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Integration of Power to Gas/ Power to Liquids into the ongoing transformation process

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1 Summary

This position paper seeks to assess the role and prospects of the power-to-gas/power-to-liquids (PtG/PtL) technology in a fully renewable energy system and to identify, in particular, the challenges to be faced in coming years in integrating and further developing this technology in the ongoing transformation process. This analysis is based on the knowledge currently available to the Federal Environment Agency and also includes a comparison with other power-to-x options and their greenhouse gas reduction effects. Its geographical focus is on Germany, recognising that in the long term an energy supply in Germany that is completely based on renewable sources must be embedded in an international energy policy, particularly for economic reasons.

Our central messages are:

- ▶ To reliably achieve Germany's long-term greenhouse gas (GHG) reduction targets (95% reduction of greenhouse gases compared to 1990), energy supply must be based on renewable sources and be greenhouse gas neutral across all sectors and applications in industry, households and transport. Determining when and to what extent PtG/PtL techniques are necessary and appropriate requires a holistic analysis of the energy system and its development.
- ▶ An energy system which is completely based on renewable energy sources and which at the same time does not use cultivated biomass for energy purposes must also supply electricity-based energy to the heating and transport sectors, if the 95% GHG reduction target is to be achieved. Integrating these new consumers into the overall energy system in a climate-friendly way should be a top priority.
- ▶ Only by using PtG/PtL will it be possible in the long term to implement an energy supply fully based on renewable sources without using cultivated biomass for energy. The long-term availability of the PtG/PtL technology is therefore of crucial importance and must be considered in shaping the transformation process. (see Section 4)
- ▶ The RE development targets and the electricity saving targets set in the German government's energy concept should be adjusted to accommodate the new additional electricity consumers in such way that the GHG reduction targets will be reliably achieved. (see Section 6)
- ▶ For regenerative, electricity-based energy supplies for heating and parts of the transport sector, technologies like power to heat (PtH) and electromobility are already available. These technologies are mature, achieve higher CO₂ savings per kWh of final energy supplied, and are less costly than PtG/PtL, at least in the short and medium terms. (see Section 6)
- ▶ The current surplus supplies of energy from renewable sources are far from sufficient for the economical operation of PtG/PtL plants. The operation of large-scale PtG/PtL installations under current conditions in Germany would therefore increase the utilization of conventional electricity generation capacity and the economic viability of fossil-fuel fired power plants, and would in practice amount to the conversion of fossil energy sources to gas (coal/gas to gas) or to liquid fuels (coal/gas to liquids). The CO₂ burden from the fuels and raw materials produced from the electricity would be many times the burden that would result from the direct use of the fossil energy sources. This would considerably jeopardize the achievement of the GHG reduction targets and must be avoided. We therefore recommend that in Germany in particular, PtG/PtL plants should only be used on a commercial scale in the coming years if this does not jeopardize achieving GHG reduction targets. (see Section 6)

- ▶ To prevent more electricity generation from fossil sources and ensure achievement of GHG reduction targets, PtG/PtL plants for provision of fuels and raw materials should obtain electricity only from additional renewable energy plants. (see Section 6)
- ▶ The legal framework for taxes and levies should be set so as to prevent market distortions between electricity storage techniques and techniques for the provision of fuels and raw materials, including by establishing different conditions for plants serving as storage solutions and plants consuming electricity for the provision of fuels and raw materials. (see Section 7)
- ▶ We recommend that the PtG/PtL technology should be further developed across all applications in the coming years by means of pilot and demonstration plants run on a commercial scale. It would be appropriate to develop eligibility criteria for such support. We also suggest that efforts to integrate PtG should start with the substitution of the fossil hydrogen economy.
- ▶ There is an urgent need for action in the aviation sector in particular. The International Civil Aviation Organisation (ICAO) has set itself the goal of making aviation's growth greenhouse-gas neutral by 2020. The main strategy currently pursued by ICAO to achieve GHG-neutral growth is, in addition to a global market-based measure, the use of biofuels produced from energy crops. We reject this for climate and environmental reasons and advocate the use of PtL as fuel in aviation as one means to achieve long-term GHG reduction targets. We believe, however, that the PtL technology, as basic alternative, can only make a small contribution to this over the 2020 time horizon. To ensure that no fuel from non-food crops will be used in aviation in the medium term, it is urgently necessary to support pilot and demonstration projects, facilitate market deployment of this technology and ensure its long-term availability. (see Section 7)
- ▶ We recommend that efforts to integrate PtG should start with the gradual substitution of the fossil hydrogen economy, perhaps focusing first on the petrochemicals sector. The blending of renewable PtG/PtL products with fossil fuels could provide a first step towards GHG-neutral transport. (see Section 7)
- ▶ We recommend that the substitution of natural gas with PtG methane for heat supply should not be supported in the coming years, as this pathway is inefficient in energy terms and in terms of its substitution effect. (see Section 4)
- ▶ Generally speaking, overarching national, European and international frameworks should be further developed, particularly those in place for climate protection, to address the large role which the PtG/PtL technology will have in the long term in a global renewable energy system. (see Section 2 and Section 7)

2 Introduction

The achievement of set climate protection goals depends crucially on the restructuring of energy supply towards a sustainable, environmentally friendly and greenhouse gas neutral overall energy system.

This transformation process involves major challenges, such as technical development, adjustment of legal frameworks and formulation of strategies at European and international level.

In its study “Germany in 2050 – A greenhouse gas neutral country” the German Environment Agency demonstrated the technical feasibility of a fully renewable energy supply for all applications.¹ The study shows how the various sectors (generation and consumers as well as the applications electricity, heating, transport, and raw materials) could in future be interlinked in an unprecedented way. The study assigns a key future role to all power-to-x technologies, particularly power to heat (PtH, direct electrical heating and indirectly with heat pumps) and power to gas/power to liquids (PtG/PtL). As new, additional electricity consumers, these technologies make it possible to supply renewable energy for all applications. Because of these complex links, only a holistic conceptual consideration of energy supply, one that is geared to the applications’ various needs but also to the climate-friendly restructuring and design of the energy system itself, is meaningful. The Federal Environment Agency therefore regards these techniques as playing a key role.

Links between the various sectors within the energy system have been in place for a long time, e.g. electricity/transport, electricity/heat. The greater coupling between sectors in a future energy system will likely mean that they will increasingly use the same generation techniques, infrastructures and import routes. In view of this, the future energy supply must be considered and strategized holistically. A fact to consider in the transformation process is that different technical options exist in the various sectors, which, moreover, are at different levels of technical development and market penetration and have different emission reduction potential. Against this background, the climate-friendly integration of new electricity consumers in the course of the transformation process should be a priority.

The UBA study shows that all applications would be connected with renewable electricity generation (net electricity generation, to be exact) and that, mainly for economic reasons, the resulting large generation capacities would in all likelihood not be provided in Germany. Rather, in order to achieve global climate protection goals, a global market for renewable energy sources would have to be established, in which global potential held by renewable sources (wind, solar, hydro, residual and waste biomass, geothermal) would be harnessed as a function of their economic viability. The development of an international renewables market is very important for the fuel and raw materials market, as its structure is already highly transnational. This is evident in transport, where forms of transport such as air, sea and long-distance road freight transport are internationally reliant on compatible local infrastructures and fuels. This clearly illustrates the international dimension of a comprehensive renewable energy supply in Germany, which requires not only national strategies but also international integration. Import-dependency, diversification of supplier countries and energy sources, and the development of international infrastructures are important strategic issues surrounding energy supply.

Based on the knowledge currently available to the Federal Environment Agency, this paper seeks to gauge the role and prospects of the power-to-gas/power-to-liquids (PtG/PtL) technology in a fully renewable energy system and to identify, in particular, the challenges faced in coming years in integrating and further developing this technology in the ongoing transformation process.

3 A brief description of PtG/PtL technology

Power to gas (PtG) is the production of hydrogen and methane using electricity, and power to liquids (PtL) is the production of liquid fuels using electricity.

The first step in both cases is the electrolysis of water, splitting it into hydrogen (H₂) and oxygen (O₂). The hydrogen produced can either be used directly or as storage medium for energy and material applications. In addition, in a catalytic synthesis (or in biological synthesis in biogas plants) methane can be produced from the hydrogen by reacting it with carbon dioxide (CO₂).

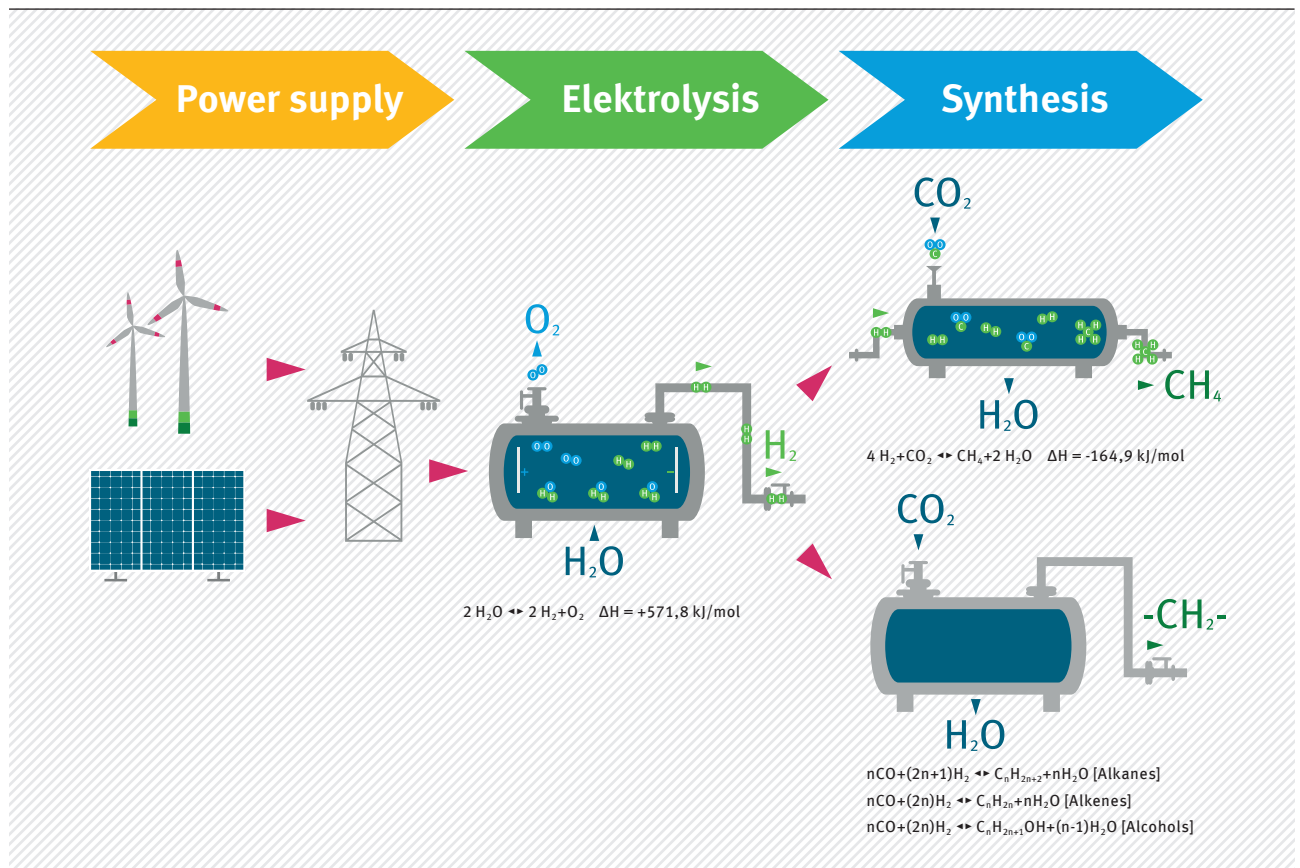
Production first involves the preparation of a hydrogen/carbon monoxide mixture or hydrogen/carbon dioxide mixture, which is then synthesised to hydro-

carbons. Various synthesis methods are available, e.g. the Fischer-Tropsch process, or methanol synthesis. The Fischer-Tropsch process produces a mixture of various long-chain hydrocarbons which must undergo further processing. Methanol synthesis occurs under moderate conditions, is particularly selective and results in products of very high purity. The energy efficiency of the various techniques decreases from hydrogen through methane to liquid fuels.

Looking ahead, other technical solutions for producing synthetic energy carriers are conceivable, e.g. ammonia synthesis. Another possibility, currently at the demonstration stage, is hydrogen storage in liquid organic hydrogen carriers (LOHCs).

Figure 1

Working principle of PtG and PtL



Source: Umweltbundesamt 2016

4 Role and prospects of PtG/PtL in the energy system

As shown by the UBA study “Germany in 2050 – A greenhouse gas neutral country” (THGND), the supply of energy and raw materials must be based entirely on renewables if ambitious climate protection targets – reducing GHG emissions by 95% by 2050 compared to 1990 levels – are to be achieved. The use of PtG/PtL makes it possible to realize such a completely renewable supply. In addition, in the medium and long terms, PtG/PtL can ease the growing competition pressure on biomass use. The long-term availability of the PtG/PtL technology is a key factor in our scenario. As the scenario excludes the use of biomass crops for energy purposes² (and the use of CCS and nuclear energy), PtG/PtL is currently the only alternative to achieve a completely GHG-neutral energy supply.

In the THGND scenario, we expect the final energy requirement in Germany in 2050 to be around 1600 TWh, divided approximately equally between elec-

tricity, methane and liquid fuels (see Table 1). The net amount of electricity¹ that must be generated to meet this demand is around 3000 TWh. We expect that Germany will have sufficient technical RE potential to produce the required amounts. However, we also assume that the renewable fuels and raw materials will be produced wherever, conditions for renewable energy generation are favourable and will therefore be predominantly imported.

Due to the use of PtG/PtL, the demand for renewable electricity generation installations (net electricity generation) in the THGND scenario is very high.

The study “Germany in 2050 – A greenhouse gas neutral country” is being updated on an ongoing basis. This will include an analysis of resource use as well as the derivation of pathways and development needs for the various technologies for 2030 and 2040.

Table 1

Final energy requirement in 2050 in the THGND scenario

	Electricity in TWh	Renewable methane in TWh	Liquid renewable fuels in TWh
Private households	104.7	44.5	0
Commerce, trade and services	90.3	62.4	18.6
Industry	179.7	198.8	0
Transport	91.1	0	533.3
Total energy	465.8	305.7	551.9
		1323.4	
Industry material use		282	
Total energy and material		1605.4	

Source: Umweltbundesamt 2014

Electricity

The main short- and medium-term needs in the electricity sector are: more flexible fossil-fuel-fired power plants; demand-side management, particularly by high-volume consumers in industry; and expansion of the national and European networks. In the short and medium term, mainly short-term storage capacity

is needed. According to current knowledge, long-term storage solutions such as PtG with reconversion into electricity will not be needed until renewable energy has gained a very large share (about 70 to 80%)³ of electricity generation, the need depending, inter alia, on the expansion of the European network, the development of demand-side management and the

1 Including losses during conversion and transport.

flexibilisation of fossil-fuel-based electricity generation. Long-term storage would have the function of ensuring system stability.

In general, in a renewable electricity system, short-term storage will be needed to offset generation deficits for some hours or days, and to stabilise the electricity system in view of the huge output variations^{II} to be expected from the fluctuating energy sources while long-term storage will be needed to cover renewable feed-in deficits lasting several days or weeks.

Heat

In general, it is important to quickly harness the considerable potential for savings and efficiency improvements in the heat supply sector. For supply of space heating, renewable alternatives to PtG will be sufficiently available in the short and medium term, notably power to heat in combination with heat pumps, and solar thermal energy. As shown in Figure 4, substituting fossil gas with PtG methane is currently inefficient (both in energy terms and in terms

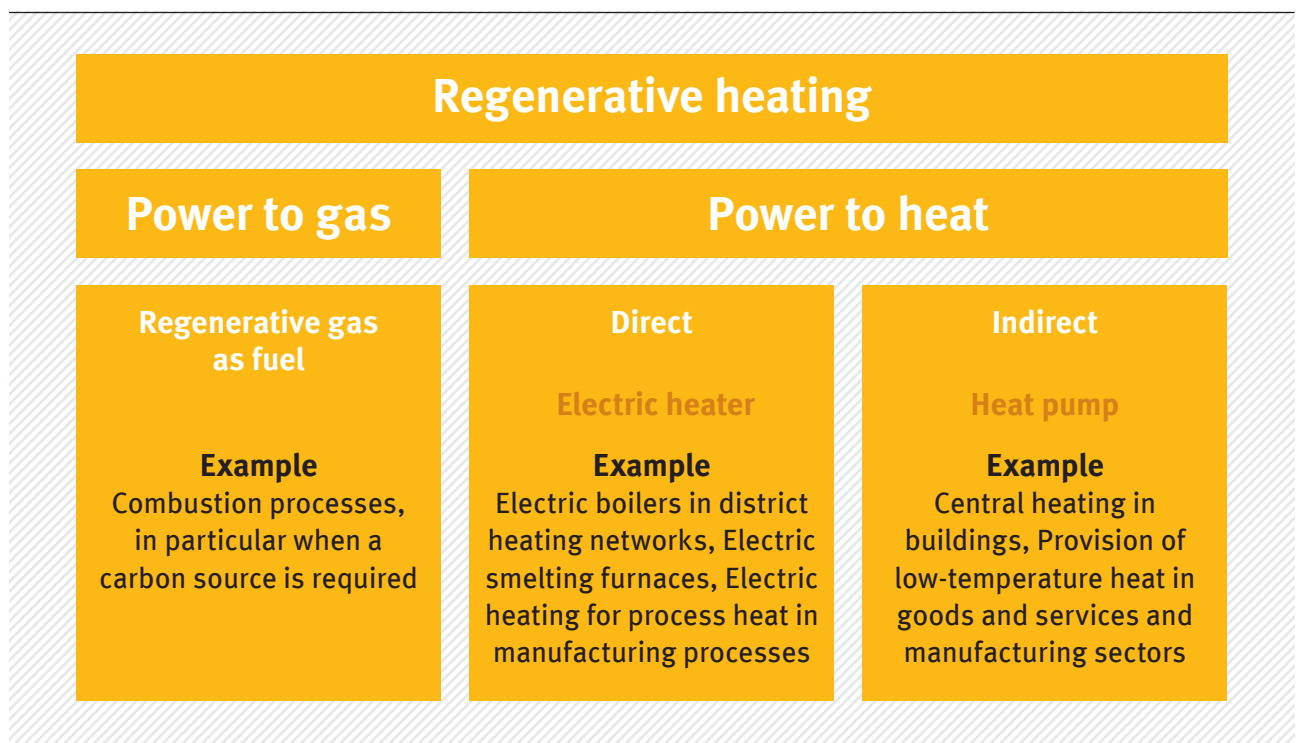
of substitution effect) and should therefore not be supported in the coming years.

In terms of climate-friendly heat supply, an integration of PtG in the next few years is not advisable. In the long term, PtG will play a significant part in the provision of renewable process heat.

As shown in the THGND scenario, PtH will, in the long term, play a key role not only in the provision of central heating for buildings, but also in the supply of process heat in industry, where processes can be modified to allow the direct use of power from renewable sources. PtG/PtL will nevertheless be needed for the supply of industrial process heat in the long term, particularly for the purpose of enabling the substitution of processes using solid fossil fuels/carbon carriers. We suggest that in the short and medium term, support should be given primarily to research and development activities aimed at moving process heat supply towards electricity-based processes and regenerative gaseous fuels (produced using PtG).

Figure 2

Overview of regenerative heat supplies



Source: Umweltbundesamt 2016

II Depending on weather conditions and time of day, high outputs from renewables installations can go on or off the grid in a very short time.

Transport

Final energy consumption must also be further reduced in the transport sector, through traffic avoidance, modal shifts and efficiency measures. In order for transport to become GHG-neutral in the long term, this transformation (avoid, shift, improve) must be accompanied by a transformation in energy terms. The most energy-efficient option for using renewable electricity in the transport sector is its direct use in electric vehicles. However, electrification is not possible for some applications. Also, to achieve a long range, electric vehicles need an additional, renewably sourced liquid or gaseous fuel (as in plug-in hybrids). In view of this, and the limited availability of residual and waste biomass, PtG/PtL is needed to ensure a completely renewable energy supply for transport.⁴ In particular, PtL can provide the liquid renewable fuels needed in aviation. PtL and PtG can also provide a renewable, GHG-neutral energy supply for shipping and long-distance road freight transport. However, we expect electromobility to play a key role for passenger cars, light commercial vehicles, buses and short-distance road freight transport, either alone or in combination with PtG or PtL. Overall, synthetic fuels produced using PtL and PtG (methane) have a significantly higher quality than conventional, crude-oil-based fuels, which can reduce the strain on conventional exhaust gas treatment systems (catalytic converters, particulate traps).

Short- and medium-term sectoral targets are laid down in the German government's energy strategy and in a number of EU directives (e.g. transposed into German law by the Biofuel Act). PtG/PtL fuels will not, however, be an alternative to achieve the short- and medium-term EU targets for the share of renewables in final energy consumption⁵ and for the reduction of the life cycle greenhouse gas emissions of transport fuels⁶ by the year 2020. The requisite amounts of regenerative electricity cannot currently be made available in Germany (neither through surpluses nor through new installations), nor can the requisite PtG/PtL plants be built in Germany in the short term.

Particular efforts currently need to be made internationally in the growing field of aviation. The International Civil Aviation Organisation (ICAO) has set itself the goal of making the sector's additional energy demand greenhouse-gas neutral by 2020. The main strategy currently pursued by ICAO to reduce GHG

emissions is, in addition to a global market-based measure, the use of biofuels produced from energy crops. We reject this for climate and environmental reasons. Additional renewable electricity generation capacities could be created here, mainly internationally, for use to produce PtL aircraft fuel, which could then be added to fossil aircraft fuel in the medium term.

Regardless of this short- and medium-term perspective, in the long term PtG/PtL fuels will play a large role in the supply of renewable fuels for transport, alongside the direct use of electricity in electric vehicles. More detailed information can be found in the UBA studies "Germany in 2050 – A greenhouse gas neutral country"¹ and "Klimaschutzbeitrag des Verkehrs – Notwendigkeit und Realisierungsoptionen einer regenerativen Energieversorgung im Verkehr"⁷ (The transport sector's contribution to climate protection – the need for and options for implementing a renewable energy supply in transport).

Industry

There is no urgent need to use electricity-based regenerative raw materials to meet short-term targets in the manufacturing sector. In the long-term, PtG/PtL will play a very large role in supplying raw materials from renewable sources and the associated potential contribution to GHG reduction to the chemical industry, as illustrated in the THGND scenario for the year 2050.1 Against the backdrop of long-term investments and production plants' long renewal and modernization cycles, efforts must be made in the short and medium term to address the restructuring of production processes, particularly with a view to greater direct use (power to heat) and indirect use (PtG/PtL) of regenerative electricity.

PtG/PtL can also supply the chemical industry with raw materials, so in this area as well, it can make a substantial contribution to reducing process-related GHG emissions. Here too, the use of PtG/PtL makes the use of biomass unnecessary.

5 The current economic conditions in Germany

At present, PtG/PtL-plants are not economically viable in Germany. This is due to the investments needed, the current high operating costs, the transformation losses, and the framework conditions (e.g. taxes and charges).

Figure 3 gives an overview of the current production costs of regenerative gases for varying electricity costs and plant operating times. The upper part of the bars represents small PtG-plants and the lower part large PtG-plants. It clearly shows that the production costs of continually operating plants, even for the limit case of power that is continually available without charge, are many times higher than for conventional fuels and raw materials. The case is even clearer for biogas, assuming continually operating plants and a wholesale price of 5 eurocent/kWh.^{III}

The transformation losses are a key contributory factor. However, these are much lower for hydrogen

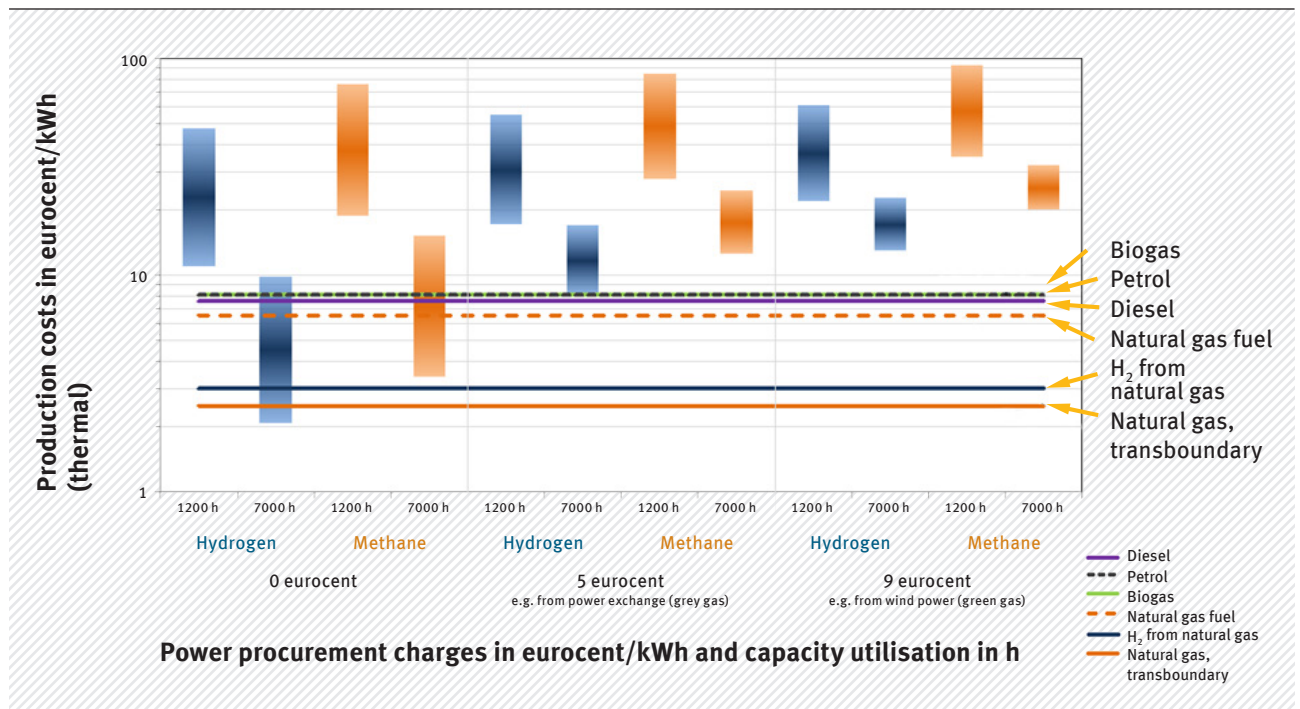
than for methane. Figure 3 also shows that the costs increase sharply if the hydrogen or methane is not produced at full capacity over the entire year, but if the hours of use are only the periods of oversupply. Such oversupplies are currently limited to relatively short periods, and in the coming years further reductions are likely as the national power grid is further improved.

The power procurement costs are determined to a significant extent by the level of charges on the procurement of power and also charges on the products produced in the PtG/PtL-plants.

A distinction is made between the PtG/PtL-plants used in energy storage plants, and those that are end-consumers for the preparation of fuels and raw materials.

Figure 3

Cost of Power to Gas compared with other fuels⁸



III Note the log scale.

PtG energy storage plants (like other storage systems such as pumped water storage or compressed air storage) are currently exempted from the levy under the German Act on Energy from Renewable Sources (EEG Umlage) and the network charges for the procurement of the electricity that is to be stored (including the storage losses). However, few of the PtG-plants currently in operation, construction or planning are energy storage plants. Rather they produce fuels and raw materials for purposes other than power recovery or are used solely for hydrogen generation and use. These plants, like other end-consumers of electricity, have to pay network charges and connection costs, as well as the renewables levy (unless they are a self-generator/consumer). This reduces the economic viability of network-connected plants for the production of fuels and raw materials in comparison with plants that do not procure power through the grid. PtG-plants that generate hydrogen and methane primarily from renewable sources of energy and feed this into the gas network enjoy privileges under the regulations of gas network connections, access to the gas network, and gas network tariffs. Under energy tax legislation, the end products (Pt-G gas and Pt-L liquids) used as fuels are classed as “conventional” energy carriers, i.e. they are subject to energy tax. If the carbon inputs in PtG/PtL plants are from sources obliged to engage in emissions trading, then the plants have to report and submit allowances under the EU Emissions Trading System.^{IV} This can represent a further cost factor.

However, in addition to charges, investment requirements and operating costs, future cost developments will also depend on a range of other factors such as the worldwide demand for PtG/PtL plants, which in turn depends on the global development of greenhouse gas neutral energy supplies, the decisions taken with regard to international energy and climate policies and their effects on carbon prices, the technical progress made with PtG/PtL plants, the development of electricity prices, the availability of sources of concentrated carbon dioxide, etc.

However, for the short- and medium-term it must be assumed that the costs for PtG/PtL will be higher than for more efficient technologies using renewable sources of energy (e.g. PtH, electromobility).

IV Requirements depend on the specific legal and technical conditions in each case.

6 Systemic challenges of integrating Power to Gas/ Power to Liquids in the transformation process

The transformation of the energy system to almost fully regenerative supplies will include an increased coupling of the individual energy markets and areas of application, involving a range of technologies.

The increased use of PtH will lead to the heating sector being linked more closely to the electricity sector. Electromobility will result in a direct coupling of the electricity and transport sectors. In the long-term, the use of PtG/PtL will link up all energy markets (electricity, heat, and fuels) as well as the market for regenerative raw materials for the chemical industry. This will present enormous challenges for the economically appropriate and climate-friendly formation of the transformation process.

A range of policy targets have been formulated for the promotion of climate protection over the entire energy sector in the European Union and Germany.

We recommend that existing and future sectoral climate protection targets should be designed to achieve the greatest possible reduction of overall greenhouse gas emissions and the effective use of energy from regenerative sources.

For partially regenerative, electricity-based energy supplies for heating and the transport sector, technologies like power to heat (PtH) and electromobility are already available. These technologies are mature, achieve higher CO₂ emission reductions per kWh (electricity) than PtG/PtL, and are less costly. Accordingly, in the short and medium terms, the priority should be placed on exploiting the options that can be supplied by these energetically more efficient technologies.

However, in the long-term PtG/PtL will play a key role in a regenerative, environmentally sound and sustainable energy system, so that pilot plants and demonstration projects should be promoted in all fields of application.

Substitution effects of new electricity consumers in the transformation process

In 2012, the peak share of renewable sources of energy in the electricity supply in Germany was 60%. Surplus supplies are attributable either to regional bottlenecks in the distribution grid for electricity from wind power generation and PV-plants or to bottlenecks in the network transmitting power from northern Germany to the industrial centres in the south. These situations are limited to relatively short periods.^V The proposed upgrading of the electricity grid in the short- to medium-term is expected to reduce such bottleneck situations in the coming years. Therefore, surplus regenerative power is not available for the operation of PtG/PtL-plants at present.

In Germany, the premature and excessive integration of PtG/PtL-plants beyond the level of demonstration and pilot plants would lead to an increased utilisation of power from fossil-fuel fired generation (and until 2022 also of nuclear power), with increased greenhouse gas emissions.

The substitution effects by new additional consumers in all sectors are highly dependent on when the power is consumed, i.e. not only the point along the time line of the transformation process but also the actual time. The scientific assessment of the greenhouse gas reduction effects from additional electricity consumers is complex. It is also necessary to take regulatory provisions into account, such as the emissions trading mechanisms.

In order to avoid creating false impression about the reduction effects in the course of the transformation process, it is assumed as a simplification that only regenerative power is used. It is then possible to make the following statements about the substitution effects of new electricity consumers (see Figure 4):

- The integration of new additional consumers in the heating sector by means of Power to Heat (heat

^V In order to reduce these oversupplies in the transformation process, the generation from conventional power stations (including nuclear power stations) and biomass plants should be made more flexible and the demand for minimum levels of supplies from conventional power stations should be reduced. In general, the power demand should be made more flexible by the use of load management for existing consumers.

pumps or direct electric) offers the best substitution ratio^{VI}. In the case of a heat pump, 1 kWh of regenerative power can lead to the conservation of some 3.3 kWh of natural gas. In addition, PtH offers the possibility to integrate large-scale consumers in the manufacturing sector by way of load management and thus to support the integration of energy from renewable sources.

- ▶ In the transport sector, the largest substitution ratio is achieved by the direct use of electricity (electromobility). Here too, synergy effects can be used with load management to integrate renewables.

However, this potential is limited to some modes of transport.

- ▶ For PtG/PtL, the largest substitution potential is achieved for the substitution of fossil hydrogen, due to the energetic efficiency.
- ▶ In order to meet climate protection goals, it makes sense to integrate technologies with a high substitution potential in the transformation process^{VII} at an earlier stage than technologies offering lower substitution potential.

Figure 4

Substitution effect^{VIII} by PtH, PtG and PtL^{IX}

Use of regenerative power			Substitution of fossil supply			Substitution ratio	Costs
Input regenerative supply			Fossil reduction		Input		
Input	Technology	Supplied end-/use energy	Technology	Input			
1 kWh regen. power	PtH Heat pump	3.3 kWh (thermal)	3.3 kWh (thermal)	Condensing boiler (105 %)	3.14 kWh natural gas	3.14	Medium
1 kWh regen. power	PtH direct electric	0.95 kWh (thermal)	0.95 kWh (thermal)	Condensing boiler (105 %)	0.91 kWh natural gas	0.91	Low
1 kWh regen. power	PtG – H ₂ material	0.74 kWh hydrogen	0.74 kWh hydrogen	Steam reforming (85.2 %)	0.87 kWh natural gas	0.87	High
1 kWh regen. power	PtG – CH ₄	0.58 kWh methane	0.58 kWh methane		0.58 kWh natural gas	0.58	Very high
1 kWh regen. power	PtL	0.5 kWh liquid fuel	0.5 kWh liquid fuel		0.5 kWh liquid fuel	0.5	Very high

Source: Umweltbundesamt 2016

When analysing the power supply system under current conditions for network-linked^X PtG/PtL-plants in Germany, it must be assumed that these lead to an increased use of fossil fuels for power generation. The gas generated in PtG-plants would therefore in fact be “Coal-to-Gas/Liquid”^{XI} or “Gas-to-Gas/Liquid”^{XII}, with an efficiency level well below 50% and would

lead to CO₂-emissions that were many times higher than from the direct use of fossil natural gas. Currently, plant operators are mostly planning to use power exchange electricity and combining these with renewables obligation certificates. However, this has no effect on power generation from fossil-fuel fired power stations.

VI The substitution ratio is the ratio of the conserved fossil energy to the regenerative electricity used to provide the same amount of energy. For example, if providing 1 kWh liquid fuel requires about 2 kWh of regenerative electricity compared to 1 kWh of fossil power, the substitution ratio is 0.5.

VII Also for lower proportions of renewables in power generation (< 80% – unverified rough approximation).

VIII Rough estimate.

IX Costs ranked on the basis of a qualitative estimate of investment costs per installed kW.

X Connection to the general supply network.

XI CO₂-emissions are much lower for the direct transformation of coal/lignite to gas without going through power generation.

XII Generation of power from fuel, followed by electrolysis and synthesis.

In order to avoid higher levels of power generation with fossil fuels and to ensure that climate protection targets are achieved, PtG/PtL-plants to produce fuels and raw materials should only use power from additional renewable sources of energy.

If PtG/PtL-plants are given state aid, it must be ensured that there is a corresponding increase in energy from renewable sources. The targets for renewables expansion must be increased correspondingly.

Under current conditions, PtG/PtL-plants to produce fuels and raw materials should only use power from additional renewable sources of energy in order to avoid higher levels of consumption of fossil fuels and to ensure that climate protection targets are achieved.

This can also be achieved by the use of plants that are not linked to the power grid. The most efficient use of these plants is then no longer possible (direct substitution of fossil fuels for the electricity supply by an additional renewables plant), but the PtG/PtL-plant do not lead to any additional power generation from fossil fuels. Operating as closely as possible to full capacity is decisive for the profitability of PtG-plants. However, appropriately designed low-speed wind power generators in northern Germany can operate for some 4,000 hours at full capacity. At good locations, plants not connected to the power grid can operate more economically than grid-connected plants, because they avoid costs for the network connection, network use charges and levies under the German Act on Power from Renewable Sources. In addition, locations in foreign countries can be used, where either yields are significantly higher than in Germany or costs are lower.

In the medium- and long-term, a shared infrastructure is crucial. This will require adopting appropriate policies that take the new electricity consumers into account and thus ensure that additional fields of application can be developed in a more environmentally-friendly way with regenerative power.

For the future, we find it important that renewables targets should not be determined solely in terms of the existing power sector. Adaptations are necessary in order to integrate new electricity consumers in an economically effective and climate friendly transformation process across all fields of application.

Carbon sources for PtG/PtL plants

Carbon sources are needed for the regenerative, power-based provision of methane/methanol and higher hydrocarbons. Various carbon sources are available:

- ▶ Biogenic CO₂ from regenerative processes can be used, e.g. by connecting up to biogas plants. In the medium- and long-term, the emphasis on the energetic use of residual and waste biomass (for environmental reasons) can severely limit the availability of biogenic CO₂.⁹
- ▶ Another option is the use of CO₂ from fossil carbon combustion processes or manufacturing processes. This CO₂ is neither regeneratively produced nor is it greenhouse gas-neutral – but at least it is used twice. The CO₂-source or the proportion of CO₂ in the carrier gas flow, e.g. in flue gas, has a considerable influence on the energetic applications and thus on the overall efficiency and the costs incurred. The combination with fossil-fuel fired power stations or manufacturing processes as the CO₂-source is a sensible option from a technical point of view, and in the transformation process it could under certain circumstances provide an effective combination for the development of the PtG/PtL technology. However, while the use of CO₂ from fossil sources offers technical advantages it should not be used to justify an increase in power generation from fossil fuels, threatening climate protection targets. Energetic advantages are offered by oxy-fuel processes (combustion with pure oxygen), which are used in some industrial applications in Germany. The combustion produces nearly pure CO₂, so that the preparation of the exhaust gas flow is much easier than in the case of combustion with air.
- ▶ The atmosphere is also a possible source of CO₂. The energy requirement for its extraction would have to be included in the overall energy balance. But the industrial extraction would require many times more energy than CO₂-separation from waste gas from oxy-fuel combustion processes.

In general, we recommend linking PtG/PtL-plants with CO₂-flows from the stationary combustion of renewables. However, since methane is usually produced and used at separate locations and a large proportion of it will continue to be used for transport (diffuse, mobile sources of CO₂), this goal is difficult

to achieve. In the long-term it must be assumed that, even if CO₂ is recycled from combustion processes, it will only be possible to provide sufficient CO₂ to close the carbon cycle by extraction from the atmosphere.

In this context, the advantages offered by the direct use of hydrogen should be noted. It makes it possible to do without a CO₂-source and the associated addi-

tional energy consumption. The power requirements for the production of hydrogen are much lower than for methane or liquid fuels. For some applications it makes sense to use hydrogen directly as an energy carrier.

7 Recommendations for the coming years

In order to achieve climate protection targets, we recommend that techniques offering high substitution potential should be integrated in the power supply system at an earlier stage in the transformation process^{XIII} than methods with a lower substitution potential (see Section 6, Substitution effects of new electricity consumers in the transformation process).

To achieve a nearly greenhouse gas-neutral economy, it is necessary to make PtG/PtL available across all sectors as a competitive technology. In the coming years, pilot and demonstration plants will be required in order to achieve learning effects, to ensure knowledge transfer and to stimulate the necessary technological developments.

Therefore we recommend that research and development work should continue and intensify in the coming years. Innovative pilot projects and full-scale demonstration plants for PtG/PtL technology will be required in all fields of application. In addition to PtG/PtL-plant technology developments, further research is needed to identify possible new fields of application.

Initially, aid should remain limited to demonstration projects of plants fed with additional energy from renewable sources with a combined rating across Germany of up to 500 MW. This will avoid excessive national competition for the development of attractive renewables locations for direct electricity use. Taking environmental and climate considerations into account, further criteria for support should be speci-

fied. Power should only be supplied from renewable sources, and PtG/PtL-plants should not give rise to additional fossil fuel fired power generation.

Further conditions for support should address the linking of material and energy flows with the manufacturing sector, increased efficiency, flexibilisation of individual plant sections, and the combination with various application technologies.

A key advantage of energy carriers that can be generated by electrolysis and further syntheses in comparison with electricity is that they are easier to store and transport. Therefore it makes sense to set up such generation capacities at favourable renewables locations in other countries that would make it possible, for example, to decarbonise the transport sector (in particular sea transport and aviation)^{XIV}.

Support for full-scale domestic PtG/PtL-plants in Germany would not be appropriate because the domestic renewables potential is still expensive. However, we draw attention to the fact that there are already regions in other countries with a very high proportion of regenerative power in their electricity supply. Taking a broader view of economic ties and international energy strategies, these locations are particularly well-suited for an expansion of their own PtG/PtL-capacities in the near future.

German state aid policies should take this into account, and address the learning potential with the targeted allocation of aid for research and develop-

XIII Also for lower proportions of renewables in power generation (< 80% – unverified rough approximation).

XIV See also UBA (2015): "Klimaschutzbeitrag des Verkehrs – Notwendigkeit und Realisierungsoptionen einer regenerativen Energieversorgung im Verkehr", Dessau-Rosslau.

ment and support for demonstration plants, in terms of learning-by-doing and learning-by-using.^{XV}

International strategies are required for restructuring the energy supplies in order to meet the global challenges of climate change. PtG/PtL can play a central role for the global supply of regenerative fuels and raw materials and for an international regenerative energy market.

Step-wise integration in existing structures

Working to meet medium-term sectoral climate protection targets and at the same time to develop individual sectors of the economy can lead to an increased demand for regenerative power-based fuels and raw materials. This applies in particular in the transport sector and the chemical industry. For example, the International Civil Aviation Organisation (ICAO) has set itself the goal of making the sector's additional energy demand greenhouse-gas neutral by 2020. The main strategy currently pursued by ICAO to achieve GHG-neutral growth is, in addition to a global market-based measure, the use of biofuels produced from energy crops. We reject this for climate and environmental reasons. There is an urgent need for action in this sector. However, in our opinion, PtL technology can only make a small contribution through until 2020.

In general, we regard it as necessary to do justice to the overall long-term importance of the PtG/PtL technology. We suggest beginning the integration of PtG with the substitution of the fossil hydrogen economy, focussing at first, where appropriate, on the petrochemical industry.

For the short- and medium-term reduction of greenhouse gas emissions from fuels, in particular emissions from the production of the fuel, the potential of current technologies in combination with PtG/PtL should be considered. This means specifically that for the integration of PtG/PtL in the transport sector, planning should take the petrochemicals sector into consideration. In particular there are opportunities there for the integration of PtG technology. Hydrogen is required at nearly every stage of the oil refining process, for example for desulphurisation of the individual fractions (kerosene, diesel, and petrol), or

for cracking long-chain hydrocarbons to form shorter-chain hydrocarbons (e.g. kerosene). The integration of PtG would offer short-term advantages regarding the direct substitution fossil hydrogen in the chemical industry, including the petrochemicals sector. Reductions in CO₂ emissions could be achieved relatively easily. The decades of experience gained with this fuel and the existing hydrogen infrastructure provides a good starting point. The increased use of this technology in the transformation process would give rise to synergy and learning effects that would be useful for the further development and broader application of PtG/PtL technology. Provided that only regenerative power was used, it would be possible, in combination with existing technology, to achieve a reduction of some 5.8 million tonnes CO₂ per annum in Germany.¹⁰

The stepwise integration of regenerative hydrogen in existing structures can proportionately reduce the greenhouse gas emissions from oil refining. Under the UN rules for international climate reporting, these reductions are allocated to industrial processes. But experts argue that an integrated consideration of all the potentials in the transport sector (Well-to-Wheel) should take these reductions in the production of fuel into account. The use of regeneratively-produced hydrogen would lower the effective greenhouse gas emissions of the fuels, including aviation fuel.

In order to avoid the use of crop biomass in the medium-term in the aviation sector, it is necessary to support pilot and demonstration projects that would make the market introduction of PtL technology possible, and would ensure the long-term availability of the technology for the greenhouse gas neutral supply for the aviation industry. As a first step, mixing with fossil aviation fuel would be feasible.

In the transport sector, we regard it as necessary, wherever possible, to use the regenerative directly (e.g. electromobility, or trolley goods vehicles), since this is the most energy-efficient and economical option. In addition, existing drive technologies should also be optimised and the PtL technology itself should be adapted for specific applications, e.g. in aviation. For example, depending on the material

XV For an extensive discussion of learning effects: (PIK 2012) „Kosten des Ausbaus erneuerbarer Energien: Eine Metaanalyse von Szenarien“.

in catalytic converters there is often a problem with the lack of aromatic compounds in PtL-fuel, making it currently usable as a substitute for diesel fuel, but not for petrol or kerosene.^{XVI} In the latter case, it will be necessary in the medium-term either to optimise the turbines, or to adapt the PtL technology.

We recommend that the existing climate protection instruments and the legal framework should be further developed so that PtG/PtL technology can be securely integrated in the medium- to long-term. This includes further steps to reform and further develop the emissions trading, in order to provide increased incentives for emission reductions, or the inclusion of the national share of international transport flows in the international climate negotiations and reporting.

For an effective, comprehensive climate-action strategy in the transport sector, power-based fuels should be given greater consideration in transport policies and legislation, in addition to electromobility. In view of the increasing competition for the use of biomass and the limited availability of areas for growing fuel crops, the long-term focus should not be on bio fuels alone; rather the direct use of regenerative power and PtG/PtL-fuels should also be integrated. Furthermore, this shall also include effective systemic measures, for example the use of multiplication factors for electromobility and PtG/PtL in the European Union directives and national legislation, also taking these into account where appropriate when determining limit values for fleets. For industrial processes, corresponding norms and standards should be developed further.

The distinction should be retained between PtG-plants as a storage solution (with reconversion to electricity) and those that are electricity consumers providing fuels and raw materials (without reconversion).

PtG-plants compete as a storage solution with other storage systems and load management. A further development of the legal framework for taxes and levies should take this into account and allow competition that makes the most favourable storage systems possible from an environmental and economic point of view. In view of the cross-sectoral challenges and the competition with other power storage systems, the

various instruments should be appropriately harmonised with one another.

Inefficient incentives for the utilisation of flexibilities for the integration of renewables can lead to distortions in the electricity market. In order to avoid this, PtG/PtL-plants for the provision of fuels and raw materials should be treated in the same way as PtH-plants and industrial load management with respect to the network charges and the renewables levy. They have the same function in the overall system, and analysis shows that they are even more efficient in the energy system.

The economic framework conditions of the PtG- and PtL-technology are to be developed further. This will require consideration of the framework conditions for the energy system as a whole. The recommendations for action cover the next few years and will have to be further developed. For example, it is necessary to consider what tax burdens should be imposed on power-based fuels. The overall goal must be to achieve the most effective sector coupling possible while avoiding false incentives.

Research requirements

PtG and PtL are in the early stages of development. Currently, a number of demonstration plants are in operation or under construction in Germany. In Iceland, a Power to Liquids-plant for the production of methanol is already being operated commercially. At present there are not yet any commercial plants for the production of longer-chain hydrocarbons in Germany.

Before PtG-/PtL technologies can be implemented on an industrial scale, considerable research and development will be required in the coming years:

- ▶ What will be the consequences of the increasing interconnections of the energy markets due to PtG/PtL? How will the resulting interactions affect climate-protective integration, sectoral climate protection targets? What will be the economic considerations and legal challenges?

XVI According to the current worldwide fuel standard (ASTM), plane turbines which have not been adapted may only run with fuel containing at most 50% Fischer-Tropsch kerosene.

- ▶ How are things developing worldwide and what are the effects of the various energy policy options for climate protection? (These also include the social and development policy impacts of the use of PtG/PtL in countries with favourable regenerative power potential.)
- ▶ How will costs develop for PtG and PtL in view of the various global energy-policy developments and energy demands?
- ▶ How should levies and charges be developed and revised for the climate-friendly and effectual integration of new electricity consumers?
- ▶ What other environmental effects arise from the use of PtG/PtL technology (e.g. consumption of water, rare earths)?
- ▶ Technical developments are necessary in the following areas in particular:
 - ▶ Adaptation to the fluctuating supply of energy from renewable sources and the availability of new efficient technologies (PEM^{XVII}, HTEL^{XVIII});
 - ▶ The identification and accessing of suitable CO₂ sources;
 - ▶ The identification of new, less expensive catalytic converters, taking resource availability into account;
 - ▶ Energetic and economic optimisation of CO₂ capture from the atmosphere.
- ▶ What methods will be developed in future for the synthesis of regenerative fuels and raw materials? For example, alternative methods to produce renewable hydrogen, such as by light-induced water splitting.
- ▶ What opportunities are there for using hydrogen as a final energy source (power generation, heating, or as an automotive fuel) and what technical adaptation will be necessary in the gas supply network?
- ▶ Considerable research is needed for the conversion to power-based and gas-based regenerative heating supplies in industry. This applies in particular for processes in which carbon-carriers are necessary. In view of the long investment cycles in industry, this is particularly urgent.

XVII Proton exchange membrane or polymer electrolyte membrane.
 XVIII High temperature electrolysis.

8 Conclusions

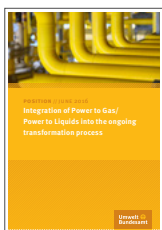
To reliably achieve Germany's long-term greenhouse gas reduction targets (95% reduction compared to 1990), the entire supply of energy (electricity, heat, fuel) must be rendered sustainable, environmentally friendly and almost greenhouse gas neutral. The direct and indirect use of renewable electricity with the help of power to heat, power to gas, power to liquids conversion and electromobility as key technologies would make this possible. However, in the transformation process, the integration of new, additional consumers will involve huge challenges in terms of climate-friendly integration, ensuring technical availability, impacts on the electricity market, and the regulatory framework.

We consider it appropriate and necessary that PtG/PtL be supported in Germany through pilot and demonstration projects. Such support should remain limited in the next few years to the installation of a total capacity of up to 500 MW in Germany. It must be



ensured, however, that these PtG/PtL plants will not cause an increase in fossil electricity generation and will obtain their electricity only from renewable energy systems. Otherwise CO₂ emissions from electricity generation would increase and the achievement of greenhouse gas reduction targets would be at risk.

Furthermore, we consider it essential that targets be adjusted to reflect the new electricity consumers and the associated opportunities for supplying renewable energy for other applications. In concrete terms this means a need to adjust the national targets for the development of renewable energy, to redefine the current electricity saving target to apply only to conventional electricity consumers and to further develop existing climate protection instruments and frameworks (including those established at the international and European levels) with a view to ensuring the integration of new electricity consumers, particularly PtG/PtL.

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- 5 2009/28/EG
- 6 2009/30/EG
- 7 UBA (2015): „Klimaschutzbeitrag des Verkehrs – Notwendigkeit und Realisierungsoptionen einer regenerativen Energieversorgung im Verkehr“, Dessau-Roßlau
- 8 DBI Gas- und Umwelttechnik GmbH, Henel, M. (2012): Ergebnisse des DVGW-Projektes Energiespeicherkonzepte (G1-07-10), DBI Fachforum Energiespeicher-Hybridnetze, Vortrag, 12.09.2012, Berlin sowie DVGW (2013): Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz; Bonn
- 9 UBA (2013): "Globale Landflächen und Biomasse nachhaltig und ressourcenschonend nutzen"; Dessau-Roßlau
- 10 UBA (2016): Climate Change 08/2016 "Klimaschutz und regenerativ erzeugte chemische Energieträger – Infrastruktur und Systemanpassung zur Versorgung mit regenerativen chemischen Energieträgern aus in- und ausländischen regenerativen Energien"; Dessau-Roßlau



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