sectors) for successful implementation of the Energiewende in the medium and especially long term. If Germany genuinely wishes to pursue its obligations to work towards extensive decarbonisation under the Paris Climate Agreement, the methods of sector coupling will have to make a decisive contribution: Power-to-heat (short-term) and power-to-mobility (medium-term) and in the long term also power-to-gas and power-to-liquid therefore play an important role in cost-efficient emissions reduction strategies.

Above all, infrastructural sector coupling via PtG and PtL is of strongly growing significance for achieving ambitious national climate protection targets with a greenhouse gas reduction target of 95 percent (in 2050 in comparison to 1990). The reasons for increased use of sector coupling are summarised in Table 4.

Today there are system studies examining sector coupling and the possibilities and costs of power-to-X technologies from an integrated perspective (Enervis 2018). Although few of them contain concrete policy recommendations, a number of qualitative conclusions and general observations can be drawn from the findings reported above. In accord with Ausfelder et al. (2017), the following policy recommendations are based on three premises:

Table 4
Advantages of intensified infrastructural sector coupling

Overall economic perspective (macro-economic optimisation)
Greater freedom to implement cost-minimising climate protection strategies (imperative for ambitious climate protection goals)
Cross-sectoral use of renewable electricity for sectors that would otherwise miss their climate targets
Perspective of electricity sector
Reduce curtailment of renewable energy
Long-term storage for renewables/renewable back-up for dark doldrums events (via PtG)
Partial alternative to expansion of transmission networks (resilience) and complement to electricity grid (redundancy)
Perspective of gas sector
Provision of green gas for industry, mobility and heating sectors
Back-up for electricity sector in a decarbonised world (via PtG and gas-fired power stations)

Quelle: Eigene Darstellung.

(1) The primary objective of the recommendations is achieving the climate targets, as the principal motivation of the Energiewende.
(2) Full security of supply must be preserved, in order to avoid opposition to the Energiewende.
(3) The economic efficiency of the fundamentally conceivable technological options and regulatory measures for achieving these two principal objectives must be optimised in an integrated way.

On the basis of these three premises, we identify a series of energy and climate policy measures that support a macro-economically sensible expansion of sector coupling and create a level playing field in relation to state-imposed charges and surcharges on electricity use. These are summarised in the following six points:

6.1 COMPREHENSIVE CROSS-SECTORAL CO_2 PRICING AS CENTRAL CLIMATE PROTECTION INSTRUMENT

The profitability of power-to-X technologies suffers because competing technologies (coal and natural gas in power stations, natural gas and oil in the heating sector, fossil fuels in the mobility sector) are not subject to the level of CO_2 pricing commensurate to the set climate protection targets (Expertenkommission 2017, Carbon Pricing Leadership Coalition 2017, MCC 2016; IPCC 2014a).

With respect to CO_2 pricing, it should be noted that even a globally cost-efficient strategy for stabilising the CO_2eq concentration at a level around 450 ppm (which would roughly correspond to limiting the rise in global mean temperature to no more that 2 degrees) would require CO_2 prices in 2030 to be considerably higher than is usually assumed in economic analyses . According to the calculations reported in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014a), the required price would be almost \$100/tCO_2 in 2030 and on average \$200/tCO_2 in 2050. While there are currently no definite figures for the CO_2 prices required to limit the rise in global mean temperature to less than 1.5 degrees, it must be assumed that they would be high enough to make the sector coupling techniques mentioned in this report profitable (for example through cross-sectoral EU-wide emissions trading) – assuming their macro-economic benefits can be demonstrated in the context of ambitious climate protection targets. This presupposes that obstacles are dismantled in the long term and sector coupling technologies that promise cost reductions through technological learning are promoted in advance of successful market penetration.

The idea that CO_2 prices in the sectors subject to EU greenhouse gas trading are generally too low has been widely discussed (see for example Carbon Pricing Leadership Coalition 2017; MCC 2016). But the biggest problem for sector coupling is that there is no CO_2 pricing at all in the heating and transport sectors. The monitoring commission also "recommends the introduction of universal CO_2 pricing in Germany, to include as many emissions sources, technologies and sectors as possible. This pricing measure would reduce the visible shortfalls in the national greenhouse gas targets for 2020 and 2030, improve the competitiveness of renewables compared to fossil fuels and facilitate the desired restructuring of the energy sector (…). Rising wholesale electricity prices would also reduce the burden of the EEG levy. Further, the ecologically inefficient electricity tax and other electricity-related surcharges could potentially be replaced at least for a time with the revenues from CO_2 pricing. Quite incidentally this would also make an effective contribution to reducing obstacles to flexibility and support the idea of sector coupling" (translated from Expertenkommission 2017: 5).

The German academies of science and engineering also underline the central importance of an appropriate cross-sectoral CO_2 price for the success of sector coupling as a central finding of their research project on future energy systems (acatech et al. 2017). They argue for EU emissions trading to be expanded to all sectors or – if that is not possible – for a corresponding cross-sectoral national CO_2 tax. As long as CO_2 prices do not tally with the climate targets and send false price signals – or the absence of corresponding CO_2 prices in the other sectors systematically disadvantages electricity-based technologies – it will be almost impossible to correct this distortion through other less powerful measures in individual sectors.

In order to avoid unwanted repercussions of higher CO_2 pricing on commuting and housing (and cushion the impact of accelerated restructuring in the coal-producing regions), alternative financial relief should be considered, for example a reform of the eco-tax or financial aid for regions especially affected by structural change.

6.2 REFORM OF OTHER STATE-IMPOSED ELEMENTS OF ELECTRICITY PRICING

"The current system of taxes and surcharges on energy prevents a cost-efficient Energiewende. The systemic inconsistencies distort generation, flexibility and demand, and cause evasive reactions. They also hinder load management, electromobility, power-to-X technologies and efficient building renovation. (…) The burden on electricity is many times higher than on petrol, diesel, natural gas or heating oil. Electricity is currently subject to taxes and surcharges of 18.7 [euro] cents per kilowatt-hour (ct/kWh), petrol 7.3 ct/kWh, diesel 4.7 ct/kWh, natural gas 2.2 ct/kWh and heating oil just 0.6 ct/kWh" (translated from Agora 2017a: 3).

Other studies (for example ewi Energy Research & Scenarios/EF.RUHR 2018) also emphasise that the current system of EEG levy and network charges, which are largely levied on the basis of electricity consumption, must be rethought in the context of sector coupling. Although the EEG levy and the network charges contain a high proportion of fixed costs, they are levied on the unit price of electricity. This creates considerable distortions in the use of flexible power-to-heat systems and generally hinders the integration of renewable electricity in the final consumer sectors. Acatech et al. (2017) therefore recommend a reform of the system for funding the expansion of renewables in order to reduce the EEG levy. "One option would be a partial financing of the EEG costs from general taxation or an expanded EEG levy on fossil fuels in all sectors. This would lower the cost of electricity relative to other forms of energy and tend to improve the economic competitiveness of sector coupling" (translated from acetech et al. 2017: 11). The authors of ewi Energy Research & Scenarios/EF.RUHR (2018) concur with that perspective.

6.3 TECHNOLOGY-SPECIFIC PROMOTION OF INNOVATIVE SECTOR COUPLING TECHNOLOGIES

Power-to-gas, power-to-liquid and power-to-mobility (for example in the form of battery-powered vehicles) are innovative technologies whose costs can be reduced through technological learning (Agora Verkehrswende et al. 2018). Many studies have shown these technologies to be macro-economically attractive or even systemically necessary for achieving high GHG reduction targets (see Chapter 5). From an economic perspective (IEA 2016) this justifies state intervention to address market failure in the early phases of market penetration (IPCC 2011). "Developing the corresponding markets and creating the required production capacity and infrastructure will take decades. If the adopted climate targets are to be achieved, the process must be started quickly" (translated from Ausfelder et al. 2017). Given the wide variation in market readiness of the various power-to-X technologies, findings on the experience with promotion of renewable energy (IEA 2016) suggest that this should be technology-specific. However, in the opinion of the authors of the present study, in order for growth in PtG and PtL to match the speed of expansion of renewable energy, the expansion should be realised not through investment subsidies, but through annual capacity auctions.

6.4 RESEARCH SUPPORT

There is still a concrete need for research into the details of appropriate technology promotion and how the market can be used to influence the network-serving interaction of the different flexibility options. In particular the BMWi's SINTEG projects (Schaufenster intelligente Energie – Digitale Agenda für die Energiewende) set a priority here (BMWi 2016e). This also includes the question of how a congestion-related dynamisation of electricity pricing components (for example, of market prices through nodal pricing or of network charges and surcharges) can promote network-serving application of power-to-X installations and discourage curtailment of renewable generation.

6.5 MACRO-ECONOMIC COST-EFFICIENCY INSTEAD OF UNNECESSARY LIMITATIONS ON TECHNOLOGICAL OPENNESS

"In its summer 2016 Green Paper on Energy Efficiency, the German government proposes the guiding principle of 'efficiency first'. The Commission of Experts welcomes this prioritisation of energy efficiency, but warns against interpreting it as giving general priority to energy efficiency over expansion of renewables. The Commission argues for a broader approach: Not all technically possible efficiency options and legal and financial efficiency incentives are sensible. Instead, systemic, economic, ecological and social criteria must also be considered. For example, storage of energy is always associated with energy losses and is therefore always disadvantageous from the efficiency perspective. But expanding energy storage may be systemically advantageous in order to integrate larger proportions of renewable electricity in the electricity supply" (translated from Expertenkommission 2017: 6). Similar statements can also be made in relation to the technologies used in the field of sector coupling (see the criticisms of the all-electric approach in Chapter 5). In macro-economic terms, technological efficiency is not the be-all and end-all (BMWi 2017). What counts is macro-economic cost-efficiency while simultaneously achieving the internationally agreed and nationally adopted climate targets.

6.6 SECTOR COUPLING IS NOT AN END IN ITSELF

Sector coupling technologies offer the potential to move towards the objective of a decarbonised energy sector at macro-economically optimal cost. The measures discussed above serve to correct multiple energy market failures (IPCC 2011): CO_2 pricing affecting all sectors equally (in relation to the external costs of CO_2 emissions) and technology-specific promotion of technologies where an expansion of market volume promises considerable cost reductions (in relation to the macro-economically suboptimal level of investment in "learning emissions reductions technologies"). Here necessary lead times and other hindrances must be identified and addressed. In order to minimise the macro-economic costs of decarbonisation, however, it is desirable for there to be competition between sector coupling methods. The observation – often mentioned by stakeholders – that certain sector coupling methods are currently unprofitable does not on its own mean that the policy and regulatory framework has to be adjusted until the business models associated with these technologies "fly". Deviating from the HYPOS position paper on power-to-gas (HYPOS 2018) and contradicting the IKEM position paper on power-to-heat (IKEM 2018), we cannot therefore confirm the demand to treat power-to-X methods as "(functional) energy storage" and in regulatory terms largely equivalent to electricity storage (which justifies exemption from state surcharges to avoid double charging).

6.7 SHORT-TERM MEASURES

Technology-related measures that can and should already be implemented today:

- Electricity-based heating methods (especially heat pumps) are more energy-efficient than PtG and PtL and close economic viability. For this reason the system studies show an enormous increase short-term and medium-term in the proportion of heating energy provided by electricity, which does not always occur simultaneously with the supply of renewable energy. But heat supply can be made considerably more flexible through the use of thermal storage. "Time-variable electricity tariffs are a possible means for incentivising flexibilisation" (translated from Ausfelder et al. 2017: 146). The authors of the present study therefore are convinced that it would be desirable, on the one hand, to reflectthe general shortage in the provision of electricity by price components which are based on time variable spot market prices, on the other hand, to reveal the occurrence of local network congestion through time-variable network charges (or in the form of nodal pricing) or time-variable bonuses, which could be realised in future markets for network-serving flexibility.
- "In the mobility sector conversion to electromobility and hydrogen power is crucial for a meaningful reduction in CO_2 emissions" (translated from Ausfelder et al. 2017: 146). In the short-term it is therefore necessary to expand the required infrastructure for charging stations for electric vehicles, in order to avoid lock-in effects.
- "The findings on conversion technologies like electrolysis, methanation and H_2-to-fuel show that these will become relevant in the medium and long term. Early development of the technologies and their trialling in pilot and demonstration projects is therefore essential to ensure that they are mature at the point where broad application becomes necessary" (translated from Ausfelder et al. 2017: 146). We concur with that recommendation.

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Abbreviations

CCS	Carbon capture and sequestration
CHP	Combined heat and power
ct/kWh	Euro cents per kilowatt-hour
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act)
GHG	greenhouse gas
GW	Gigawatt
Mt	Megatonne
ppm	Parts per million
PtG	Power-to-gas
PtH	Power-to-heat
PtL	Power-to-liquid
PtX	Power-to-X
PV	Photovoltaic
R&D	Research and development
TWh	Terawatt-hour

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