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STORE&GO

Innovative large-scale energy storage technologies and power-to-gas concepts after optimisation

D8.10

Roadmap and policy recommendations for power-to-gas in the EU up to 2050

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Disclaimer

This summarising document "Roadmap and policy recommendations for power-to-gas in EU up to 2050" is building on all components of the STORE&GO project and therefore uses the insights of the demo sites and the broad knowledge and analyses that have been conducted in the cross-cutting activities. Some parts and paragraphs are cited as an exact copy of the corresponding Deliverable.

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Executive Summary

The STORE&GO project was funded by the EU under the Horizon 2020 scheme and started in March 2016 in order to fathom the application of different power-to-gas technologies in three different European countries (Falkenhagen/Germany, Solothurn/Switzerland, Troia/Italy), acting as reality labs. This special multinational and interdisciplinary project design puts the technology to the test. Above this, it gathered valuable insights on administrative and regulatory aspects during the implementation of large-scale PtG applications. The results and findings of the project have been collected within a roadmap for large-scale power-to-gas conversion.

In order to reach the EU's 2050 climate targets, greening of electrons (power) so far seems on track. Greening of molecules (gases) however is lagging far behind, with only a few percentages of green-only and little perspective on serious progress towards 2030 targets and thereafter. This lack of green molecules is a serious shortcoming of the energy transition, since currently, energy molecules (gas/oil/coal) cover over 70% of the EU energy system. Instead of transporting fossil gas, the existing European gas grid is fit already today to transport green gases produced via power-to-gas – in the case of green methane even without technical adaptions.

This roadmap draws the energy picture of the EU 2050 and shows the technological characteristics and potential technical and economic development of the power-to-gas technologies. In addition, the roadmap shows measures and policy recommendations that are needed for further development of the legislation on power-to-gas.

The European energy picture in 2050 derived in this roadmap shows a wide range of 1860 TWh to 4700 TWh for the total annual gas demand, which needs to be covered predominantly by green gases. Our research did not show a low future gas demand, even with a high CO_2 reduction target. Since even high electrification scenarios estimate 40–60% need of molecules in 2050, the 1860 TWh are assumed to be the absolute lowest estimation. Further investigations by the STORE&GO project conclude with higher gas demands. The top-down analysis finds a future gas demand of around 4400 TWh, and also the bottom-up analysis indicates it in the upper range of the estimated corridor.

Additional demand for power-to-gas is seen in key areas of application, i.e. energy storage, energy transport, mobility and balancing of the electric grid. These benefits are unique and indisputable, further underlining the necessity for a power-to-gas strategy. However, the magnitude of the need to provide green gas is the major overarching and more fundamental argument in a class of its own.

So how much green methane can the EU potentially produce? CO_2 for methanation can be provided by biomass, direct air capture, and from industrial processes. Availability of biomass is limited, and it may be claimed for other uses. Thus it is assumed that there will be a future trade-off between the different possible sources for CO_2. Biological sources alone can provide for 1190–1390 TWh/a of methane from power-to-gas. When also considering industrial sources, the EU can produce 1320–1650 TWh/a of green methane, thereby covering their energy demand to a significantly higher share domestically than today. Direct air capture is not even accounted for in this potential study, and will lead to additional green methane production if implemented at large scale. For covering a remaining gap between the production potential and the future demand for green methane, various import options will exist.

Technology-wise, rapid development is ongoing in power-to-gas technologies. The main components of the PtG technology – electrolyser and methanation systems – show significant cost reduction potentials thanks to scaling effects and technological learning. Depending on the chosen electrolyser application, the specific investment costs for large scale systems could decrease

respectively to around 300 €/kW[1], 170 €/kW[2] and 270 €/kW[3] in 2050 for different technologies. Large scale methanation systems are expected to reach specific investment costs of about 120–125 €/kW. Depending on the use case, SNG production costs in the range of 5,5–12,6 Cent/kWh can be achieved in 2050 with large plants in Europe, depending on the electricity source used for SNG-production.

The consortium has identified three major categories of measures that need to be tackled in order to get power-to-gas to the level of market uptake. In addition to this, there are also several cross-cutting specific issues that should be addressed as soon as possible.

The evaluation concludes that power-to-gas currently finds itself in the valley of death, without a perspective of a functioning market for green gas on the other side of the valley. Several suggestions for fitting measures are given and categorised correspondingly. This can be done by creating specific support and subsidy schemes for both research and development as well as for investors, by granting feed-in remuneration for operators and by reforming regulation policies. Simultaneously, a market for green gases needs to be established, and here instruments such as a mandatory admixing quota with cross sectoral impact, penalizing CO_2 emissions financially and providing a framework of guarantees of origin for renewable gases can be the options of choice. The latter is the internalisation of external costs and coordination of regulations in the electricity and gas markets, which the project partners see as mandatory for the energy transition. Such measures would result in economic incentives for investors and operators, which are missing today.

A realistic and effective strategy to assure a successful introduction of power-to-gas could be, as illustrated in Figure 1:

1. **Substantial demonstration projects** at short notice (pre-2030) to collectively cover the feasible technology ranges of PtG i.e. some **10 demo projects requiring ~100 million Euros** of public funds each. This can be supported as R&D projects and/or with investment subsidies. Preferably also as “sandbox-projects” to simultaneous gain experience for the higher development stage.

2. **Introduce policy measures** to establish the credibility in PtG to potential investors that there will be a serious **market for renewable and carbon neutral gases** (post-2030) as well as derived products **both** in the **feedstock** and **energy market**.

    a. The **feedstock market** could be the first market segment with policies and measures on a mandatory basis and within a clear timeframe – i.e. **obligatory quota for renewable gases** is suggested to be implemented already by 2025**.**

    b. To reach the **total energy market** for gas, the **obligatory admixing of renewable gases** to the EU gas system seems to be a profound way forward. It might start at **5% by 2025** and needed to base on a **guarantees of origin** system. Imported gases into the EU should be subject to the same rules.

    c. **If the common European approach of “quota obligation” should not be possible** in the designated timeframe, **“feed-in tariffs” for renewable gas** on national level is suggested as an **optional way forward** with proven potential of impact. With due caution to

[1] AEC
[2] PEMEC
[3] SOEC

adapt to the gradually evolving market and sinking costs of technology to reach the desired effect to the lowest public cost, **this measure can also be made fit** to serve as an alternative to support a market for renewable gas for an **extended period of time**.

3. Assure that the overall **benefit of power-to-gas to the energy system** and environment in total are **reflected in possible business models** and **by coordinating the provisions of power-to-gas across all sectors** and applications. Priorities should be on the **avoidance of unfair double network tariffs, definitions of power-to-gas and eligible roles for different stakeholders**.

4. **Clear the path** for power-to-gas be eliminating all detailed current detailed issues all unnecessarily hindering the development of power-to-gas such as: **"Clarification of the position of SNG in the RED", "Harmonised gas quality standards in the EU"** etc.

5. **Finally, create incentives** for further **continuous PtG development** via appropriate consideration of power-to-gas in the **research programmes.**

In a future perspective, the gas system will not only be confronted with one type of gas, and there are many politically driven strategic decisions influencing the future development. For example the question of import from outside or renewable gas production inside of the EU, CCS and CCU, to mention some. The decarbonisation of European energy can be considered as an opportunity to further strengthen European leadership on innovative energy technologies, energy-related transport technologies and services, as well as the application and implementation of matured and climate-friendly gas-related technologies. The results of this Roadmap underline this and show how power-to-gas could and should become a part of this future.

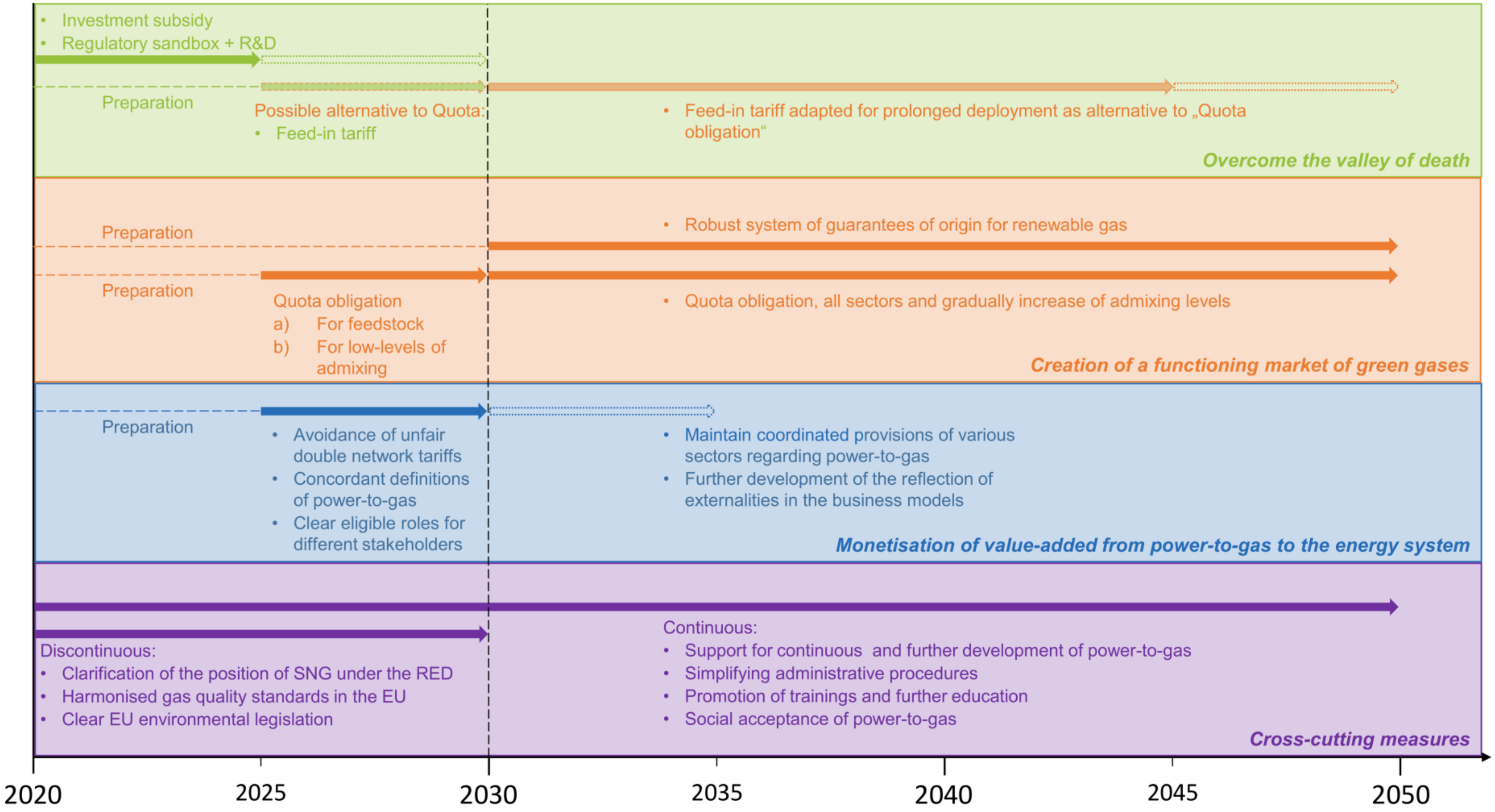

Figure 1: Timeline of the different types of policy measures for the establishment of power-to-gas in the energy system

1 Introduction

The current European Energy Roadmap is aiming to cut the continent's greenhouse gas emissions by 80% to 95% by 2050 [1]. These ambitious plans set the target for Europe to be a pioneer in implementing an ecologically sustainable energy supply that is economically viable and socially acceptable. On December 11th 2019 and thus at the end of the development process of this roadmap, the EU commission, recently new in office, introduced their ambitious package of measures, called the European Green Deal. Herein the goal for Europe is to be climate-neutral in 2050 [2].

The vital role of gas and power-to-gas technology (PtG) in this context is undisputed. Complementary to green power (electrons), PtG will produce the green gases (molecules) needed to reach the climate targets. Not only are energy molecules a vital feedstock for numerous industrial processes, they would also reduce carbon emissions if produced from renewable sources. Additionally, they offer significant possibilities for storage, which electrons do not offer. Power-to-gas, moreover, is a pivotal element for coupling the electric and gas infrastructure, thereby facilitating the integration of renewable forms of energy into well established and high performing energy storage and distribution systems. Low carbon electricity generation and the use of gases make it possible to increase the share of renewable forms of energy throughout all the relevant sectors, i.e. electricity, industry, heating and mobility.

In the technological field, PtG has already successfully overcome numerous challenges. The benefits from steep cost learning curves and upscaling effects are ready to be tapped. Regulatory aspects and market design differ within Europe, and often act as barriers to successful market entry.

In the future perspective, the gas system will not only be confronted with one type of gas. In a PtG process, one option available is to use the hydrogen directly from the electrolyser. The other option is to continue the process and produce methane. Besides these two options there are several routes of other bio-based methane, as well as hydrogen from natural gas that is made climate-neutral by means of Carbon Capture and Storage CCS and Carbon Capture and Utilization (CCU). Furthermore, today a substantial part of the supply for the EU demand of "energy molecules" is imported. Scientists and technological experts are still discussing on how to adequately approach these issues. What is obvious already at this point: The answers can only be found in combining renewable hydrogen as well as renewable methane in the natural gas mix, utilising existing infrastructures, and by incorporating both energy imports and EU domestic generation. These questions are subject of and highly influenced by national and European interests. The scope of STORE&GO focuses on the aspects of production of methane in a European production perspective. However, the technologies, market conditions and the regulatory framework needed for a positive development of renewable synthetic methane from power-to-gas are also estimated to have positive concurrent effects on other renewable gases in the energy system if the conclusions from the project and the measures presented in this roadmap are deployed. The decarbonisation of European energy can be considered as an opportunity to further strengthen European leadership on innovative energy technologies, energy-related transport technologies and services as well as the application and implementation of mature and climate-friendly gas-related technologies.

1.1 Motivation

Before focusing on the role of gas in the energy transition, the need for an energy transition in the first place should be explained. Global warming is a serious threat to humankind and to our planet. Its effects have already started to be seen globally. Within the last 20 years, there have been 18 of the warmest years. Moreover, the intensity and the frequency of extreme weather events have increased as well. As a concrete example in Europe, it can be seen that there have been extreme heatwaves in four of the last five years. In the summer of 2018, temperatures higher than 5 °C above the mean were recorded. Events like the rapid loss of glaciers, severe droughts in large sections of Europe, and floods (especially in Central and Eastern Europe) have affected the biodiversity [3].

According to a report published by the Intergovernmental Panel on Climate Change (IPCC) in October 2018, the temperature increase has already reached 1 °C when it is compared with pre-industrial times due to the anthropogenic activities and the CO_2 and other GHG emissions to the atmosphere. Furthermore, temperature increase is around 0.2 °C per decade globally. That means, if the necessary consequences and measures are not taken as soon as possible, the temperature increase could reach 2 °C by 2060 [4].

But, what does it really mean, and what will happen if the temperature increase reaches to 2 °C? In order to visualize its consequences, a couple of examples can be given. For instance, 99% of the coral reefs could disappear; or, melting of Greenland ice could result to a seven meter rise of the sea levels, which will affect especially the coastal areas crucially. Furthermore, not only European economy but also the global economy will be affected because of the damage to infrastructure, food production, public health, biodiversity, and political stability. It is estimated that the annual damage due to river floods in Europe could cost €112 billion by 2100 (the current cost of damage due to river flood is €5 billion). Also, 16% of the present Mediterranean climate zone might become arid, and as a result of this, food availability might become a crucial problem. By taking the necessary actions in a cost-effective and accelerated manner and by thus increasing the pace of the energy transition, the temperature increase could be limited to 1.5 °C, which will help to mitigate and prevent most of these negative impacts and the likelihood of extreme weather events [3] [4].

According to the EU Commission, it is important to have a successful energy transition in order to be the first carbon-neutral continent in the world by 2050. Europe's commitment to bring its Energy Roadmap 2050 to life needs a systemic approach in every aspect of the energy transition. Established power-to-gas technologies have proven their maturity and their versatility across all sectors. Within STORE&GO even highly innovative technologies were tested in real operation conditions. Successful commercialisation of power-to-gas is viewed as a key element to implement the energy transition – thus unfolding the full potential of power-to-gas is a key enabler for decarbonisation.

Having a successful energy transition with power-to-gas would not only be helpful to cut the expenses for the energy import but also increase the security of supply in the energy system in the EU. Today, around 55% of the energy, mainly oil and gas, is imported to EU. One of the sectors which is highly dependent on import is the transportation sector. Today, the transport sector in the EU highly depends on fossil fuels with a ratio of 94%. In other words, this means the EU economy is strongly dependent on the outside because mobility has a very crucial role in the economy and most of the oil is imported from other countries. Low emission transportation would give Europe an opportunity to be less independent on imported oil, as well as it would create an opportunity for innovation and new job creation [5]. In the long-term strategic planning, the European Commission aims to decrease the energy import by 20% until 2050. This decrease would positively affect the European economy by cutting the fossil fuel expenditures, which is currently €266 billion. For instance, the amount of cumulative savings due to the reduced fossil fuel import could reach 2–3 € trillion per year between the years 2031 and 2050 [3]. As inland produced power-to-gas results in a correspondingly smaller import, looking to the future gas demand in each sector is a further motivation to look into a roadmap for power-to-gas.

1.2 Why gas can complement an increasingly volatile electrical system

Looking at the European energy system of today, a distinction between energy carriers in the form of electrons (electricity) and molecules (gas, liquids, solid matter) can be made. This allows to make some overarching observations:

1. The final energy consumption of 2017 shows us that only 22,7% is consumed in the form of electrons and 72,8% in the form of molecules (rest is consumed as derived heat) [6]
2. There are existing and well-functioning infrastructure and technologies for the purpose of production, distribution and transformation/consumption of all energy carriers to meet today's needs.
3. The electricity system needs continuous balancing, whereas molecules distribution systems are much more robust
4. Electricity lacks storage options in significant orders of magnitude concerning time, volumes, energy density and costs. The molecules in fuels are stored energy per se and corresponding infrastructure for gas is already installed throughout Europe.
5. If one only looks at the property of being renewable with regard to the sole production, renewable electrons are less complicated to produce than corresponding renewable molecules. Using "power-to" technologies opens up new possibilities for renewable molecules, no longer limited to the availability of biomass.
6. For both electricity and gas, there is a pan-European, cross boarder transmission and distribution grid.
    a. Electricity grid is already subject to a change by carrying higher shares of renewable energy and reaching it limits.
    b. There is also the potential to change the content of the gas grid to higher shares of renewable gases, though this existing potential is not yet utilized.

Taking the need for future GHG reduction in the energy sector into account, it gets apparent that the inherent strengths and weaknesses between the "electrons" and "molecule" worlds could be cancelled out correspondingly by the introduction of "power-to"-technologies.

From the molecule energy carriers, natural gas is already the one with the lowest GHG emission rate when utilized. It is also the cheapest and most efficient one to be made renewable by means of "power-to" technologies.

The gas grid is used to transport and distribute 20% of the EU's primary energy consumption (~5000 TWh of natural gas per year); also, it connects European gas production sites, import points on the EU borders and LNG terminal entry points. Currently, about 260.000 km of transport lines and about 1.4 million km of distribution lines exist in the EU. The gas transported via the gas grid gives us the opportunity of a flexible, storable form of renewable energy, which is currently mainly used in buildings, high temperature industry processes, gas-fired power plants and the production of chemicals. It is a flexible system because it can react to the year-to-year, season-to-season, day-to-day and hourly demand changes [7]. In addition to the flexibility of the gas grid in the EU-28, it also has a storage capacity of almost 1100 TWh [8] [9]. When the future possible gas demand is considered it is estimated that the current gas grid in the EU can accommodate the future gas demand easily [7].

Apart from its technical benefits, using the currently existing gas grid would also bring other advantages for social acceptance. Drastic changes in people's lives due to new implementation of technologies and large economical investments to these technologies might be seen by society as unwanted. Using gas infrastructure here will provide another benefit and it could go hand in hand to create a fossil-free future. The attempt for electrifying some sectors will be very costly, and using the existing gas grid with the combination of power-to-gas technologies could help us to save around €217 billion annually by 2050 [7].

The existing infrastructure and technologies to serve all sectors (Heat, Mobility, Industry) seems to make power-to-gas and the existing natural gas infrastructure the perfect partner to volatile RES to utilize common strengths and compensate for adverse weaknesses in the future energy system. In other words, less investment is going to be needed to make the energy system more flexible.

1.3 Demo Sites in the STORE&GO Project

As a part of the Horizon 2020 research funding scheme for exploring innovations for Europe's energy transition, the STORE&GO project tested different available power-to-gas technologies in three different European countries, and thus under different regulatory frameworks.

Starting in March 2016, 27 European partners have been investigating the potential of PtG applications in the European energy grid as an important step for the energy transition. STORE&GO proves that Europe can reduce its carbon footprint and at the same time cover large parts of its future energy demand by making the most efficient use of renewable energies. However, the integration of growing amounts of renewable sources poses technological difficulties. STORE&GO has run three pilot plants with different innovative power-to-gas technologies, as shown in Figure 2. Each of the concepts being demonstrated at the three STORE&GO pilot sites involves new methanation technologies, and each has been adapted to the respective demonstration site. The plants are integrated into the existing power, heat and gas grids. Specific technical characteristics are shown in Figure 3.

The first power-to-gas plant is located in Falkenhagen (Germany). The existing process to produce hydrogen was expanded in May 2018 by a methanation unit with a capacity of approximately 1 megawatt (MW). The methanation process is based on a honeycomb reactor concept developed at the Engler-Bunte-Institut of the Karlsruhe Institute of Technology (KIT). Since January 2019, synthetic methane has been fed into the regional natural gas transmission network. The plant produces up to 1,400 m^3 of Synthetic Natural Gas (SNG) per day, equivalent of approximately 14,500 kilowatt-hours (kWh) of energy.

The second STORE&GO demonstration site is located in Solothurn (Switzerland). It employs a special methanation method. Microorganisms, so-called Archaea, convert the hydrogen obtained in the electrolyser with carbon dioxide into methane. The hybrid plant in Solothurn with a capacity of 700 kW has been producing synthetic methane since May 2019, feeding it into the regional gas network.

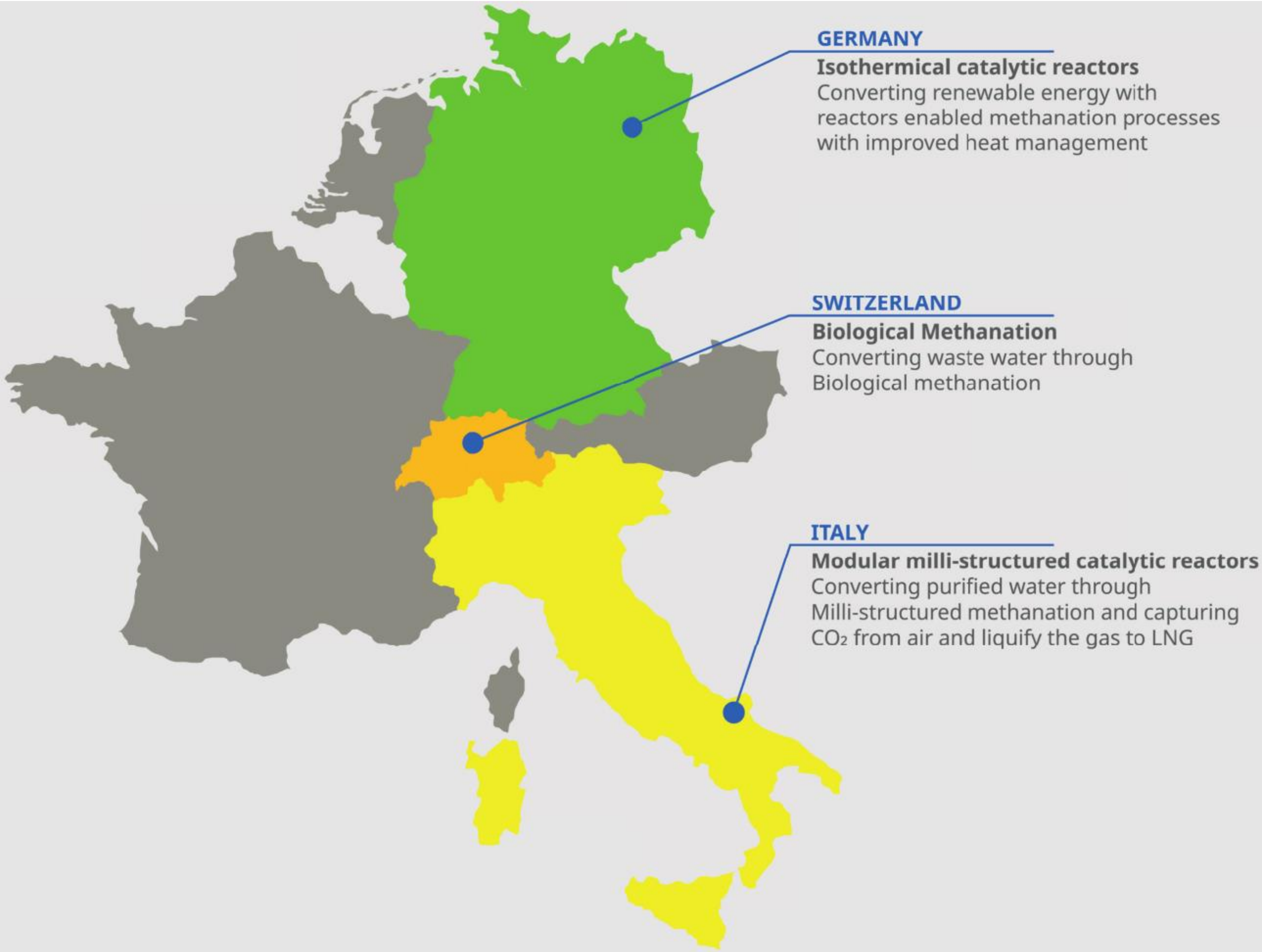

Figure 2: Map of the three demonstration sites and their characteristics[4]

The third demonstration site was built in Troia, Italy. It showcases that direct air capture of CO_2 represents a technical option for the supply of CO_2 that fully closes the carbon cycle and is location-independent. The plant combines a novel micro reactor for methanation with an innovative liquefaction plant. Since April 2019, the Troia plant has produced Liquefied Renewable Gas (LRG).

Even if power-to-gas technologies currently cannot compete with fossils from a commercial point of view, the perspective of continued learning effects, economies of scale, and increasing international competition, PtG capacities will be available at significantly less costs than today. The opportunities lying ahead of power-to-gas as a pillar technology for the energy transition will accelerate this development.

The STORE&GO project was finalised in February 2020, presenting its findings in a series of publications on specific aspects, and most importantly in a European roadmap for successful market implementation of power-to-gas technologies.

[4] Detailed info can be found here: https://www.storeandgo.info/demonstration-sites

Category/Head	Demonstration site Falken-hagen/Germany	Demonstration site Solothurn/ Switzerland	Demonstration site Troia/Italy
Representative region with respect to typical generation of Renewable Energy Sources	Rural area in the North East of Germany with high wind power production and low overall electricity consumption	Municipal area in the Alps region with considerable RES from PV and hydro production	Rural are in the Mediterranean area with high PV capacities, considerable wind power production, low overall electricity consumption
Connection to the electricity grid	Transmission grid	Municipal distribution grid	Regional distribution grid
Connection to the gas grid	Long distance transport grid	Municipal distribution grid	Regional LNG Distribution network via cryogenic trucks
Plant size (in relation to the el. power input)	1 MW	700 kW	200 kW
Methanation technology to be demonstrated	Isothermal catalytic honeycomb/ structured wall reactors	Biological methanation	Modular milli-structured catalytic methanation reactors
CO_2 source	Biogas or bioethanol plant	Waste water treatment plant	CO_2 from atmosphere
Heat integration possibilities	Veneer mill	District heating	CO_2 enrichment
Existing facilities and infrastructure	2 MW alkaline electrolyser, hydrogen injection plant	350 KW PEM electrolyser, hydrogen injection plant, district heating, CHP plant	1.000 kW alkaline electrolyser

Figure 3: Characteristics of the three demonstration sites

2 Methodology & Approach

The methodology used to develop this technology-specific roadmap is based on, but not strictly following, the methodology the International Energy Agency describes in "Energy Technology Roadmaps – a guide to development and implementation" [10]. The methodology of this roadmap development is divided into two phases "Planning and preparation" and "Visions and roadmap development" as well as two categories, the first being "Expert judgement and consensus" and the second being "data and analysis", as illustrated in Figure 4.

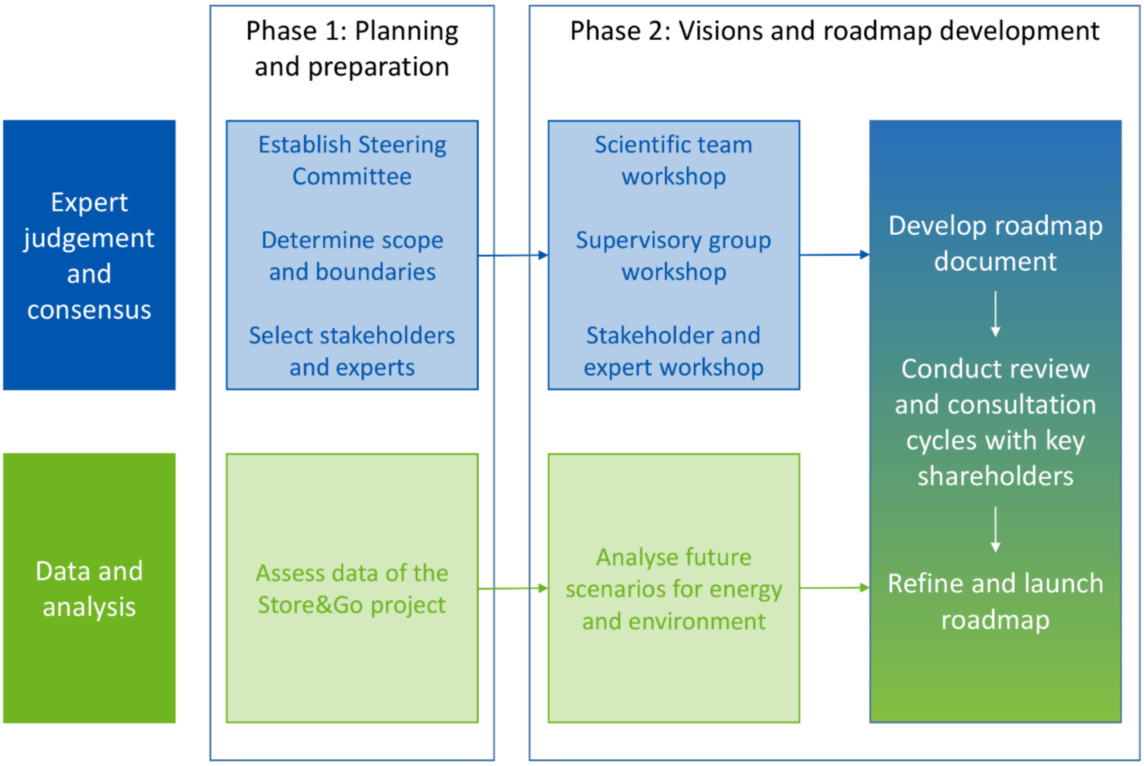

Figure 4: Methodology of the roadmap development process of this roadmap based on **[10]**

In the first phase of the category "Expert judgement and consensus", a steering committee was established consisting of the senior partners as a sub group of the roadmap scientific team. The scope and the boundaries were determined and suitable stakeholders and experts were selected, consisting of the demo site operators, technology providers and technical & scientific associations involved in the project and deeply involved in national activities around the topic of power-to-gas. In parallel in the category "Data and analysis", the existing and further growing data of the STORE&GO project was assembled and evaluated.

In the second phase, scientific team workshops were conducted to develop the visions and the roadmap as such. This includes identifying long-term goals and objectives and also the core-technologies, secondary technologies and further technologies and the specific potential of each. The knowledge was mainly derived from the findings inside the STORE&GO project but also critically mirrored to leading European research relevant to each element (Data and analysis – Phase 2). In the supervisory group workshops, a quality and conformity check was performed, barriers were identified, and the prioritisation of policies was handled. Policy Recommendations from finished insights inside the STORE&GO project and parallel ongoing activities inside the project were derived and mirrored with the stakeholder and national demands from organisations such as DVGW and SVGW to get a further reality check and prioritisation feedback. Finally the recommendations were categorised and a specific suggestion of a coherent regime of policy measures was extracted.

All activities in both categories were merged in the further development process of the roadmap draft document. In recurring conduction of review and consultation cycles with the key stakeholders, e.g. the STORE&GO demo site operators or the roadmap supervisory group, the roadmap was refined and finally launched at the end of the STORE&GO project timeline.

3 Scope of the roadmap

The energy transition sets the overall boundary for the roadmap, thus only scenarios that consider and achieve the obligations in COP21 can be considered. The EU corresponding strategy for this is described in "A Clean Planet for all – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy" and reflected in the "SET Plan 10 Key Actions". Although many energy system analyses deviate in details from this, the overall objective of sufficient GHG reduction to meet the +1,5 °C maximum mean temperature increase until 2050 is considered as a "must achieve" goal in this roadmap. Furthermore, it is important to mention that the recently published ambitious measures from the EU Commission, The EU Green Deal, are also in line with the goal of this roadmap.

3.1.1 Focus on renewable synthetic methane from power-to-gas

There is a number of routes to produce renewable methane. Most common today is the fermentation process leading to biogas and bio-methane. It is also possible to produce renewable synthetic methane by means of thermo-gasification. Renewable gas can also be in the form of hydrogen if it is produced from methane of biological origin or by means of renewable electricity in power-to-gas electrolysers. There are many synergies between renewable synthetic methane from power-to-gas and the other renewable gases. For example, this roadmap considers the surplus CO_2 from the biological methane production to be re-used for methanation of hydrogen from power-to-gas and thus make the hydrogen 100% compatible with the existing natural gas infrastructure and technologies. Many of the key technologies and required adaptions of the regulatory framework and market conditions are also the same for renewable hydrogen and methane, and are independent of the actual future share of biogas, renewable hydrogen and methane.

This roadmap focuses on the technologies, market conditions and the regulatory framework needed for a positive development of renewable synthetic methane from power-to-gas. Positive concurrent effects are expected also for biogas and renewable hydrogen in the energy system if the concluded measures of the roadmap are deployed.

3.1.2 Focus on grid injection or alternatively bio-LNG

In order for power-to-gas to provide grid balancing services to the electricity system, the facility needs to be situated in areas with production of renewable electricity exceeding the grid infrastructure and rate of consumption. It is suspected that the location of the source of renewable energy will generally not be in the immediate circumference of high gas consumption and underground storages (North Sea region might be an exception). Thus the roadmap considers grid injection as vital for maximizing the system benefit of power-to-gas. Another factor is access to CO_2 from renewable sources. Many biogas facilities are not connected to the gas grid, and future locations might not be in areas close to the gas grid. Since LNG is one of few alternatives to defossilise heavy transport, the consortium also sees bio-LNG production from power-to-gas as a valid route for power-to-gas.

3.1.3 Areas of application

Power-to-gas is one of the few, if not the only, technology that can provide solutions to four key areas of the future energy system with one technology. The key areas are: Energy Storage, Power Grid Stability, Energy Transport and Sector Integration.

- "Energy Storage" is an inevitable part of an energy system which relies on volatile means of production, just as the past energy production relied on molecules such as i.e. coal, which in itself is energy stored in solid matter. Storage is needed for different duration rates from long term to short term. It is already clear that an energy system that needs to be renewables-based around the year needs to shift produced energy from the summer season to the winter season.

The natural gas system already incorporates 1100 TWh worth of seasonal storage capacities that could be utilized for storing renewable energy by means of power-to-gas. It can be seen from Figure 5 that batteries, pumped-hydro, flywheels and other technologies could promise some degree of storage options, but none of them is offering a seasonal storage and the range of "discharge time" and "storage capacity" like power-to-gas [11]. Future development of technology, efficiency and cost of power-to-gas might in-crease this range even further.

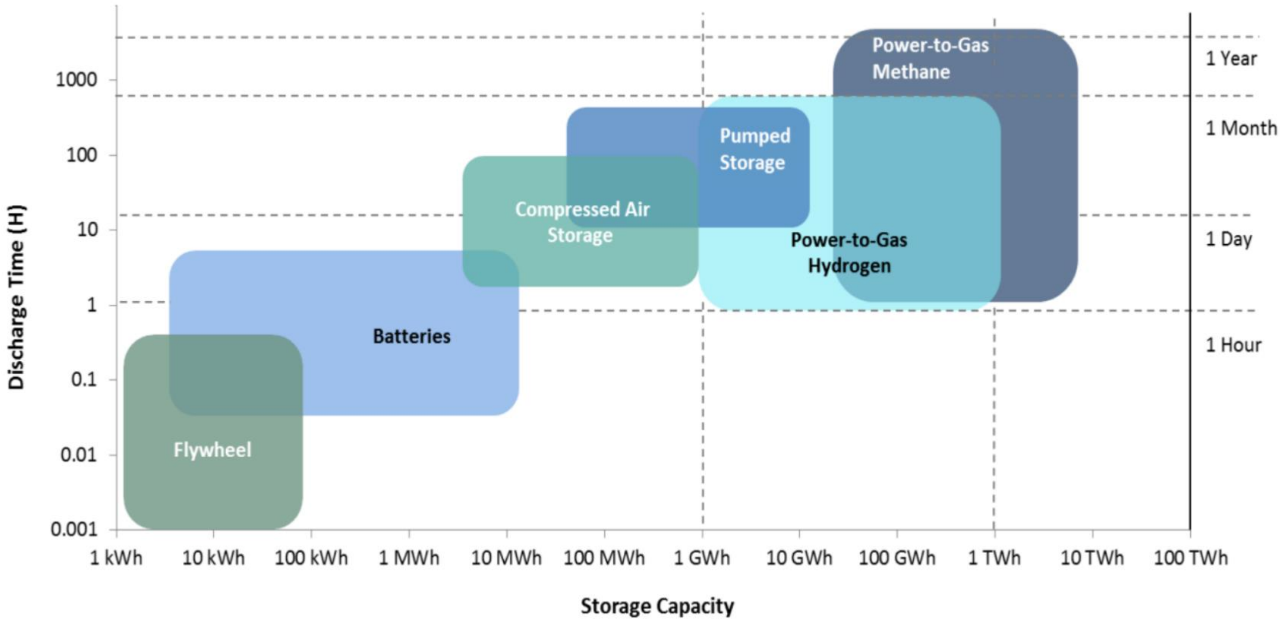

Figure 5: Storage options for electricity **[3]**

- When it comes to "Power Grid Stability", the challenge is the instant mismatch of time of production and time of consumption, which is also accompanied with the more regional aspect of power grid stability. Renewable electricity is often produced in large quantities in areas of few consumers and thus, lower capacity power grids. Green CO_2 and gas infrastructure often match the sources of production of renewable electricity production, and thus power-to-gas facilities can act on grid demands as a flexible load [12].

- In "Energy Transport" the challenge consists in bridging the distance between the location of production and the location of consumption. By power-to-gas, the gas grid can be utilized in parallel to the power grid. Via a trading system based on certificates, the exchange can be instantaneous.

- "Sector Integration" is about making renewable energy available in all sectors of consumption. This includes also greening the feedstock for the chemical industry. Just as "Energy Storage", this is one of the key areas for power-to-gas. This is due to the already established natural gas infrastructure and technologies available and present in the market.

Furthermore, electrification is no option at the moment for some sectors. This includes aviation, long-range shipping, and long-range heavy-goods road transport, due to their demand for high energy density fuels; as well as some industries where very high temperature processes are necessary.

These are the criteria that the roadmap will put special focus on when looking at the future energy system, the role of power-to-gas therein and the corresponding need for development of technology, market and regulation.

4 The energy picture of the EU by 2050

The big picture of Europe's energy system in 2050 shows an energy union, with all Europeans having reliable access to secure, affordable and climate-friendly energy. This is not only beneficial for the health and wellbeing of the population, but also crucial for the industry's competitiveness. How can this vision be brought to life?

The European Commission published a report on a strategic long-term vision (A clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy) for this energy transition to happen. According to the report, the temperature increase can be stopped by 1.5 °C levels by following seven main strategic building blocks [3]. Moreover, these important pathways (which can be seen below) are also in line with the SET (Strategic Energy Technologies) 10 Key Actions [13];

1. Maximising the benefits from ***energy efficiency*** including zero emission buildings
2. Maximising the ***deployment of renewables*** and the use of electricity to fully decarbonise Europe's energy supply
3. Embracing clean, safe and connected ***mobility***
4. Having a ***competitive EU*** industry and ***circular economy*** as a key enabler to reduce GHG emissions
5. Developing an adequate ***smart network infrastructure*** and ***inter-connections***
6. Reaping the full benefits of ***bio-economy*** and creating ***essential carbon sinks***
7. Tackling remaining emissions with ***carbon capture and storage (CCS)***

Furthermore, in December 2019 (11th December 2019) the EU Commission shared their vision in "A European Green Deal". According to the document, the EU is aiming to reach carbon neutrality by 2050, and be the first continent in the world achieving this. With this new vision, the EU Commission increases its climate protection ambitions; for instance, the new target for GHG emissions in the EU by 2030 is now 50%–55% instead of 40% [2].

Electricity production from renewable sources has substantial importance as can also be seen from the 7 main building blocks above. Moreover, the 1st core priority of the SET Plan is to be number 1 in renewable energy. To be able to achieve the number 1 ranking in the renewables globally, two key actions are stated; (i) sustaining technological leadership by developing high performance renewable technologies, and the integration of these technologies into the energy system, and (ii) reducing the key technology cost [13]. The cost of the renewables is already showing a great decrease. Variable renewable sources have come so far from the high prices and low installed capacities. Due to the ambitious targets taken by the European Commission, the installed capacity of renewable sources (mainly variable renewable energy sources; PV and wind energy) will most likely increase in the future, and the share of renewables in our energy system is expected to be high. According to the study made by IRENA, it is highly possible to see that the renewables could double their share in the energy mix from 17% (in 2015) to 34% by 2030 in a cost effective manner [14]. Furthermore, it is also important to understand the maximum technical potential of the variable renewable energy (wind and solar PV) capacities. In literature, there are different sources on this matter. A study which was done by FVV (Research Association for Combustion Engines) in 2016 shows that by 2050 significant amounts of electricity could be produced by renewable sources, mainly onshore[5] and offshore[6] wind, and solar PV[7]; technical potential of electricity produced from renewables could be between 9.000 TWh and 14.000 TWh per year [15]. In short, these numbers show that the EU has a substantial potential for the renewables, and if it is utilized well, the climate targets could be reached quicker than expected.

All studied projection scenarios show that gas and power-to-gas must play a major role. Today over 70% of the European energy system rely on molecules as energy carriers (in some specific sectors such as mobility, this ratio goes even higher to 90% levels). Projections toward 2050 indicate that this share will remain substantial. Even in high electrification rate scenarios, 40–60% of final energy consumption needs to be satisfied with molecules [16].

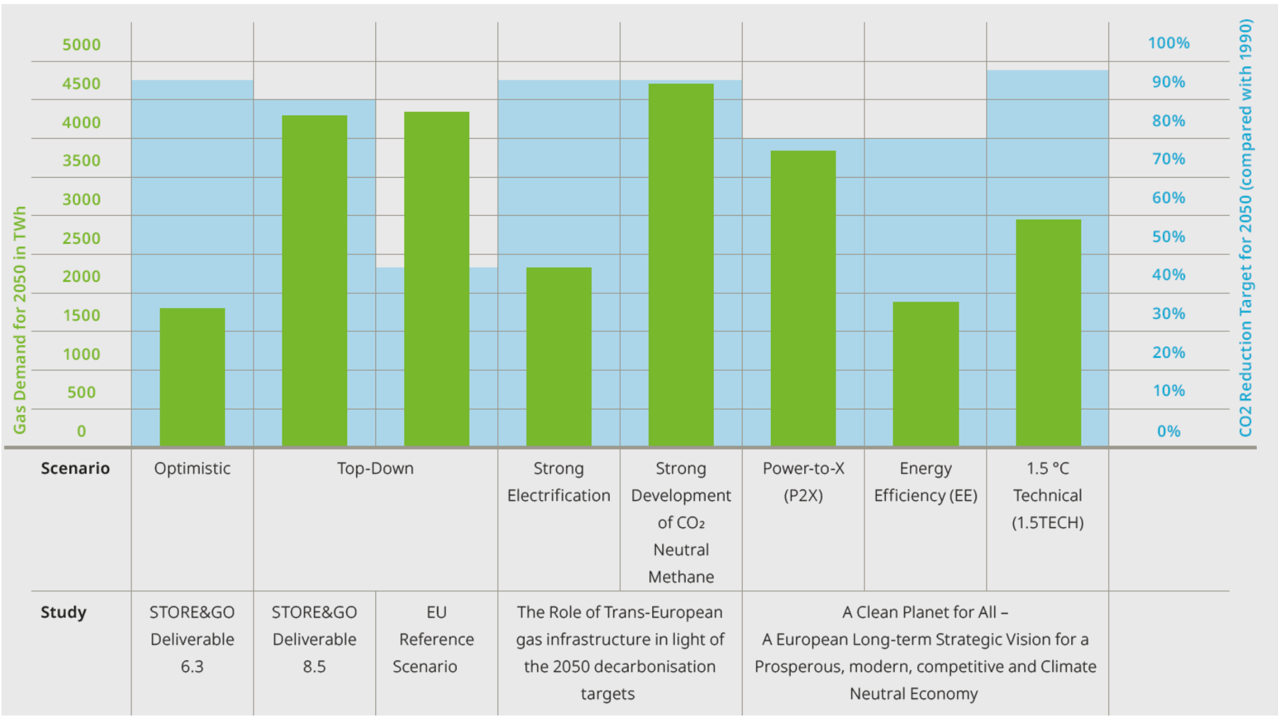

Figure 6: Gas demand projections for 2050 from different studies, summarizing demand for hydrogen, CO_2-neutral methane, and natural gas **[3] [17] [18] [19] [20]**

In this chapter, the energy picture of this energy union will be discussed. Firstly, the future demand for green gases will be discussed for the different sectors. And then, the role of power-to-gas and the gas infrastructure will be introduced to the reader by considering different key areas for the energy system. Since the methanation step needs CO_2 for the process, section 4.4 will deal with this issue and bring some light to the CO_2 sources.

[5] Technical potential for offshore wind energy in the EU could reach between 2132 TWh and 3735 TWh per year [15].
[6] Technical potential for onshore wind energy in the EU could reach between ~2500 TWh and ~3750 TWh per year [15].
[7] Technical potential for PV in the EU could reach between ~1500 TWh and ~2250 TWh per year [15].

4.1 The practical demand for green molecules

Considering all the sectors in the energy system, the need for green gases in the form of hydrogen and synthetic methane will be important – even if the overall EU energy demand should decline towards 2050 due to future renewable energy policies.

Sector integration, or sector coupling, is one of the four areas of application of power-to-gas. This application connects different energy systems (gas grid, electricity grid, heating grid), mobility and industrial infrastructures with each other in order to increase the uptake of renewables in a cost efficient way [3]. The concept has been gaining importance in Europe. For the European Commission, sector coupling is an important strategy, as well as energy storage. With the help of combining different sectors, the ambitious climate targets can be achieved cost-effectively [21].

A number of studies commissioned by the EU ([3], [18], [19]) estimates a range of 1860 to 4700 TWh for the total gas demand in 2050 (see Figure 6), which by then must be covered predominantly by green gases. Detailed analyses indicate that the future demand for renewable gas is often underestimated and a demand in the upper range is more likely. According to the STORE&GO study on the short, medium and long-term perspective of various market segments for green gases, the future gas demand in 2050 is estimated to around 4400 TWh [20]. The maximum scenario of the STORE&GO project estimates the need for 550 GW installed capacity of power-to-gas to cover 75% of the future gas demand in the EU by 2050 [17].

4.1.1 Electric sector

The electric sector is facing growing challenges to phase out coal-fired power generation, and to simultaneously build up renewable energy generation. Deployment of renewable energy sources has crucial importance for the energy transition since it will directly cause a decrease of fossil fuels, which leads to a substantial decrease of GHG emissions. In order to achieve the clean energy transition, a high share of the primary energy supply needs to be provided by renewable sources. The EU had an agreement recently that the new target for the renewable energy share in gross final energy consumption will be 32% by 2030 [3]. It seems a feasible target to reach for 2030 if the deployment rates of renewables will continue at the same pace. However, increase in the capacity of renewable energy brings another problem with it; curtailment of the renewables. The amount of curtailed renewables keeps increasing. For instance, in Germany the average load profile fluctuates between 50 GW and 80 GW on weekdays and between 40 GW and 60 GW on weekends. When the renewable electricity generation from wind and solar is higher than the demand, there is surplus electricity in the system, and in order to balance the grid, this surplus renewable electricity either needs to be curtailed or stored somehow. In 2015, this phenomenon has occurred several times, and 4,7 TWh of renewable electricity from intermittent sources (PV and wind) were curtailed. As a result, the network operators needed to pay €315 million [11]. In addition to this, also in Germany in 2017, times with negative power prices increased by 50% and reached 146 hours; representing 1,6% of the total operation time [21].

To maintain a stable system, a share of conventional power production will always be needed. In an immediate step from coal to natural gas, substantial CO_2 savings could be made, and by gradually greening the gas, further CO_2 savings could be achieved. Conventional gas and gas-CHP (CHP: combined heat and power) is the optimal partner for renewable volatile electricity production. The net renewable gas demand in 2050 of the electric sector in the top-down assessment is around 1200 TWh. The share provided by power-to-gas is estimated to be about 0–5% [20] [17].

4.1.2 Industry sector

In the industry sector the top five branches consuming the largest amounts of **final energy** are the (petro)chemical industry (19%), the iron and steel industry (18%), followed by the non-metallic minerals industry (12%), the paper and pulp industry (12%), and the food and tobacco production (11%). Electricity and gas are key energy sources used in the industry sector (running up to around a 2/3 share of total final energy uptake in the industry sector). Still, there are specific industries with a relatively high dependence on solid fuels, such as the iron and steel sector, or other industries with relatively high levels of renewable energy, such as the pulp, paper and wood industries. Phasing-out of solid fuels will have the highest impact on the iron and steel sector due to its high dependence on this type of fuel. However, the sector could easily switch either to electricity or renewable gases. Oil has a relatively small share (around 10%) in the energy use for industry and for most of the industries in EU-28 countries, it is feasible to replace oil with (renewable) gas. Petro(chemical) industry uses already a high share of gas in their energy mix. Therefore, it is technically possible to have a quick transition to renewable gases for this specific industry. There are currently some industries with relatively high levels of renewable energy such as the pulp, paper and wood industries. Furthermore, another sector which could adopt the higher share of renewables in their energy mix is the food and tobacco sector. This transition could happen due to the production of biogas by anaerobic digestion of food processing residues [20].

In the short-term and medium-term, there could be a good opportunity for the electricity consuming technologies to be used for enhancing residual/waste heat use which is available on site. However, full electrification of all industries in the long-term seems unlikely. The net renewable gas demand in 2050 of the industry sector’s final energy consumption in the top-down assessment is about 630 TWh. The share provided by power-to-gas is estimated to be about 10–65% [20].

Within the industry sector, the **final non-energy consumption** involves the use of fossil fuels and other resources, mainly as feedstock to produce non-energy products in various sectors. When it is compared with other sectors, the industry sector consumes almost 96% of all resources. The chemical/petrochemical sector is consuming the largest amount of energy feedstocks with a share of almost 78% because of its heavy reliance on mainly oil and gas as key feedstocks. The output of these industries are non-energy products such as chemical fertilizers and plastics. Phasing-out from oil will substantially impact the (petro)chemical industry from the final non-energy point of view. Carbon containing renewable gases (i.e. renewable methane), hydrogen or natural gas are the candidates in order to substitute oil use in this branch. It is expected that the (petro)chemical sector will stay reliant on carbon containing liquids and gases up to 2050, and renewable gases are one of the few viable options here to change this dependency on oil and natural gas. The net renewable gas demand in 2050 of the industry sector’s non-energy consumption in the top-down assessment is about 570 TWh. The share provided by power-to-gas is estimated to be about 30–60% [20].

4.1.3 Heating sector

The fossil fuels in heating systems will need to be replaced at an affordable cost for private households. Integration of climate-friendly fuels from power-to-gas would be a measure allowing for quick and affordable implementation as major parts of the infrastructure could stay in use [20].

The heating of buildings and industry is another important sector where green molecules will be needed. Most of the GHG emission reductions will be expected to come from buildings, according to the EU Commission’s long term strategic plan [3]. Energy demand in residential and services sectors is responsible today for around 40% of the energy consumption in the EU; and around 75% of these buildings were built before the energy performance standards existed. Though the total amount of heating energy is expected to decrease due to building renovations (for already existing buildings) and efficiency measures[8], a large-scale replacement of molecule-based heating systems in favour of electricity-based ones is unlikely in the next decades. Technical and economic challenges both in replacing infrastructure and appliances indicate a slow change of the status quo, especially in the built environment in cities. This demands for a replacement of fossil energy molecules by green molecules as an efficient measure to speed up progress. The net renewable gas demand in 2050 of the heating sector in the top-down assessment is about 756 TWh. The share provided by power-to-gas is estimated to be about 30–60% [20].

4.1.4 Mobility sector

The mobility sector is another important sector where a reduction in GHG emissions would help tremendously to the energy transition. GHG emissions from the mobility sector are substantially high; since it has a high influence on the society. It affects the way one lives and plays a crucial role in the economic growth of the country since it helps the other sectors to grow more [22]. The GHG emission levels from mobility were increased by approximately 20% since 1990. That makes the sector the only major economic sector in the EU where GHG emissions have risen until now when it is compared with the 1990 levels [23]. Furthermore, in 2017, the transportation sector had a share of 27% of the total EU GHG emissions. After excluding international aviation and the maritime, the share of GHG emissions from the transport sector drops to 22%. Road transport was responsible for around 72% of greenhouse gas emissions in 2017; it was followed by aviation (~14%) and maritime (~13%) [24].

It is estimated that there will be a significant growth in this sector until 2050. Between 2010 and 2050, passenger transport is expected to increase about 40%; and the fastest growth rate will be seen in the aviation sector due to the increasing GDP and the growing middle-class numbers. Similarly, freight transport is estimated to increase around 58% while road freight transport will be the highest share of 70%. Current estimates show that due to the climate policies in EU countries, the GHG emissions in transport in 2050 would decrease by 8% below the 2010 level. It would happen mainly due to the technological development in the car industry. Nevertheless, according to this estimation, the GHG emission level in 2050 would still be 15% higher than the 1990 level [25]. This is why the European Commission has put emphasis on mobility in addition to the other sectors both in “A Clean Planet for all” study and in the SET Plan – 10 Key Actions[9] [3] [13].

Electric mobility has a crucial importance not only to reduce the GHG emissions but also to increase the uptake of renewable energy in the mobility sector. However, electrical drives based on batteries still struggle with acceptance issues as well as daily mileage. Even if the mileage issues and the duration of the charging is improved, 100% electrification of the mobility sector is unrealistic from a technical as well as undesirable from an economic point of view (especially for long-distance maritime transport, freight transport and aviation). For instance, when trying to electrify commercial planes, the electric motors would not be able to provide the necessary thrust. Furthermore, due to their low energy density, even batteries anticipated for the future do not fit for implementation in freight transport and long distance maritime transport, not to mention long-distance flights. Therefore gaseous (such as green hydrogen[10] or green methane[11]) and liquid e-fuels from power-to-gas applications should be a complementary fuel alternative for air, marine and heavy road traffic. The role of gas mobility therefore is important because in the first place gas engines or LNG engines do hardly

[8] EU has agreed a new binding energy efficiency target of 32.5% by 2030 [3].

[9] Diversifying and strengthening the energy options for sustainable transport is the 4th Core Priority for EC.

[10] Green H_2 can be used in Fuel Cell Vehicles. Fuel cells have already proved themselves from the Life Cycle Assessment (LCA) point of view. With the help of Green H_2, lower results for well-to-wheel emissions could be reached.

[11] Green methane can be used in CNG/LNG engines without the need of additional investments in these technologies.

need further improvements from the technology side. Also from the cost point of view, the costs are very similar when compared with diesel cars; and they are cheaper than battery or fuel cell vehicles. From the life cycle analysis' point of view, well-to-wheel emissions of the gas/LNG vehicles are better than the fossil counterparts when renewable gas is used. Furthermore, gas mobility will allow us to use already existing gas infrastructure as well; only some new connections need to be made to the fueling stations for CNG or LNG engines [7] [11] [26]. The net renewable gas demand in 2050 of the transport and mobility sector in the top-down assessment is estimated to about 1012 TWh, and therefrom about 30–60% would be provided by power-to-gas [17] [20] .

Branch/sector	Net gas demand 2050 (TWh) acc. to top-down assessment	Share possibly provided be PtG
Electric sector	1163-1233	0-5%
Industry (energy consumption)	628	10-65%
Industry (non-energy consumption)	570	30-60%
Heating Systems	756	30-60%
Mobility	1012	30-60%

Figure 7: Gas demand across the sectors **[20]**. "Non-energy consumption" denotes usage as feedstock.

Considering all the sectors in the energy system, the need for green gases in the form of hydrogen and synthetic methane will be important – even if the overall EU energy demand should decline towards 2050 due to future renewable energy policies. Figure 7 summarises the net gas demands per sector in 2050 and the possible share provided by PtG.

4.2 A critical cross-check of results of the sectors: the current demand estimations could still be too low

Key factors in the energy transition are the speed of the phasing-out of fossil energy and – depending on this development – the phasing-in of green alternatives (renewable electricity and gases). Further key drivers are the anticipated share of solids/liquids, the share of electricity in the aggregated future energy mix and energy savings/efficiency improvements. A detailed analysis of representative countries in the European Union indicates that the gas demand in 2050 is more likely to be on the upper scale or even beyond currently leading studies [20].

Especially in countries that have to devote both considerable time and resources on the phasing-out of fossil energy sources and phasing-in of renewable energy as well as implementing energy saving measures, there is an overhanging risk of failing to realise the necessary transition at the required speed and scale. Depending on the country, this can relate to poor transition economics and financing, the lack of sufficiently skilled workers to actually 'build the transition' or inadequate regulatory and institutional regimes not able to fairly share risks and returns along the value chain. The conclusion of the detailed assessment is that there is a considerable risk that several scenarios could significantly underestimate the future demand for renewable gases in the EU-28 [20].

4.3 The role of power-to-gas and gas infrastructure in a cross-sectoral energy system

Considering the future demand for green molecules across all sectors, the sheer gas amount which is needed clearly illustrates that power-to-gas has to be given serious consideration, and that its introduction has to be promoted with urgency. Apart from this, the energy system faces three further major challenges: energy transportation and distribution, power grid balancing, and energy storage.

With PtG technologies, the existing gas network can store and transport very large amounts of electrical energy in the form of gas – from volatile generation sources such as wind and solar. Moreover, the existing natural gas infrastructure is a key component in the development of hybrid networks. Hybrid networks integrate changing mixes of power generation, transmission and distribution, delivery and control. Hybrid networks are able to connect different energy systems bi-directionally and facilitate an optimised integration of the existing structures with all future energy networks: electricity, gas systems, heat power, water supply as well as transport networks. This allows for more freedom for strategic decisions in the energy planning.

4.3.1 Transportation and distribution

Electric power surpluses increasingly occurring out of wind plants must be transported either directly to the consumers or to conventional electricity storage facilities, such as pumped hydro storages. Therefore, huge investments in the expansion of the European power grid are expected in the future. However, the lack of acceptance in the public to such infrastructure projects very often hinders this development.

By shifting the energy transport from the power grid to the natural gas grid, required new power lines could be partially substituted. The realisation of large-scale high-voltage power lines through Europe, which could face great resistance in the population, could be avoided to some extent. The existing gas network can absorb very large volumes of renewable energy without expanding. Any necessary expansion of the natural gas network, beyond that, would also result in much less topographical intervention in relation to the expansion of the electricity grid.

4.3.2 Power grid balancing

A reliable electricity infrastructure is crucial for an energy system; there should always be sufficient capacity available in order to match demand and supply. However, unlike the gas grid, the problem with the electricity grid is that there is no large electricity storage over long periods. Today, this balancing is done by the large-scale dispatchable power generation; coal-, oil-, and gas-fired power plants are used for the balancing purposes because it is easier and cheaper to store these energy carriers for a long time. With increased electrification in the energy system; for instance, due to the increased number of electric vehicles or heat pumps in households, the demand in distribution level is going to increase. Moreover, the decentralized way of producing electricity through PV panels on the rooftops will become the standard. The increased electricity demand will most likely be compensated by large-scale wind and solar farms, which are usually far away from cities. This will inevitably increase the load on the transmission lines [7].

There are different use cases in which the application of PtG in the electricity distribution grid can act as a balancing instrument. By an optimised operation of the plant, according to the needs of the power grid instead of optimal gas production rates, value could be added to the power grid operator. Contrary to the electricity grid expansion, PtG units can be designed and scaled accordingly to the specific requirement. Especially for cases of oversizing with discrete power grid expansion measures, PtG is an alternative. The net beneficial use of PtG, i.e. in the low-voltage level, can be relieving in the entire distribution grid and thereby, acting both as balancing and energy transfer device, reduce the necessary electricity grid expansion across all voltage-levels [27].

A power system that heavily relies on renewable energy sources must cope with their intermittent supply. The uptake of renewables comes with some great challenges such as curtailment of renewable energy sources, flexibility issues and long-term storage [11]. PtG plants can be operated in order to take up excess power from the grid when wind or solar plants generate surplus electricity.

Curtailment, one of the largest challenges of renewables, could thus be decreased and waste of renewable energy reduced.

Vice versa, in times of high demand and low renewable power generation – especially in case of so-called dark doldrums – e.g. in winter, when low renewable electricity generation is confronted with high demand, importing energy from other areas might not be a sufficient response, or even be possible. In such cases, stored SNG could cover the baseload via natural gas power plants.

In short, having a highly flexible electricity grid will not only necessary to have the demand-supply balance. It will also help tremendously to increase the uptake of renewables, and using PtG for this purpose could help us to do that.

4.3.3 Energy storage

The key advantage of storing energy in the form of gas: energy can not only be stored and released locally and in the short term. It also facilitates converting large amounts of energy for long term storage. Renewable methane from power-to-gas can be injected into the gas grid without any constraints when the gas quality is taken into consideration. This facilitates tapping the full potential from intermittent renewable sources like wind and solar, by storing energy in times of surplus production, and feeding it back into the grid when wind or solar cannot meet the demand.

Using gas as long-term storage option of intermittent renewable electricity could be a very promising solution for the future. Molecules (in this specific case molecules in renewable gas) have higher energy densities and easy storage options, which allows to store them in large quantities for a long period of time. Batteries, pumped-hydro, flywheels and other technologies can serve as storage options to a certain degree but none of them is offering a seasonal storage like PtG does [11]. Even if the battery cost decreases to 60 €/kWh by 2050, storing the surplus renewable electricity for seasonal storage in batteries will still be more expensive than storing it as gas via PtG [7].

To be able to have a future with a high percentage of volatile renewable energy, seasonal storage will be of crucial importance. When the renewable electricity production is abundant, this energy needs to be stored for long-term use purposes (i.e. using this stored renewable energy during “dark doldrums”). Insights from literature about how much energy needs to be stored seasonally to have a stable energy system vary. Still it remains undisputed that with high penetration of renewable energy sources in the energy system, energy storage is required [28].

Underground gas storage facilities can be classified in two different groups: cavern storage facilities and porous storage facilities. The type of the storage facility depends on the geological properties of the region. Renewable methane can be stored in both of these storage facilities without any problem, whereas for hydrogen this is only due for the caverns type [29]. The current gas storage capacity (operational) in Europe (EU-28) is around 1131 TWh according to Gas Infrastructure Europe (GIE). These gas storage facilities can deliver up to 22 TWh (withdrawal capacity) natural gas per day. Moreover, this gas storage capacity is planned to increase to 1300 TWh in the future [30]. So the question here is how much gas needs to be stored seasonally. According to some studies, around 10% of the final energy consumption is the amount of electricity required as seasonal storage per year in order to balance a system that relies heavily on power from renewable energy sources [28]. That means, if it is assumed that the final energy consumption in EU in 2050 is around 11000 TWh [3] [18] (which is the expected final energy consumption according to the observed EU studies in this document), 1100 TWh of energy needs to be stored seasonally. It can be easily concluded that the existing storage infrastructure is sufficient to cover this. Due to the intermittent supply of wind and solar in the winter season, when low renewable electricity generation and high demand come together, large-scale long-term storage capacities are needed. With power-to-gas technology, the gas infrastructure could serve for this purpose due to its huge storage capacities – without building up additional infrastructure.

The Ten-Year Network Development Plan (TYNDP-2018, published by ENTSO-E and ENTSO-G) conducted an analysis of the total gas demand in high demand cases (peak day and 2-week cold case) in the EU for 2040. Cold cases are defined as high demand cases, where the maximum aggregation of gas demand has reached over 14 consecutive days once every twenty years in each country to capture the influence of a long cold spell. According to this analysis, the gas demand in a "2-week cold case" is between 25–28 TWh/day with a maximum peak demand of 35 TWh/day. Assuming that the total gas demand will be 25 TWh per day for two weeks, the overall amount sums up to 350 TWh. Even in longer "cold-cases", it can be concluded that the gas storage capacity will be enough to store enough energy for "dark doldrums" [31].

4.4 Potentials of Renewable Methane in Europe and the Supply of CO_2

In a scenario relying on large-scale methanation as common practice throughout the EU, notable quantities of CO_2 are required as a feedstock. Two major sources provide green CO_2: biomass and direct capture from air. Industrial processes based on fossil energy carriers are the source of so called grey CO_2. The future share of these three sources will be a trade-off. The availability of biomass will be reliable and many times over today's degree of exploitation, but in principle limited. In addition, usage competitions will arise. At the same time, strict CO_2 reduction targets will lead to substantial replacement of fossil fuels in the energy-intensive industries via fuel switch to hydrogen or electricity as well as general efficiency gains and alternative production routes. Accordingly, less CO_2 from today's industrial sources will be available.

Two scenarios were created for the potential analysis. A ***limited CO_2 availability scenario**,* where a 95 % reduction of the industrial CO_2 compared to 2015 levels is achieved, and a ***balanced CO_2 availability scenario**,* where a CO_2 reduction of 90 % is achieved by 2050. As a result, the CO_2 from industrial sources potentially provides 130 to 260 TWh/a of synthetic methane, as the analysis shows [32].

The dominating potentials for methane production will be based on the use of green CO_2. Estimates of the biomass potentials across Europe differ widely, ranging from 1,000 to 8,300 TWh [33] A study by Thrän *et al*. [34] as well as additional data from authorities and studies were added to include as many European nations in the study as possible (EU27+CH+IS+NOR+UK). For the limited CO_2 availability scenario, the minimal biomass potentials for residues and forestry from literature were further reduced to 1/3 for integration in subsequent methanation potential calculations. Energy crop potentials were even reduced to 1/6 in order to consider lacking acceptance and ecologic drawbacks of energy crop cultivation. By these steps, an ecologic rather than maximal exploitation of European biomass potentials is taken into account. At the same time the strict limitation to the biomass availability accounts for evolving usage competitions that the energy sector will face. For the balanced scenario, the curtailment of energy crop potentials was loosened to 1/3 of the literature potential. The energy crops partly compensate for deficient CO_2 reductions in industry that coincide with increased gas demand from green sources. The total potential amount of methane from green sources reaches values of 1190 – 1390 TWh/a, thus outperforming the 2050 industrial methanation potentials by far.

Producing methane from both, green and grey CO_2 leads to total potentials of **1,320 and 1,650 TWh/a** for the limited CO_2 availability and the balanced scenario, respectively. This corresponds to approximately 35 to 70 % of the future total gas demand for the corresponding scenarios presented in Figure 6 (bars 4 and 5). It should be noted that the bars in Figure 6 comprise not only renewable methane but also other green (and fossil) gases, so the potential for PtG-methane actually covers most of the methane demand in the 2050 scenarios. The resulting European power-to-methane potential map for the balanced scenario is presented in Figure 8. For details and explanations, please see Deliverable D8.9 [32].

An alternative CO_2 feedstock for methanation investigated in STORE&GO can be realized by direct air capture. Currently, direct air capture is the most expensive technology option for CO_2 provision (see chapter 5.4.1). Nevertheless, its production potential is solely limited by its energy demand. The specific direct air capture technology tested within STORE&GO offers the opportunity that its energy input is provided primarily by low-temperature heat. If waste heat from the methanation unit is utilized in the DAC, the heat demand is reduced by 66% [35]. By integrating heat from the electrolysis, the reduction potential is up to 90%. Therefore, although direct air capture is not accounted for in the above-presented potential study, it may lead to significant additional green CO_2 provision if implemented at large scale and with the corresponding cost reductions. For covering a remaining gap between the production potential and the future demand for green methane, various import options will exist. Green gases produced outside the EU may for example be imported by sea in liquefied form. Nevertheless, if Europe exploits its green methane potentials, today's energy import dependency will be reduced significantly.

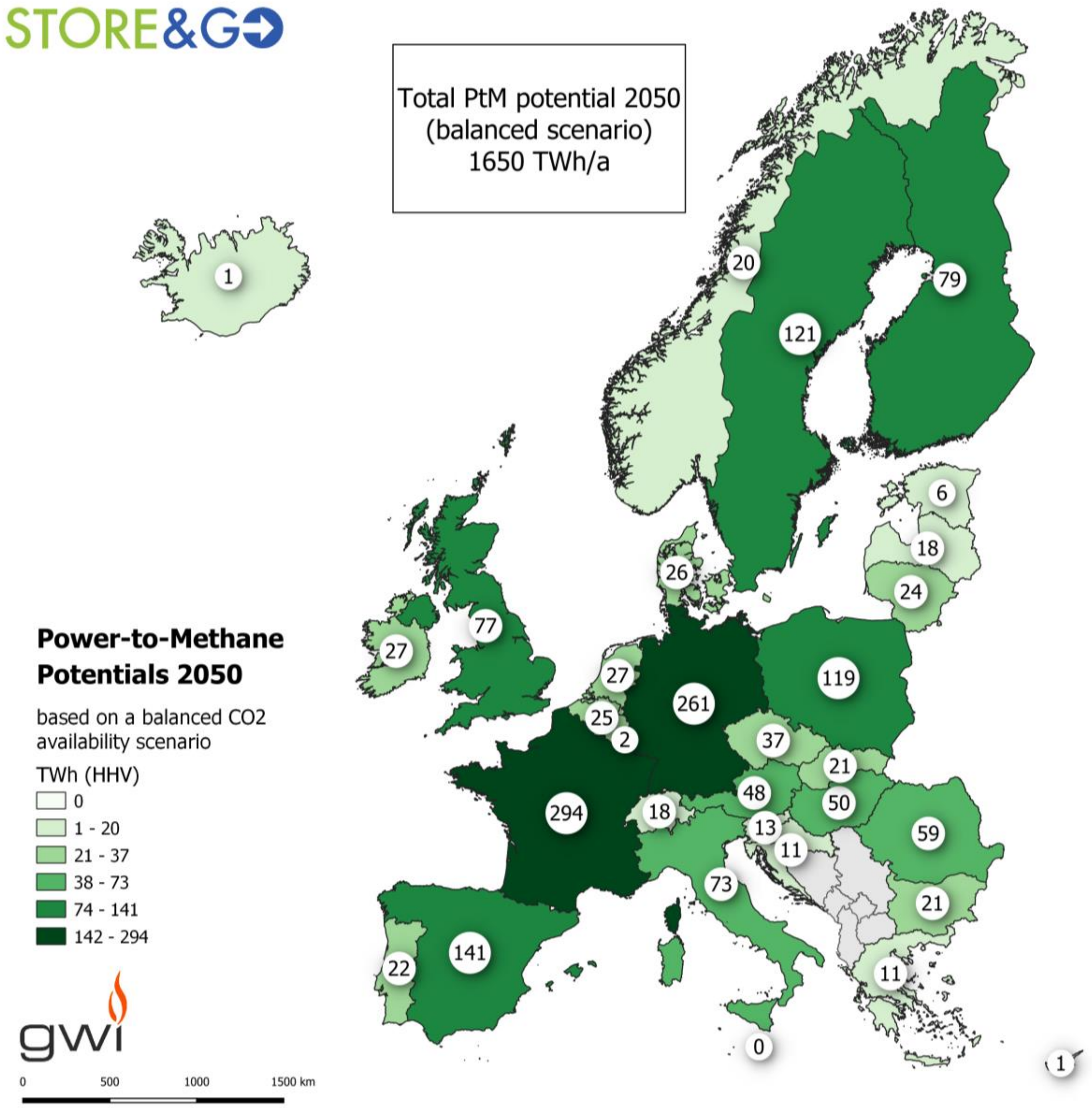

Figure 8: Total power-to-methane potential in balanced scenario by 2050

4.5 Conclusion and discussion on chapter four

The big picture of Europe's energy system in 2050 shows an energy union, with all Europeans having reliable access to secure, affordable and climate-friendly energy. This is not only beneficial for the health and wellbeing of the population, but also crucial for the industry's competitiveness. How can this vision be brought to life? This chapter tries to find an answer to one part of this question, the Target Picture in the EU by 2050, by investigating the possible future projections from various sources. To be able to shed some light to the future and show how the demand of energy in the future could develop, studies (some of these studies are commissioned by the EU and some of them are the Deliverables from the STORE&GO project) were used. Furthermore, the key strategies (both for long and short term) from the EU Commission were also considered while analyzing these studies.

The EU Reference Scenario [18] and other EU studies [3] [19] sketch out a scenario in which some 1200 GW wind and some 2000 GW solar generate around 5000 TWh per year, with further 2500 TWh coming from EU hydro and nuclear capacities [20]. If the final energy consumption will be around 11000 TWh in the EU in 2050 (projections in EU-related studies vary by around 2000 TWh), then the described domestic EU carbon-neutral power supply could deliver about three quarters of the 2050 EU energy uptake [3] [18]. It should be noted that all sources mentioned – wind, solar, hydro, and nuclear – generate carbon-neutral power, not green energy molecules. Around one quarter of the overall energy uptake then would be left to non-electric sources – i.e. energy molecules. This is far from the mentioned EU's own as well as Eurelectric's projections, which indicate a future demand of energy molecules of up to 40–60% in 2050 [16].

Becoming a carbon-neutral energy union cannot be accomplished by switching all applications to green electricity alone. Electricity – as energy in form of electrons – cannot take over the leading role among energy carriers across all energy sectors [3] [17] [18] [19] [20]. The scenarios from various investigated studies show that the estimated gas demand in 2050 in EU changes between 1860 to 4700 TWh (Figure 6), and that power-to-gas must play a major role. Today 70% of the European energy system rely on molecules as energy carriers. Projections toward 2050 indicate that this share will remain substantial. Detailed analyses show that the gas demand in 2050 is more likely to be on the upper scale or even beyond currently leading studies.

In the electric and mobility sector, renewable gas demand is the highest, estimated to go beyond 1000 TWh each. In the heating, industry and non-energy consumption sectors, the demand of renewable gas each lies in the range between 570 to 756 TWh. Especially in the sectors mobility, heating and industry (including non-energy consumption), shares of PtG in the renewable gas demand are estimated as high as up to 60–65%.

This demand for green molecules alone presents a major argument for the build-up of substantial PtG capacities. For the methane production, CO_2 is needed and there are two alternatives; using green or grey CO_2. Industrial processes like cement and steel production are the source for so called grey CO_2. This source is expected to decrease when the key strategies of the EU are considered; i.e. "A Clean Planet for all" and "The EU Green Deal". An analysis in STORE&GO project shows that producing methane from green CO_2 and grey CO_2 could cover 35 to 70% of the total gas demand for the corresponding scenarios presented in Figure 6. Direct air capture offers potential for additional supply of green CO2, which is only economically limited, not physically.

Moreover, the systemic benefits of power-to-gas in the electrical system illustrate another argument. Seasonal storage facilities for electricity of 1000–1100 TWh would be required annually to balance the system. The existing gas storage infrastructure[12] as it stands at the moment would already be able to cover this. An analysis from ENTSO-E and ENTSO-G ([31]) shows that the total gas demand in high demand cases (peak day and 2-week cold case) in the EU for 2040 could be between 25–28 TWh per day. Assuming that the total gas demand will be 25 TWh per day for two weeks, the overall amount sums up to 350 TWh. In other words, the current gas infrastructure has enough capacity to deal with "dark doldrums". Furthermore, additional services for energy transport and grid balancing might be provided with the same technology.

An 'electrification scenario' without enough energy molecules would pose major problems, particularly regarding energy transport and storage infrastructures – leading to considerable costs. It is important to realize that the decarbonisation of the economy should not be thought of as representing a negative burden for society. An 'electric scenario' would lead to extra costs for EU taxpayers. A system based on molecules, which would play a significantly larger role by combining the existing gas grid with power-to-gas technologies, could help us saving more than 200 billion Euros annually by 2050 [8] [7] [36]. This alternative scenario already includes a substantial build-up of the required capacities for bio methane and blue hydrogen production as well as power-to-gas conversion. The scenario would allow for extensive sector coupling – meaning the integration of all energy consuming segments with the power generation sector.

Key factors in the energy transition are the speed of the phasing-out of fossil/nuclear energy and – depending on that – the phasing-in of the green alternatives. Green methane from PtG will play a major role in such a system due to its compatibility across all sectors, its high energy density and its connection to the existing system for natural gas.

[12] The current gas storage capacity (operational) in Europe (EU-28) is around 1131 TWh according to Gas Infrastructure Europe (GIE) and it is expected to be increased in the next years up to 1300 TWh.

5 Technological characteristics and market requirements

As in the energy picture of the EU by 2050 (for details see previous chapter 4) described and shown, an ecologically sustainable energy supply that is economically viable and socially acceptable is a high priority in European policy. The European energy supply must be transformed due to energy-related, social, economic, and environmental/climatic factors. The use of green gases on the basis of renewable electrical energy (as hydrogen, synthetic methane, or alternative hydrocarbons from hydrogen) has numerous advantages, which can significantly assist Europe in transitioning its energy system. These gases can also address major issues facing the development of renewable energy sources, including the long-term storage of fluctuating renewable electricity sources, alternative energy transport via the existing gas infrastructure, the reduction of greenhouse gas emissions, the need to find new renewable energy sources for mobility and industrial processes, and the increase in local production and use. Sector coupling via power-to-gas is fundamental to the transformation of the European energy system and a significant economic parameter. Further, the conversion to an energy system based on renewables must be seen as an opportunity to decisively boost European leadership in innovative energy technology, energy-related transport technology and services, and the application and implementation of mature, green gas-related technologies [37]. The market launch and development of PtG technology depend on, among other things like energy and climate policy decisions, the technological characteristics, market requirements and profitability of the plant. This chapter provides a brief introduction, followed by a short definition of PtG within the STORE&GO project. The next part discusses the relevant technological characteristics (state of the art and future perspectives of selected parameters like CAPEX/OPEX, efficiency and Technology Readiness Level TRL) of the main and additional components of the PtG technology. Further, an economic evaluation, resulting in specific SNG production costs for different applications and operating modes, is presented in order to determine the main drivers of SNG production cost reduction and to demonstrate the potential of PtG. Finally, a connection of the technological characteristics and market requirements to the target picture is established.

5.1 What is power-to-gas

Within the STORE&GO project, the term "power-to-gas" is defined as the use of electrical energy from predominantly renewable energy sources to produce hydrogen, and to synthesise it in a second step with carbon-dioxide to methane. The process chain of PtG within the project STORE&GO is shown in Figure 9.

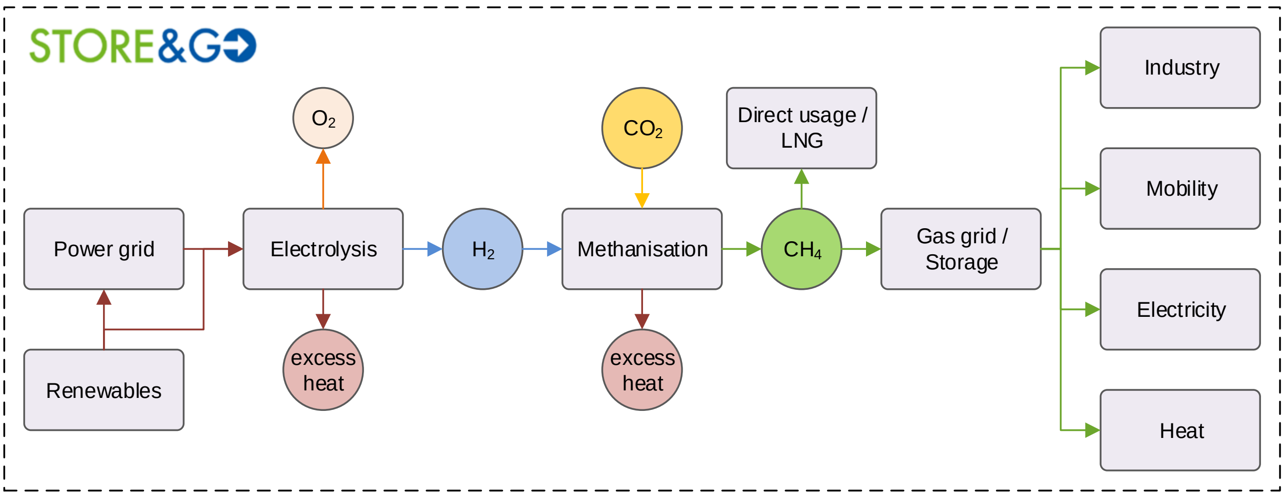

Figure 9: Process chain of PtG within the project STORE&GO

5.2 The core technologies – electrolyser and methanation

The main components of a STORE&GO plant are the electrolyser and the methanation unit, accompanied by the technologies of carbon-capture and liquefaction, which offer special options. Depending on the application of the power-to-gas system, different technologies of different maturity with their respective advantages and disadvantages are currently in use. Evaluating the future techno-economic developments and possible improvements in PtG technologies also requires well-grounded knowledge of the current state of the art. Therefore, in the next sections the state of the art (current situation) of the main components of a PtG plant will be discussed.

5.2.1 Electrolysers today and potential further development

A main component of a power-to-gas plant is the electrolyser. An electrolyser uses electrical energy to split water into hydrogen and oxygen. Depending on the used electrolyte, three electrolyser technologies are available: the alkaline electrolyser (AEC), the proton exchange membrane electrolyser (PEMEC), and the solid oxide electrolyser (SOEC). AEC and PEMEC can be grouped under low-temperature electrolysis, while SOEC performs a high-temperature electrolysis. The three electrolysis technologies differ in their individual characteristics, like energy input (electricity and eventually heat), operating temperature, pressure and start-up times. The electrolyser technologies AEC and PEMEC are key for the short-term perspective, while SOEC has the best long-term development potential with PEMEC being the overall cheapest per nominal option.

The AEC technology has already matured and is commercially available today (TRL 9). The investment cost for AEC with a nominal electrical power of 5 MW is about 1.040 €/kW [38]. This technology is available for large systems of 10 MW or higher. The efficiency of the system is about 75% with a lifetime of about 60000 hours of operation. The cold start duration is about one hour [39]. Since the technology is in its maturity level not much development is expected regarding system efficiency (up to 80%) [39]. However, it is expected that the investment cost of the system could decrease to around 300 €/kW for 2050 [37].

The PEMEC technology is mature and the technology is complete and qualified (TRL 8). However, commercialization of large systems is in its beginning stage. The efficiency of PEMEC is in a range of 70 to 75% with a lifetime of about 45.000 hours of operation. One of the advantages of this technology is the relativly low cold start duration of around 10 minutes; which offers a very high dynamic operation. Apart from this, PEMEC also offers high performance density [39]. Since the technology is not commercialized at large scale yet, the investment cost for a system with 5 MW electrical power are about 1.050 €/kW [38]. In future, a significant cost reduction and performance development is expected. The specific investment costs PEMEC could decrease until around 170 €/kW in 2050 [37]. PEMEC efficiency is expected to reach 81% (~10% increase with its current level) [39].

The SOEC technology is considered as a potentially disruptive technology (TRL 6; demonstrated in industrial environment), which offers significantly high efficiency levels today (~93%) and substantial cost reduction potential for the future. High efficiency levels can be reached due to heat integration. Although it provides high capacity and very high efficiency, the lifetime of the electrolyser is currently about 25000 hours of operation. Also the cold start duration is currently relatively high, which makes SOEC up to now not suitable for dynamic applications [39]. Since SOEC is a very new technology that is under development, it is hard to get reliable sources on investment cost. Nevertheless, the investment costs are comparatively high, about 2.160 €/kW [38]. While the pre-commercial status and intense development of high-temperature electrolysis makes a detailed analysis of individual parameter evolution difficult, the values given for the current state of the art show that the technology is about to progress along with concurrent low-temperature systems. However, no verification of performance in large-scale applications has been made. Because of its early stage of development, this technology has a high potential for technology improvement and CAPEX reduction. It is expected that very high efficiency could be seen in the future; around 97%. This is technically possible, because the high temperature nature of the process allows for using the heat in tight system integration [39]. Like the efficiency improvement, the CAPEX value for the SOEC could show some sharp decrease and come to the levels around 270 €/kW until 2050 [37].

Due to still low demand, electrolyser companies use little automation and typically manufacture products to order with high labour content. Suitable processes for higher production volumes are already known from other applications and industries. These processes could also be used in the electrolyser industry in the future to reduce manufacturing costs. Overall, there is no need to develop fundamentally new production processes [2].

Renewable hydrogen has gained increasing attention due to its potential fields of application in a carbon-free energy system (e.g., mobility, energy storage), and electrolysis technology has significantly evolved over recent years.

In general, there was a positive development of water electrolysis over the last 10 years. For several characteristics, like stack and system capacity and stack lifetime and degradation, the development so far outperforms the values proposed 10 years ago. Systems have significantly improved, especially in terms of PEM electrolysis. For example, the maximum available system and stack production capacities are currently far beyond the values proposed only a few years ago. The same is true for stack lifetime and degradation rates, as well as flexibility properties. This highlights the efforts that have been put into the technology and shows its relevance for future energy systems.

5.2.2 Methanation today and potential further development

If the hydrogen shall be further converted to synthetic natural gas, methanation is required. In this case, the second major component of PtG plants comes into play: the methanation unit, where hydrogen and carbon dioxide react with each other to SNG (CH_4). Chemical CO and CO_2 methanation processes have been investigated for over a century [40], so the underlying processes are mature. Therefore, most recent developments have tackled the optimisation of reactor technologies, upsizing, and cost reduction [40] [41] [42] [43]. In the power-to-gas – or rather power-to-methane – process chain, methanation is used in order to integrate the produced gas into the existing infrastructure, such as regional grids, and thus to ensure rapid implementation.

There are two different methanation technologies: biological methanation on the one hand and chemical, or catalytic, methanation on the other.

Catalytic methanation is a thermochemical process, which occurs with the help of catalysts at high temperature (between 200–700 °C) and high pressure (1–100 bar). The technology is commercially available (TRL 8) since it has been used in the industry for a while. The efficiency of the system is about 80% (if there is a strong heat recovery implemented, a higher efficiency of about 95% is possible). While modern electrolysers can be operated with very high load flexibility, the chemical gas catalytic process of methanation does not yet meet this requirement [44] [45]. According to current information, the specific investment costs for catalytic methanation plants with a rated power of 5 MW SNG-output are in the range of 580 €/kW [37]. In future, the CAPEX per SNG-output could be expected to reach until 125 €/kW by 2050 [37]. Furthermore, the efficiency levels for this technology would most probably stay the same because the 95% efficiency is the maximum limit for the technology.

Biological methanation is carried out at comparatively low temperatures (30–70°) and pressures. The conversion of hydrogen and carbon dioxide is done by microorganisms. The system is more dynamic, i.e. a quite fast start-up and shut-down is possible. Biological methanation is at about TRL 7. It is currently being tested at pilot and demonstration scale. Efficiency of the system reaches up to 80%. Due to the low rate of methane conversion, higher numbers of reactors (or big volumes of reactors) are needed, causing a limited suitability for large scale applications [44] [45]. Since the biological methanation system is not commercially available yet, the specific investment costs are estimated in the range of 600 €/kW for a plant with a rated power of 5 MW SNG output [37]. In future, an increase in the efficiency is not expected because 80% is the limit for the technology. Furthermore, the investment cost could decrease until 120 €/kW by 2050 [37]. Since biological methanation is in its development stage and not fully commercial yet, it promises higher development than the catalytic methanation.

Each of the two methanation technologies comes with a specific profile and should be employed according to the best use of its respective strengths: in cases requiring high capacity and less system flexibility, catalytic methanation is the technology of choice. In applications relying on fast response times and dynamic operation – e.g. for securing grid stability – biological methanation serves the best results. In addition, both systems can be used depending on the need in the sector coupling applications.

5.3 Summarised information about the CAPEX and efficiency values for core technology fields

Figure 10 and Figure 11 show that both main components of the power-to-gas technology, electrolyser and methanation systems, display promising cost reduction results related to technological learning (cost reductions through an increase of the production volume) as well as scaling effects (cost reductions in consequence of an increase in size in form of upscaling). The produced volume of power-to-gas plants and therefore the gained experience (technological learning) will depend on the development of the future global demand for power-to-gas products, which is subject to climate and policy measures (e.g. carbon taxes, the scope of government R&D, subsidies, and market introduction programs) and economic factors (e.g. economic growth).

State of the art applications of AEC and PEMEC systems already range at multiple-megawatt installations, and economies of scale already today represent a valuable factor for investment decisions. The SOEC technology is expected to catch up with this development in the intermediate future, especially regarding increased electrical efficiencies (up to 97%) by integrating derived heat or thermal coupling to exothermal processes like chemical methanation.

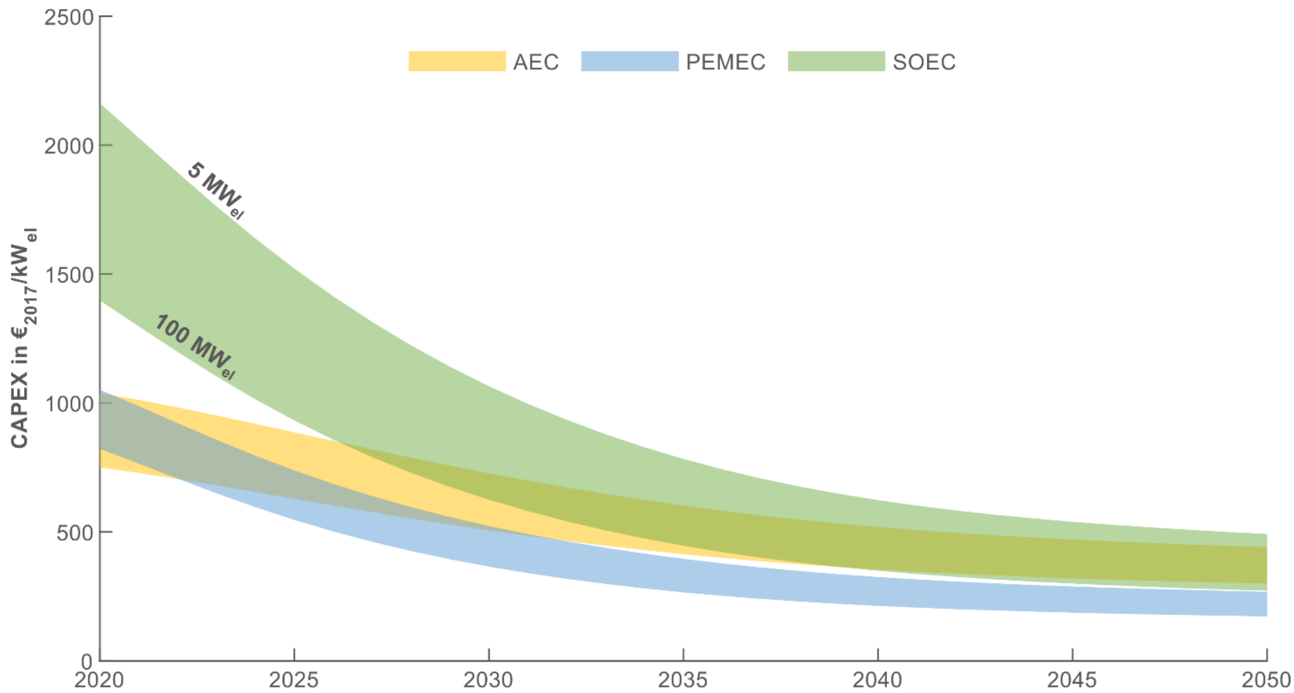

Figure 10: Cost development of electrolysis systems related to scaling effects and technological learning

In contrast, methanation systems are not expected to make great leaps in efficiency. However, other important characteristics such as load flexibility and stand-by behaviour will be improved by further development. Furthermore, significant cost reductions can be expected based on learning curve effects.

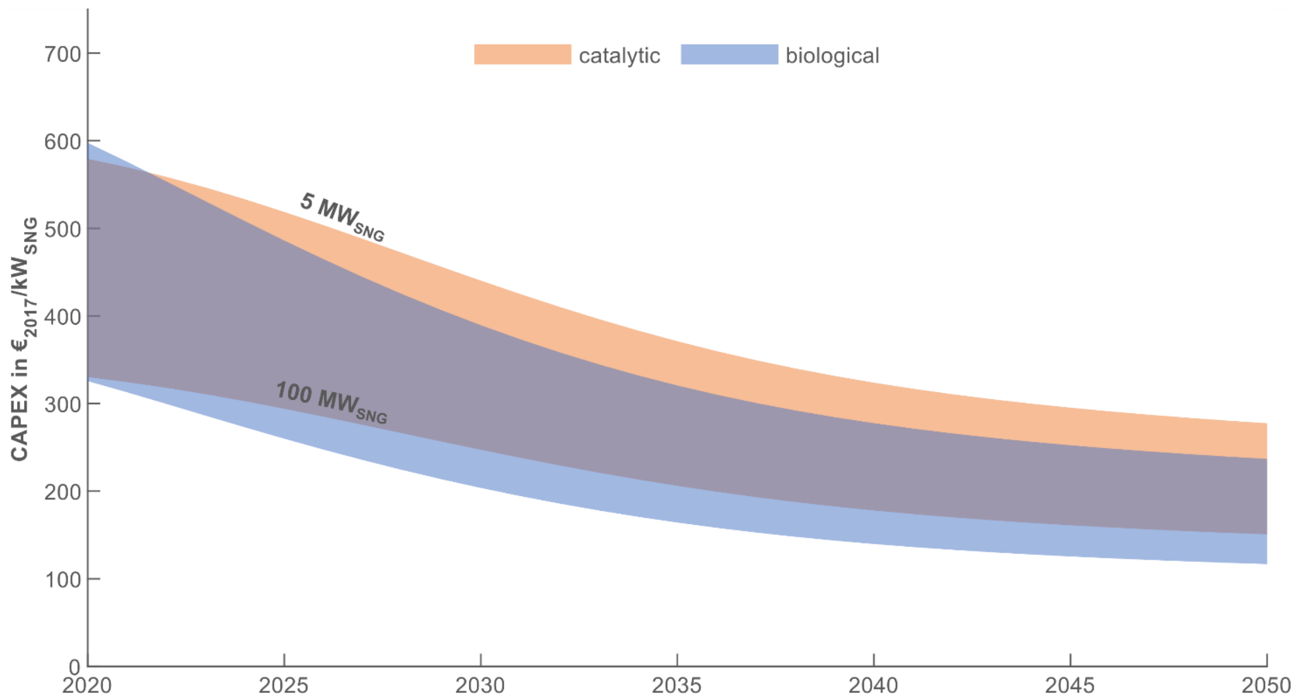

Figure 11: Cost development of methanation systems related to scaling effects and technological learning

Table 1 gives a short summary of what was explained in the previous two sections; CAPEX and efficiency values for electrolysers and methanation reactors for 2017 and 2050.

Table 1: Summarised information about CAPEX and efficiency values for core technology fields (based on [37] [38] [39] [46])

Core Technologies		CAPEX €/kW		Total efficiency (%)		TRL
		2020[13]	**2050**[14]	**2017**	**2050**	**2017**
Electrolyser	AEC	1040	300	76	81	9
	PEMEC	1050	170	73	81	8
	SOEC	2160	270	93	97	6
Methanation Reactor	Catalytic	580	125	80–95	max. 95	8
	Biological	600	120	80	max. 80	7

Alongside with existing technologies, further research on the material side could result in significant reductions in hydrogen production costs due to increased efficiency, decreased CAPEX, and reduced sensitivity to impurities in feed water. Furthermore, new water electrolysis concepts, like membrane-less cells and plasma electrolysis, will provide low-cost alternatives.

5.4 Auxiliary technologies and specific options

5.4.1 Carbon capture

Besides hydrogen, carbon dioxide is the second necessary feedstock to produce green methane or SNG. It comes mainly from three different sources: CO_2 capture from industrial applications, from renewable sources such as biogas or sewage plants, or captured directly from the air.

Carbon capture from the industry shows a TRL between 7 and 9 [47]. Defining the cost precisely is challenging as it highly depends on the concentration of the CO_2 in the source stream. Thus, CO_2 from ammonia production is less expensive than from a natural-gas-operated power plant. Cost values from research literature for a ton of CO_2 vary between 12 €/ton and 101 €/ton [38].

Carbon dioxide from biogenic sources is a well-developed carbon capture technology with a TRL of 9 [47]. The cost for the technology ranges between 0 €/ton (as by-product of a biogas plant) and 111 €/ton CO_2 [38]. For both carbon capture from industry as well as from biogenic sources, costs are closely related to the plant size and decrease with increasing plant size.

Direct air capture (DAC) is the most expensive carbon capture technology due to the low CO_2 concentration in the air and due to the maturity level of the technology (TRL 7–9) [47]. The costs for this technology lie between 80 €/ton and 475 €/ton according to D7.5 [38]. Theoretically, the amount of heat derived from the methanation process is sufficient to cover the energy demand of direct air capture. The methanation process releases heat (exothermic chemical reaction), and adsorption-based direct air capture processes require heat at moderate temperatures in order to regenerate the sorbent and release the CO_2 [44].

5.4.2 Liquefied Natural Gas (LNG)

Liquefied natural gas (LNG) is the liquid form of natural gas, which is obtained by cooling the gas to around -162 °C. Natural gas occupies 600 times less volume in its liquid form than at atmospheric

[13] system size: electrolyser 5 MW input power; methanation 5 MW of SNG output
[14] system size: electrolyser 100 MW input power; methanation 100 MW of SNG output

pressure; thus it can be transported easily in specially designed thermally insulated vessels via ship, truck or train. That is the reason why liquefying natural gas is preferred in cases where constructing a natural gas pipeline is not possible or economically not feasible. Alternatively, LNG can be used in maritime transport and in heavy duty trucks because of its smaller volume compared to its gaseous state, or it can be stored in LNG hubs and used for peak shaving [48]. The liquefaction technology is commercial. The specific energy consumption is in the range of 0,4 to 1,5 kWh/kg of LNG. There is no need for further development of the large-scale liquefaction process. For small-scale liquefaction, the same technology as for large-scale can be applied, however, the cost should be further improved [49].

LNG infrastructure is already quite developed and the technology for storing LNG in hubs and terminals has been already in use. It can be used for liquefied renewable gas (LRG) without further changes. Terminals are located near the sea/ocean/river and hubs are used for the intermediate storage and reloading.

5.5 Resulting potential development for green SNG from power-to-gas

An ecologically sustainable energy supply that is economically viable and socially acceptable is a high priority in European policy. The use of green gases on the basis of renewable electrical energy (as hydrogen, synthetic methane, or other hydrocarbons) has numerous advantages, which can significantly assist Europe in transitioning its energy system. Therefore, since the market launch and development of the PtG technology depend on the profitability of the plant, among other things, the expectations of SNG production costs and potential cost reductions are discussed.

The economic evaluation was undertaken based on the calculation of the specific production costs for SNG in 2020, 2030, and 2050 for a power-to-gas plant with 100 MW electrical input. Three different fields of application were considered a) a PtG plant powered by a photovoltaic power plant (PtG-PV); b) a PtG plant powered by a wind farm (PtG-Wind); and c) a PtG plant powered by the public grid (PtG-Grid). Different PtG technologies are analysed, which are combinations of an AEC, PEMEC, and SOEC, with a catalytic or biological methanation unit.

Figure 12 below summarises the results of all the calculations performed, providing a range of costs for each use case.

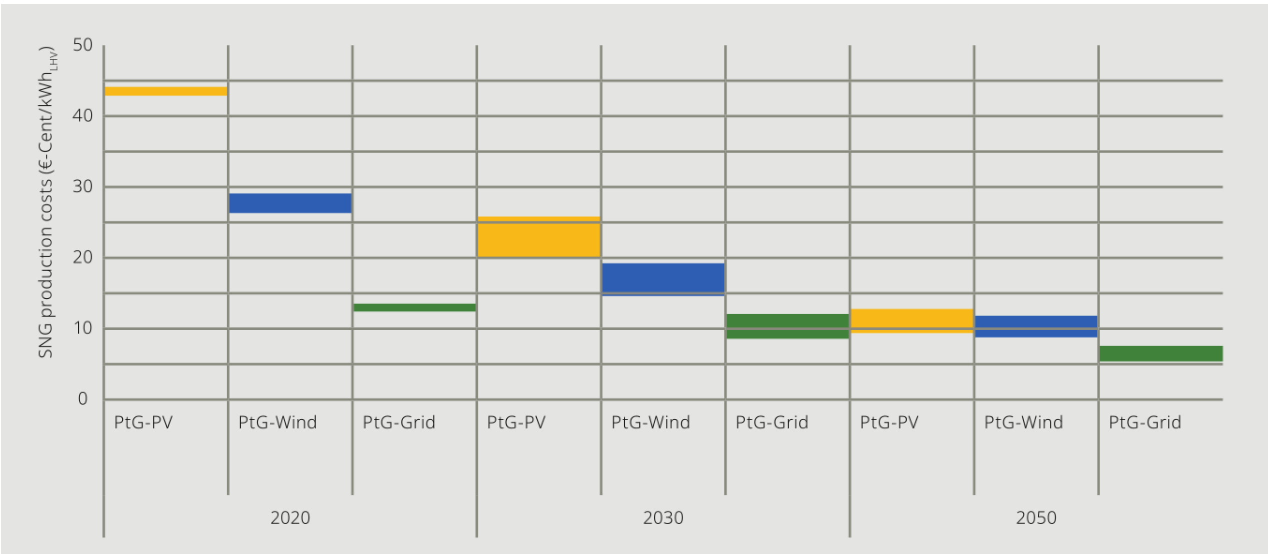

Figure 12: Range of SNG production costs of a 100 MW plant in 2020, 2030 and 2050 for different scenarios.

The variety among the costs is due to the different technologies used for SNG production. In early applications (i.e., 2020 and 2030), the sole use of surplus, electricity from PV or wind does not provide acceptable SNG production costs, due to the still relatively high investment costs and the low achievable full load hours of the plant. In the PtG-Grid operating mode, the power-to-gas plant is connected to the public electricity grid and operates at times with the cheapest electricity prices on the spot market. In early applications, power-to-gas plants will need to run at high full-load hours (> 4000 h/a) to achieve low SNG production costs. In future, the lowest costs will be achieved with a lower number of full-load hours (3000 h/a) when the plant is operated only during periods with the lowest electricity prices. However, several factors, such as the need to produce green gas, may argue for higher full-load hours, albeit with higher SNG costs [37].

In general, there is little difference in SNG production costs with regard to the technology used, whereby future power-to-gas plants with an alkaline electrolyser will have slightly higher SNG production costs than those with a PEM electrolyser, and a power-to-gas plant built with an SOEC and catalytic methanation will tend to have slightly lower SNG production costs. Concerning the methanation technology used there is hardly any difference in the SNG production costs. The lower SNG production costs of the power-to-gas plant with an SOEC and catalytic methanation unit can be attributed to higher system efficiency. However, to achieve these very high efficiencies, the SOEC requires an additional waste heat source, which is not available at every location. By contrast, it is assumed that waste heat can be sold in the variants where an AEC or PEMEC is connected to a catalytic or biological methanation unit. If waste heat cannot be sold, then the SNG costs would rise in these variants. Thus, the SOEC variant would have the lowest SNG costs by far [37].

A power-to-gas plant can be used in a variety of ways in the energy system. In most of the cases, the fundamental goal is the production of renewable gas. It may be reasonable (while taking the market situation for renewable gases into account) to not operate the plant with about 3000 full-load hours in order to achieve the lowest SNG production costs but, rather, to increase the output of the power-to-gas plant by increasing the full-load hours, although this would lead to higher SNG production costs. However, as mentioned, excessively high full-load hours (> 5000 h/a) leads to significantly higher SNG costs. Incidentally, in a renewable energy-based energy system with a large share of fluctuating energy sources, the power-to-gas plant should be operated in such a way as to ensure that the power grid is not additionally charged but is best supported. This can be done, for example, by converting the surpluses from wind and PV produced in summer into SNG and transferring them into the winter months (i.e., long-term storage, sector coupling). Since power generation bottlenecks are likely in the winter months (less electricity production form PV), leading to higher electricity prices, the power-to-gas plant should not be operated at these times. Thus, a continuous operation (full-load hours > 6000 h/a) of the power-to-gas plant is not desirable. The full-load hours for reasonable power-to-gas plant operation (gas production, SNG production costs and grid suitability) are regarded to be in the range of 3000 to 5000, incurring costs of about 5,5 to 7,5 Cent/kWh in 2050 in an optimal case [37].

The sensitivity analysis indicates that reducing the production costs for SNG requires purchasing low-cost electricity, maximising plant efficiency, reducing investment costs, and in cases where the plant is connected to a photovoltaic plant (PV) or wind park, building the PV or wind park in viable locations with high full-load hours [37].

However, the development of power-to-gas technology is subject to fundamental energy and climate policy decisions; thus, assumptions made about the future can change significantly. This has a major impact on the future SNG production costs calculated in this report [37].

5.6 Alignment of potential technology development with the energy picture in the EU by 2050

Taking the global perspective on the role of green molecules in the future energy mix highlights the opportunities for Europe to take a pioneer role in the power-to-gas technology [38]. The potential future investment cost reduction of the main components of the power-to-gas technology, electrolysis and methanation, must be seen globally due to learning curve effects (technological learning). Based on the green gas demand stated in the energy picture of the EU by 2050, a global green gas demand is assumed to be ten times higher than the European green gas demand. However, this implies that the future global energy system (especially the share of green gas demand) will behave similarly to the energy picture of the EU by 2050 presented in chapter 4.

As a consequence, technology for greening energy molecules will also find significant market opportunities outside of Europe. The future investment cost reduction for the main components of power-to-gas technology (electrolysis and methanation) is additionally illustrated when considering the global perspective, e.g. in the case of catalytic methanation: For 2020, CAPEX for catalytic methanation systems is around 600 €/kW. A perspective based on European developments alone shows a reduction of about 70% by 2050. Including the worldwide perspective for all positive effects on cost reduction, the 2050 scenario shows a reduction of around 82% for catalytic methanation. Positive effects on costs due to learning curve effects (technological learning) show an impact of additional 10%.

Thus, the main impact on cost reduction for power-to-gas technology lies within the European perspective, with additional benefits coming from global effects. At the same time, the worldwide market opportunities for Europe as a technological pioneer seem very favourable and exceed the chances of a perspective limited to Europe alone. This context highlights the significance of the EU's decision concerning its policies towards power-to-gas.

5.7 Conclusion and discussion on chapter five

Operating power-to-gas in conjunction with innovative technologies and processes is one of the achievements of the STORE&GO project. With its three demonstration plants in three different European countries, the project has shown the technological maturity of power-to-gas. The technologies have achieved a high level of technology readiness for the market and an ongoing rapid development. Furthermore, a full range of technologies is available allowing to choose the best suitable configuration for a specific power-to-gas plant (large/small, alternating/continual production). Research indicates a promising cost reduction potential related to scaling effects and technological learning in the range of 75–90% for electrolysers and 80% for methanation. Projections of efficiency development also show significant potential with figures of 80% efficiency and higher – even up to over 90%. In many use cases of today, the electrolyser presents the largest individual potentials of cost reduction. By scaling up the production of electrolysers, immediate and substantial cost reductions could be achieved. The last ten years show that certain components have outperformed the projected values. For methanation, two technologies are available with individual strengths, which can be chosen for the specific needs. The estimations of potential cost reductions and efficiency increases correspond to the future demands for power-to-gas according to "The energy picture of the EU by 2050". To tap the full potential of further technological developments, installed capacities have to increase.

From the technological point of view, power-to-gas can act as the key enabling technology for the energy transition. A detailed look into the state-of-the-art technology of its main components as well as the potential for further technological improvements clearly shows this.

6 Policy approaches for further implementation of power-to-gas

As shown in the previous chapter, power-to-gas is technology-wise ready to use. It has both the potential for significant cost reductions in the future, and to act as a key enabling technology for the energy transition. In this chapter, the needs on policy regulations are discussed. Studies done within the STORE&GO project to this matter were investigated and mirrored to national positions of project partners such as DVGW and SVGW/VSG. Finally, the demo site operators were interviewed regarding the completeness of measures and their priority. On this basis, the scientific roadmap team made their analysis, structured the input and made their conclusions, deemed necessary in order to enable the market uptake of power-to-gas.

6.1 Background and identification of the need for new regulation for power-to-gas

The market for power-to-gas is still in the early development stage. There are different R&D and pilot projects ongoing or being developed. As shown in chapter 4 “The energy picture of the EU by 2050”, the EU’s energy and climate ambitions ask for a fast-track solution to establish a mature market for power-to-gas. This requires a different policy approach within the EU and its member states. Implementing a strong power-to-gas (ready) policy framework is challenging, since the current market for “green” gases (e.g. biogas, biomethane, hydrogen, methanised hydrogen) is still under development (section 6.1.2), with market penetration rates for green gases remaining below a few percent of total annual production and consumption in different EU member states. On top of that, the technology currently finds itself in the so-called technology ‘valley-of-death’, where the type of support is not matching the required innovation acceleration and upscaling needs (section 6.1.1). In addition, there is a broad set of specific (cross-cutting) legal aspects within the various existing relevant legal / policy frameworks that can hinder further power-to-gas developments today and in the future (section 6.1.4). Despite all these challenges, power-to-gas provides a series of system services and/or externalities that enhance its relevance and value to the broader EU society (section 6.1.3).

6.1.1 The current situation of Power-to-gas in the innovation process

B. Merrifield (1995) introduced the notion of the Valley of Death in relation to the transfer of agricultural technologies to developing countries. Abraham, P. and Gundimeda, H. (2014) use the valley of death concept (illustrated in Figure 13) to explain the different barriers to the deployment at different stages of development of low carbon technologies (i.e. from laboratory to market). They state that “innovations which speedily cross the valley of death will have an easy deployment space”. However, bridging the valley of death is a challenging process, as the nature of the technology development risks and type and characteristics of the financial and policy support needs can differ significantly in each development stage [50] [51]. While the TRL of power-to-gas technology is rising, it starts to outgrow the realm of basic research. Public funding resources for research and innovation do no longer match the risk profile to satisfy the changing research and innovation needs for the technology. It is at this stage where the private sector has difficulties to mobilise sufficient capital. At this stage ‘Angel investors’ and venture capitalists are needed before the technology can become more mainstream and becomes ready for upscaling. This is particularly problematic for power-to-gas due to the relatively high capital intensity of the technology. This high CAPEX levels increase the (financial and technological) risk for first movers entering the competitive gas market at this early stage of technology development. This could lead investors to take a “wait and see” position. Without a strong incentive structure in place, bridging the valley of death might take too long and in the worst case could lead to a complete shutdown of the further development and market uptake of power-to-gas [52].

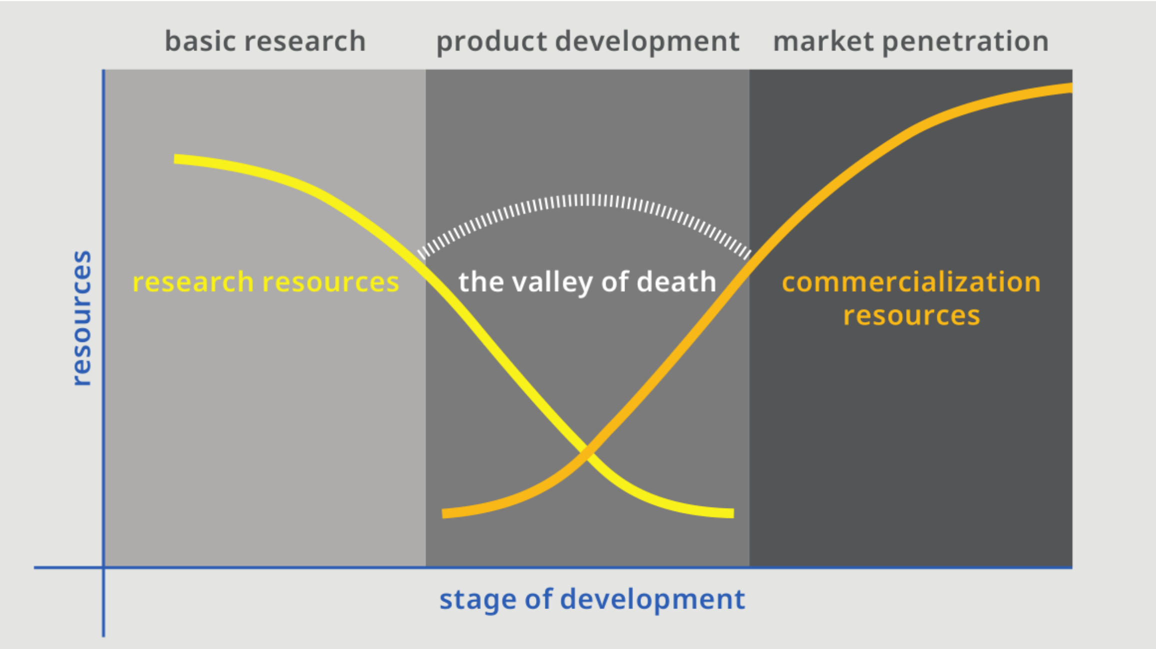

Figure 13: Illustration of the technology valley of death that needs to be bridged for power-to-gas to penetrate the market

To bridge the valley of death, it is clear that additional policy support for power-to-gas during the different development stages will be needed, so that the technology can contribute to meet the ambitious energy and climate goals within the EU. One of the key questions will therefore be, what policy framework is needed, and which policy approaches are available to bridge this gap.

6.1.2 Functioning market for green gases

After overcoming the valley of death, a properly functioning market for green gases both drives green gas supply and creates sufficient gas demand. While at the supply side there can be a range of financial support schemes (e.g. quota obligation schemes, network tariffication, feed-in tariffs, or Investment subsidies) to cover for the higher cost of production (relative to fossil), at the same time also adequate demand volumes are needed to ensure that green gases will be absorbed. Thus, from the supply side perspective, there is a need for ‘security of demand’, while at the demand side ‘security of supply’ is needed. For both sides an acceptable market equilibrium price is needed (i.e. one that is sufficiently stable and can compete with current prices). Especially in the coming decades, in which the energy system transition will take place, it will be a major governance challenge to manage both demand and supply. One way to manage an erratic market transition is by managing demand for green gases. There already is an extensive debate about which (sub)sectors should get access to the largest volumes of green gases first. Will the energy (and carbon) intensive industry be seen as the first ‘sink’ for green gases to fast track decarbonisation, as it limits the infrastructure costs? Or should it be used in mobility where often a premium price is paid to support early stage power-to-gas business cases? Given that (green) gases are versatile in terms of end-use application and can be used in industry, transport, as well as in the built environment at significant volumes, there is likely to be competition for the currently still limited green gas supplies. In order to avoid too extreme market (and price) volatility in an infant market and throughout the valley of death stage, there could be arguments to also manage the demand side in terms of demand volumes.

Within the current market regime in most EU member states, the incentive structures for green gases mainly target the supply side (e.g. feed-in tariffs, R&D/investment subsidies), while the measures at the demand side generally have a more voluntary character. Policies on the demand side can ensure that end-users in the different sectors will also start buying green gases at the right point in time. In between supply and demand side measures lies a broad spectrum of rules, regulations and policies that govern the transport, distribution and transactions of green gases.

6.1.3 Externalities of the power-to-gas technology

Especially in markets where there is underinvestment in a given technology, due to a low or negative net present value (NPV)[15], the existence of significant positive externalities of these technologies can help to argue for and drive policy change. The STORE&GO project has analysed externalities in greater detail in D8.8 [52]. Figure 14 provides an illustration of the different positive externalities that are associated with power-to-gas. Identified positive externalities from power-to-gas upscaling include climate, health and environmental benefits, as well as benefits for energy security. The figure shows that investing in power-to-gas under the current support regime will likely result in an unfavourable NPV for the (private) investor in the technology; while at the same time power-to-gas has broader socio-economic and system benefits [52].

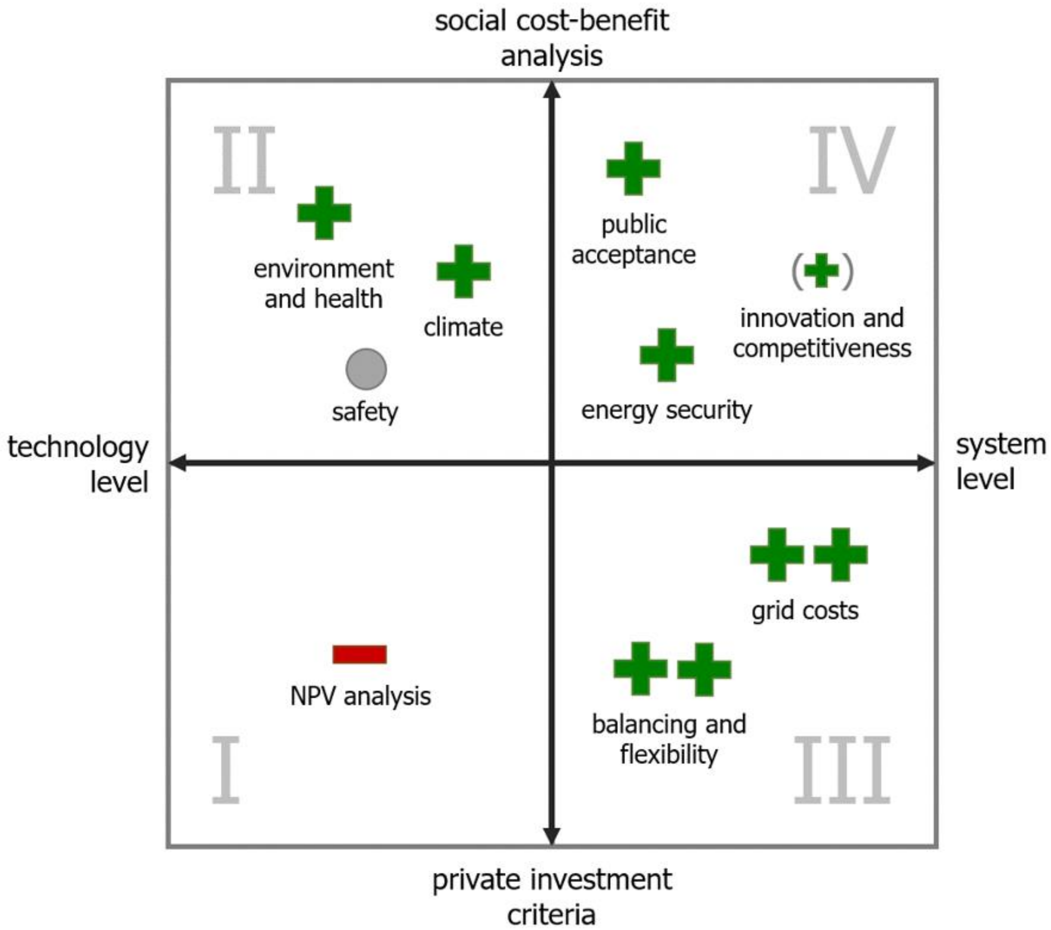

Figure 14: The four quadrants filled with key positive and negative effects of power-to-gas **[52]**

[15] For a more detailed discussion on the NPV of power-to-gas business cases, see Van Leeuwen, C. (2018). *Software of the stochastic net present value (NPV) model for a bottom-up assessment of the feasibility of investment in the power-to-gas conversion and storage technology (D8.4).* STORE&GO project.

For example, power-to-gas can lead to substantial cost savings by avoiding additional investments in the electricity grid expansion and reinforcements. These savings are on energy system level. It also can contribute with a positive external effect to energy system emissions (emissions to air, water and soil) and can have a positive effect on energy security. So far, these positive effects are not or only to certain small extents considered in the current legislative framework concerning power-to-gas [52].

6.1.4 Cross-cutting aspects hindering the way

By tackling the measures to overcome the valley of death, by the legal anchoring of regulations leading to a functioning market for green gases, and by taking steps to help to monetise the value added from power-to-gas to the energy system, the foundation for strengthening the development of the power-to-gas technology and for realizing the positive systemic effects of it has already been laid. However, even after the successful implementation of the aforementioned measures, there are still some cross-cutting regulation elements, such as a continuous support for R&D, a clarification of the position of SNG under the renewable energy directive, or harmonised gas quality standards in the EU. These help to cancel out specific hindering aspects, and ease a smooth implementation and should therefore not be neglected.

6.1.5 Overall transition situation for a power-to-gas market uptake

The four aspects mentioned in the previous four sections lead to the current status of the overall transition situation of power-to-gas, illustrated in Figure 15.

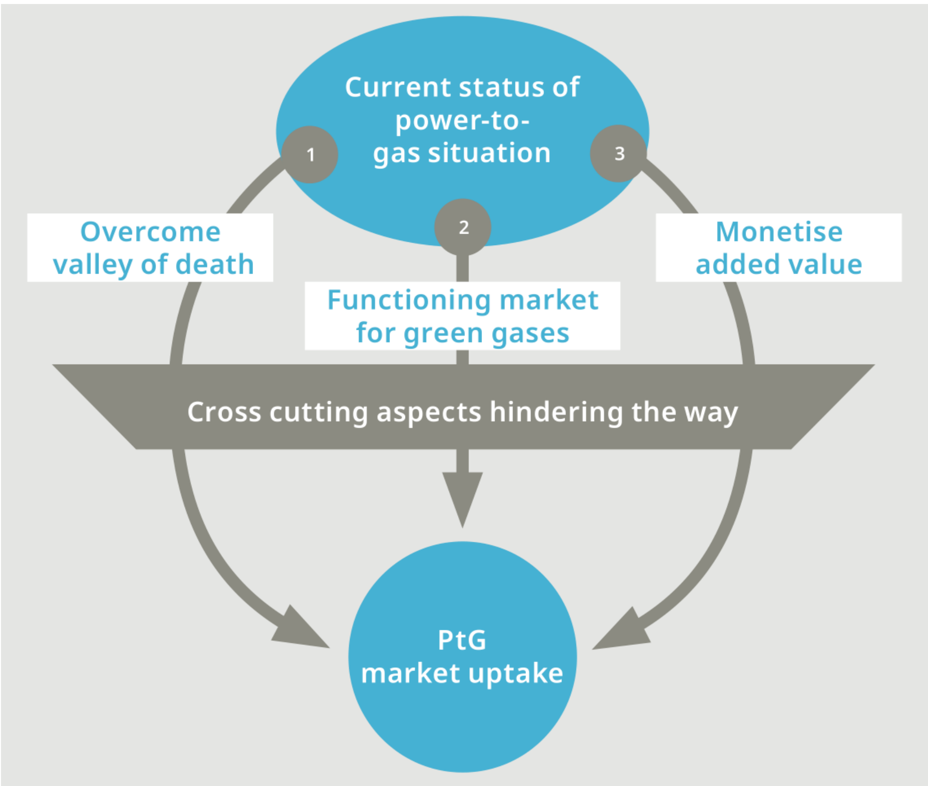

Figure 15: Three possible policy approaches for large-scale PtG deployment in the EU and the cross-cutting aspects to achieve an uptake of PtG in the market.

There are four barriers that need to be overcome, the first two being the valley of death and the establishment of a functioning market for green gases. In the bridging of the valley of death, the transition from basic research funding to a commercial market penetration needs to be accomplished. This transition is a time-limited process, and so are the measures that are needed to be taken. At the same time, there needs to be a functioning market for green gases established to provide incentives for investors already during the product development stage, and also to assure that there are fair market conditions once the measures for overcoming the valley of death are phased out. If this is not done, there is no real market to penetrate, and thus bridging the valley measures would have to extend eternally. Economically this would not be desirable, and thus the market conditions are key to minimise the overall cost for governments to implement power-to-gas and decarbonise the molecule part of the energy sector. The third barrier is the internalisation of the current positive externalities of the power-to-gas technology, since the introduction of power-to-gas to the energy system brings benefits beyond the core application of producing green gas. This should be reflected accordingly in incentives for the investors and operators. Finally, there are different cross-cutting individual issues that are hindering a power-to-gas market uptake. In the following four sub-chapters, specific measures and policy recommendations to each of these barriers are presented, and their contribution on how they help to overcome the respective barrier is shown.

6.2 Measures to overcome the valley of death

What are possible regulation elements that help power-to-gas to overcome the valley of death? In this chapter, the measures will be introduced, and it will be shown how they can contribute to bridge the gap between basic research and market commercialisation. These measures are of a more time-limited character, since their aim is to overcome the valley of death, but are not economically desirable to sustain on a long time period from a governmental point of view.

6.2.1 Investment subsidy

Investment funding provides governmental or private capital for investment purposes. There are different types of capital sources, such as angel investment funding, venture capital investment funding and government investment funding. In the following, the focus is set to the governmental investment funding, which in turn would be a form of subsidy. Investment subsidy can target the development of a specific technology, i.e. power-to-gas, but depending on the TRL and the innovation phase, i.e. basic research phase, product development phase, market penetration phase (see Figure 13), the character of the funding can vary. In the following, investment subsidy concerning overcoming the valley of death – linking the basic research stage and the product development stage – will be discussed.

According to the knowledge gained from the project (analysis and construction of the demonstration plants) and the opinion of the experts involved, the financial aspects (currently no economic competitiveness of the overall power-to-gas system) represent a greater challenge than the solution to technological and technical challenges. Especially in early (<2025) applications with low full-load hours (solely use of wind or PV power), the hydrogen and SNG production costs are dominated by the share of the investment costs. Investment subsidies would lead to a reduction of CAPEX, which would then reduce the production costs of hydrogen and SNG.

On the basis of the European regulations, an investment subsidy in the sense of a funding of environmental-related expenditure is particularly suitable. The investment subsidy thereby reduces the negative market distortion of external effects like carbon dioxide emissions – which are not internalised without regulation mechanism. Investment subsidies are a tried and tested policy instrument to provide support to specific technologies.

Within the EU, the EU ETS could serve as a mechanism to generate funds for PtG activities. Under the current EU ETS regime, however, power-to-gas plants are not able to monetize any CO_2 savings. This is because PtG plants do not typically fall under the scope of the EU ETS. Nevertheless, the EU ETS can be used to generate funds to support PtG investments, similar as has been done through the NER300 program [52].

For the NER 300, Commission Decision 2010/670/EU governs *"the monetisation of the allowances referred to in Directive 2003/87/EC for the support of CCS and RES demonstration projects, and the management of the related revenues."* For the NER300, 300 million EU emission allowances from the new entrants reserve were used to generate funds. The NER300 comprised a 2 bln. EUR funding programme for a range of CCS and RES technologies, and with that provides a meaningful reference policy structure for supporting large-scale PtG demonstration projects [52].

The 2018 EU ETS Phase IV (2021 – 2030) revision[16] includes an Innovation Fund that basically is an extension of the NER300 scheme[17]. The Fund uses revenues from auctioning 450 million allowances for funding innovative projects in the 2020–2030 period. At current EUA market prices, this fund could be over 10 billion EUR. The first call for project proposals for this fund is expected to be opened 2020, and also targets *"Large scale demonstration of renewable hydrogen production and its use for energy storage (e.g. electrolysis of water coupled with hydrogen storage systems)"* [52].

The Innovation Fund has a number of selection criteria which a project has to meet in order to obtain funding:

- effectiveness of greenhouse gas emissions avoidance,
- degree of innovation,
- project viability and maturity,
- scalability,
- cost efficiency (cost per unit of performance)

The guiding principles and manner in which these criteria will be applied is stipulated in Commission Delegated Regulation C(2019) 1492 final that was published on 26-02-2019.[18] Within this regulation it is stated that: *The […] support should depend on verified avoidance of greenhouse gas emissions", and that "[s]ubstantial underperformance on planned greenhouse gas emission avoidance should […] lead to the reduction and recovery of the amount of the support […]"* [52].

This suggests that a PtG project proposal for this Fund also has to include a calculation of the expected GHG emissions savings. However, the delegated regulation is not clear on which GHG accounting method should be applied. It is considered that ideally a cradle to grave LCA-based approach and protocol to estimate and verify the avoidance of GHG emission reductions is most likely to be used in this framework. During a workshop organised by Hydrogen Europe in the framework of the Innovation Fund on 30 September 2019[19], most respondents from a survey indicated that LCA will play a decisive and key role in calculating and verifying the GHG avoidance potential. However, the exact methodological LCA-approach is yet to be determined (e.g. system boundary, reference / baseline selection, consideration of non-climate trade-off impacts), which adds to the regulatory uncertainty especially in regard to RED2. With several sectors (e.g. hydrogen, fertilizers and refineries) referring extensively to (green or blue) hydrogen as a promising technology pathway a lot can depend on the exact LCA method and rules that will be applied. The LCA studies from the STORE&GO project [53], [54], [55] can serve as valid input for developing a robust GHG accounting methodology for PtG within the Innovation Fund [52].

The proposed instruments aim at the reduction of the investment costs of the power-to-gas technology, and thus help to create further development by supporting with covering the high CAPEX. As

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[16] See: https://ec.europa.eu/clima/policies/ets/revision_en
[17] See: https://ec.europa.eu/clima/policies/innovation-fund/ner300_en
[18] See: https://ec.europa.eu/clima/sites/clima/files/innovation-fund/c_2019_1492_en.pdf
[19] For more information, see: https://ec.europa.eu/clima/policies/innovation-fund_en#tab-0-2

CAPEX will decline in line with the technology progress as shown in chapter 5, this tool is deemed especially fit to help to overcome the valley of death.

6.2.2 Regulatory sandboxes and expenditures for R&D

The promotion for research and development is seen as a central field of action for assuring the economic and energy efficiency targets of power-to-gas based on learning curves and production improvements. The focus is not only on research into technical and technological aspects, but also on the connection with the energy economy and the requirements of the respective market situation (e.g. regulation effects). Support for R&D is relevant to all stages of development, and thus a typical and important cross-cutting measure (see further in 6.5.1). However, some types of support are viewed as especially helpful to overcome a valley of death situation.

A regulatory sandbox, for example, enables people/companies to operate their new business models temporally and spatially limited, without already being subject to all legal precautions and having to comply with them [56]. This allows the addressees of the sandbox to test its models, products, processes, techniques etc. The aim of a regulatory sandbox is to test the necessity of a legal change, and implement it if this is the case, or to include an existing project-related exception as a rule beyond the project [57]. Therefore, in order to foster experimentation, and support emerging innovative energy technologies such as power-to-gas, regulatory sandboxes should be established. Regulatory sandboxes are of crucial importance for power-to-gas in particular, as this technology is not only used in a single sector or area, but also links them (gas producer, electricity consumer, electricity supplier, network stabilisation). Further, sandboxes are minimizing the risks for the energy sector, because the technology is tested and introduced at first in specific regions for a limited duration. By reducing the risk of the investment, this instrument supports the bridging of the valley of death.

6.2.3 Feed in tariff for green gas

According to Article 4(1) Renewable Energy Directive 2018 (hereafter RED II), Member States may apply support schemes in order to meet or exceed the Union target for the use of renewable energy set out in the Directive[20] and their respective national contribution to that target.

Article 2(5) RED II defines support schemes as “any instrument, scheme or mechanism applied by a Member State, or a group of Member States, that promotes the use of energy from renewable sources by reducing the cost of that energy, increasing the price at which it can be sold, or increasing, by means of a renewable energy obligation or otherwise, the volume of such energy purchased, including but not restricted to, investment aid, tax exemptions or reductions, tax refunds, renewable energy obligation support schemes including those using green certificates, and direct price support schemes including feed-in tariffs and sliding or fixed premium payments”.

All Support schemes need to be compatible with the European rules on state aid. Feed-in tariffs or premium payments are possible instruments under the regime of the cited rules. They can be structured in such a way that the plant operators receive either a fixed tariff for a certain period of time, or a premium on top of the gas price obtained [58].

Experience with fixed feed-in tariffs in the electricity market has shown that such guaranteed returns are considered to distort market prices, as analysed in detail in STORE&GO D7.2 [58]. As a result, since 2016 these tariffs are no longer allowed. The German EEG-Umlage has been a surcharge on the consumer’s energy bill, which could have been raised to balance an increase in subsidies. Steep raises such as from 2012 to 2014 threatened to diminish the public support. Still the success in the

[20] Article 3(1) RED II.

early stage of the market uptake of electric renewable energy production via the e.g. German EEG is evident [58] [59].

The alternative to fixed feed-in tariffs are market premium schemes. A possible model could be that the energy is sold directly to the market, and the difference between the market price and a technology-specific set price is received on top of that. The current scheme in Germany for electricity generated from storage gas is similar to the one generated by a windfarm, which may have produced the electricity to produce the storage gas. D7.3 puts it as follows: “In other words, electricity generated from storage gas of which the electricity source is a wind farm, receives the same amount of support as electricity generated by that windfarm” [59]. Thus follows that the costs involved for the storage process are not considered in the market premium for electricity generation after storage, and the benefits of storage are not internalised. A flexibility premium already exists for the generation of electricity from biogas, which has the aim to increase renewable electricity production from programmable installations in times of high demand. Providing energy storage and flexibility is a balancing service to the grid, and in combination with a CHP plant can also contribute to the programmability of electricity from renewable sources, and thus a similar flexibility premium would be appropriate [59].

If the premium would be sufficient to render the business case of power-to-gas positive, this would be an important lever for integration of green gases (incl. power-to-gas) into the market and thus overcome the valley of death.

6.3 The creation of a functioning market for green gases

What are possible regulation elements that help to create a functioning market for green gases? In this chapter, the proposed measures will be introduced, and it will be shown how they can contribute in the establishment of a separate green gas market.

6.3.1 Quota obligation for renewable gas

A quota obligation entails that a supplier of gases also has a certain share of gas from renewable origin in its supply portfolio. As such, this system would affect all suppliers of both renewable and non-renewable gases within the EU. Such a system – similar to the one in the transport sector through the EU Biofuels Directive (2003/30/EC) – could also be introduced for the gas sector. The conventional approach could be that a certain percentage of renewable gases[21] as part of the total gas supplies has to be supplied to end-users (e.g. starting with a share of 5% of renewable gases supplied to market by 2025 and 10% by 2030) and gradually increase over time. An alternative to this is to introduce an obligation for gas suppliers to meet a certain GHG emission performance for their gas supply portfolio (e.g. max. 15 g CO_2-eq. of life cycle emissions per average unit of gas supplied to market) [52].

To enable both policy pathway varieties, a regime for transparent monitoring, accounting, certification and transfer of renewable energy quota (both for physical and administrative blending) and/or greenhouse gas emissions is needed. Both alternatives imply a more market-based approach where certificates/guarantees, permits or allowances are traded to stimulate production and supply of a ‘green’ (or ‘blue’) product relative to an existing ‘grey’ (or fossil) alternative. For the portfolio blending obligation this can be based on the existing system of Guarantees of Origin (GoO) for renewable gases that allows both physical as well as administrative admixing. Here, a robust system and registry for GoO’s for renewable gases is needed at the EU level (for details see chapter 6.3.3). A central

[21] The term „renewable gas“ here denotes any type of non-fossil gases, such as biogas, biomethane, hydrogen from PtG, or methane from PtG (i. e. SNG).

registry for (renewable) gases, like the European Renewable Gas Registry (ERGaR[22]), also would have to be linked with the EU registry and GoO system for renewable electricity. This is in order to avoid any double-counting, since most PtG plants will eventually run on renewable electricity. In addition, in the event that PtG plants will make use of renewable carbon from biomass-to-energy plants (e.g. captured from biogas or biomethane plants) as a feedstock for methanation, there might be a need to also ensure that certain minimum sustainability criteria (as stipulated in the e.g. Revised Renewable Energy Directive (EU) 2018/2001) are met [52].

For the portfolio GHG emission performance standard, the policy design has some specific challenges as well. If it is assumed that for GHG accounting the entire PtG value chain needs to be covered (i.e. a life cycle approach), there might be some issues in terms of GHG accounting and compliance as part of the supply chain of renewable gases, and H_2 suppliers will fall under the EU ETS regime. Considering that ETS GHG accounting does not cover indirect emissions[23] of fossil gases production processes, there will be a need to extend the current EU ETS monitoring regime so that full life cycle emissions for all (fossil and renewable) gases are accounted for by existing ETS operators and new entrants[24] [52].

While applying a life-cycle based approach for GHG monitoring and reporting both for renewable and fossil gases should be feasible, there are different policy design choices with respect to GHG emission compliance. For compliance purposes, a fossil gas supplier could buy renewable or low-GHG footprint renewable gases to meet its portfolio performance. Alternatively, since the fossil gas supplier is likely to fall under the EU ETS regime, the ETS operator could in principal also be allowed to 'compensate' its surplus GHG emissions by buying additional EU allowances (EUAs). In addition, producers and suppliers of fossil gases could also be given the opportunity to compensate (or offset) their own surplus life cycle GHG emissions by purchasing non-EU ETS offset credits through the voluntary market. The latter refers back to the EU Linking Directive (Directive 2004/101/EC) that allowed EU ETS operators to use offset credits (e.g. CERs and ERUs) from project activities for compliance under the EU ETS regime. Here it is positive to note that the interest in non-EU ETS carbon offset schemes in the EU is growing in recent years (e.g. Puro, Finland[25]; Label Bas Carbone, France; Peatland Code, United Kingdom[26]; MoorFutures, Germany[27], and the Green Deal National Carbon market, in the Netherlands[28]). Such schemes could become net suppliers of offset credits [52].

One possible drawback of a market-based approach – relative to a direct investment subsidy – is that the price of the tradable certificate or emission allowance can fluctuate in line with market developments. This price uncertainty makes it more challenging to develop a robust business case for power-to-gas. Although the ETS market is relatively mature and liquid, the EU markets for non ETS offset credits as well as for guarantees of origin for renewable gases are still in its infancy stage. In addition, a choice has to be made what the scope and coverage of this quota obligation scheme will be. Will it only target captive production and supply of renewable gases? Or will it also cover non-captive capacity? While natural gas and biomethane (upgraded biogas) are generally produced and

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[22] http://www.ergar.org/
[23] Note: only some categories of indirect emissions (e.g. in relation to electricity use) are covered under the EU ETS GHG accounting and allocation regime.
[24] This might also require an alternative view on the benchmarking approach for fossil and renewable gases under the EU ETS, e.g. as stipulated in the Sector specific Guidance Document n°9 on the harmonised free allocation methodology for the EU-ETS post 2020 (link)
[25] https://puro.earth/#section-challenge
[26] http://www.iucn-uk-peatlandprogramme.org/peatland-code
[27] https://www.moorfutures.de/
[28] https://nationaleco2markt.nl/

sold under open market conditions (i.e. via the public grid), the bulk of renewable gas use in the EU is supplied to industry via captive production capacity [52].

Both alternatives have the aim that suppliers have to have a certain share of gas from renewable origin in its supply portfolio. This directly supports the creation of a market for renewable gases. In view of a NET zero economy, these quotas could be scaled to achieve full market penetration and climate neutrality.

6.3.2 Financial penalty for CO_2

A financial penalty for emitting CO_2 can take the form of a CO_2 tax, or the form of a market-based cap-and-trade scheme, like the EU ETS [60]. Both measures would have the aim to establish cost for emission of CO_2, and thus provide incentives for consumers to rather turn to renewable gases than fossil gases and thereby establish a market for renewable gas.

In the view of the project team, a market based approach seams favourable in line with the EU open market policy. But the EU ETS does not cover the transport and other sectors where CO_2 is emitted during the combustion of fossil fuels [61]. Currently, the EU ETS covers basically CO_2 from power and heat generation, energy-intensive industry sectors (including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals) and commercial aviation on the one hand. On the other hand, also N_2O from production of nitric, adipic and glyoxylic acids and glyoxal and perfluorocarbons from aluminium production, are also included. The financial penalty for emitting a unit CO_2 (or CO_2-equivalents) renders the greener alternative (i.e. green hydrogen or green gases) more competitive as producing the fossil or grey alternative would become more expensive [62]. However, under the EU ETS regime for the 2021–2030 period, still a large portion of the required emission allowances will be freely allocated[29] to the production of industrial gases (NACE-4; 20.11) under the carbon leakage regime.[30] This also includes the production of hydrogen and the production of gases based on fossil fuels, like natural gas and coal.[31]

Post 2030, most fossil gas production would then have to purchase most of their EU emission allowances (EUA, either via auctions or open market transactions). Only then the competitive position of green gases will improve. However, pre-2030 it can be anticipated that it is unlikely that the EU ETS price levels will be sufficient to bridge the cost price gap between green gases/hydrogen and grey gases/hydrogen. Assuming that one kg of grey hydrogen causes about 10 kg of CO_2-emissions, and with a cost price difference of EUR 1 to 2 per kg of hydrogen, the EUA price would have to rapidly climb up to levels of between 100–200 EUR per ton of CO_2 to ensure competitive parity. With most EUA price projections for the period up to 2030 remaining well below 45 EUR per ton [63], such structurally high prices seem unlikely unless the ETS regime is changed significantly.

A regulatory based approach in the form of a CO_2 tax or similar financial sanctions imposed by the government might be a further option and would provide the government more direct control over the height of the tax. If constructed accordingly, such an approach would provide less uncertainty for investors. But a tax also faces the same challenge as the cap-and-trade scheme: To reach the desired effect in market behaviour, a tax would need to be un-proportionally high. For this reason, it

[29] The share of freely allocated emission allowances will gradually decrease from 80% (in 2021) to 30% in 2030 of the benchmarked allowances.

[30] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/1146-Carbon-Leakage-List-2021-2030

[31] The production of synthesis gas belongs to NACE code 20.11 and the PRODCOM number of hydrogen is 20.11.11.50. There is no single PRODCOM number for carbon monoxide (20.11.12.90 is inorganic oxygen compounds of non metals) or synthesis gas.

seems questionable if this measure is likely to gain acceptance, or to be implemented in the first place at all.

6.3.3 Establishment of a robust system of guarantees of origin for renewable gases

A guarantee of origin is, according to Article 2(12) RED II, an electronic document which has the sole function of providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources.

So far, there is no obligation to issue guarantees of origin for renewable gases in any of the demo site countries. The establishment of a system of guarantees of origin on a national basis is necessary, especially in accordance with harmonised rules on the EU level for (cross-border) trade in gases from renewable sources.

With the help of guarantees of origin, imported gases can also be credited. This enables producers to produce where it is most cost-effective [64]. Implementing a robust, transparent and EU-wide system of GoO certification for green gases is therefore useful if one wants to make use of the existing gas transmission, distribution and storage infrastructure. A GoO certification system typically covers the technical aspects and requirements for injecting green gas into the grid (e.g. gas quality criteria, feedstocks used in production, etc.), and allows the (administrative) tracking and tracing of the green gas throughout the gas infrastructure. Such certification for gas injection can be more cost-effective than building dedicated green gas supply infrastructure for physical delivery to specific end-user groups.

Apart from enabling the administrative transfer of green gas from A to B, GoO certification systems are being used more and more as an administrative platform to which governments link their support instruments for renewable energy. For example, the Dutch GoOs for green gas indicate whether or not a feed-in subsidy has been received on a unit of green gas. The same GoO certification system is also used by fuel suppliers to show that a unit of green gas is (administratively) used in the transport system (e.g. in order to fulfil the renewable fuel quota obligation under the EU Biofuel Directive). The GoO certification system can also be used to avoid double counting and overstimulation, for example that GoOs on activities that received feed-in subsidy at the production stage are not counted as renewable transport fuel under the EU biofuels directive (i.e. avoid double subsidization). The GoO system for green gases (nowadays still mostly biogas/biomethane) is also linked to sustainability certification (e.g. the ISCC EU certification scheme). Such sustainability certification is needed in case the green gas is intended to be used in transport under the quota obligation scheme for biofuels in transport. Such (voluntary) sustainability certification schemes[32] cover a range of (minimum) sustainability criteria that have to be met, including the need to monitoring and report on life cycle GHG emissions. If and when larger volumes of green gas will be produced and supplied not only for transport and heating, but also to EU ETS companies, this life cycle GHG accounting could be aligned to the EU ETS GHG emission accounting system (so that the EU ETS scope will also cover more categories of indirect emissions).

While the RED stipulates that "a guarantee of origin can be transferred, independently of the energy to which it relates, from one holder to another." [65], a GoO system can thus also be used as a basic platform for a) enabling cross-border trade in green gases, b) avoiding overstimulation or double-subsidization, and c) facilitating the link to a range of support schemes (e.g. feed-in tariff, quota obligation scheme, EU ETS scheme). To avoid double counting at the EU level it is critical that the various EU GoO trade registries are properly linked and work according to the same rules and regulations regarding issuance, registration and redemption. Also the individual GoO certification

[32] https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/voluntary-schemes

schemes, which are generally implemented at the national level, need to be sufficiently harmonised in order not to distort or inhibit/restrict the administrative (cross-border) trade in green gases in the EU. Of course, the national GoO certification schemes should apply the same definitions of green gases (e.g. to also include green gases derived from power-to-gas plants), but also apply the same definition and interpretation of the concept of mass balancing. It is known that some GoO certification schemes only allow administrative trade in green gases to occur within a given gas network balancing zone, while other GoO certification schemes also allow for transfer between different gas balancing zones. It is clear that the former interpretation puts greater limits on the tradability of green gases in the EU than the latter.

6.4 Monetisation of value added from power-to-gas to the energy system

What are possible regulation elements that help to monetise the value added from power-to-gas to the energy system? In this chapter, measures concerning this will be introduced and it will be shown how they can contribute in internalising external costs of the power-to-gas technology.

6.4.1 Need to coordinate the specific provisions of the various sectors covered by power-to-gas

One of the major benefits of power-to-gas to the energy system as a whole is its ability to combine all major sectors such as heating, industry, mobility as well as the electricity sector. However, the rules are currently found in various provisions in the different sectors. It is often unclear how these are related to each other, and should therefore be clarified in a Directive/Regulation that represents the sectors in interaction.

This is especially burdening for a versatile technology such as power-to-gas where many different purposes can be pursued with one and the same facility – it can both be production of fuels for mobility, feedstock for industry, and at the same time provide flexibility services to the electricity system. Furthermore, in combination with the gas infrastructure, power-to-gas can provide energy storage and transport, and thus the combination of the electricity and gas sector can be viewed as the first piece in the value chain that needs attention. Although regulations largely exist for the respective sectors, it is very often unclear how these are to be assessed in combination. One example are the unbundling rules, which are defined in both the 2009 Gas Directive and the 2019 Electricity Directive. The 2009 Gas Directive prescribes that network system operators need to refrain from production and supply activities. The 2019 Electricity Directive provides a conditional ownership and operation of energy storage facilities by network system operators. As power-to-gas falls under the 2009 Gas Directive (as gas producer) and the 2019 Electricity Directive (as energy storage), ambiguities remain on how these ownership regimes align and to what extent power-to-gas is both an energy storage and production activity. A Directive/Regulation that would represent both sectors in interaction would provide clarity [58]. Concerning the demo site countries: The analysis of the legal situation in the demo site countries shows that a clearly delimited legal definition of storage in the electricity context is either absent (Germany and Switzerland) or is limited to power-to-power technologies (Italy).

It was also found that Germany, Italy, and Switzerland all lack national unbundling rules which explicitly address the ownership and operation of power-to-gas facilities by system operators. The consequence of power-to-gas being classified as gas production is, however, that transmission system operators in all three countries under assessment must refrain from operating such a facility. At the distribution level, only Swiss law would allow a distribution system operator to operate a power-to-gas facility, as Swiss unbundling rules at that level are less stringent than those in Germany and Italy. For these two countries, the EU rules prescribe that a distribution system operator has to be legally and functionally unbundled from (gas) production.

In all three countries the power-to-gas conversion is considered gas production. In Italy and Switzerland, also power-to-gas-to-power is considered electricity production. Whether this is the case in Germany is not clear. Achieving a unification and a clarification for power-to-gas as a sector-coupling technology supports the creation of a functioning market for green gases, since it provides more regulatory clarity and security to all market participants.

Without clarity on the question of how power-to-gas can be considered across all sectors, and a simplification of who is allowed to operate the facility, even though a combination of different purposes for power-to-gas is applied in one and the same facility, the system benefit of power-to-gas is hindered to unfold.

6.4.2 Reflecting externalities in electricity pricing for power-to-gas applications

The production costs of green gases change fundamentally if not only the direct costs but also the externalities are considered. For instance, power-to-gas systems contribute to the reduction of infrastructure expansion and to energy security. The prices and fees for electricity needed for power-to-gas applications should reflect this. The costs for natural gas have ranged between 1,3 €-cent/kWh and 3 €-cent/kWh in the last 12 months, depending on the situation on the world market [66]. In comparison, generation costs for green methane from power-to-gas could start at around 14 €-cent, according to calculations from the STORE&GO project, and decrease to around 6 €-cent by 2050 [37]. This gap must be closed or rather even inverted to create business cases for power-to-gas. An appropriate and effective legal framework that takes the mentioned positive effects into consideration is therefore crucial to monetise positive external effects of power-to-gas.

The total price of electricity consists of several components. Therefore, different options are possible in order to reflect externalities. One possible way to internalize the external effects are price reductions via network tariffs.

Network tariffs currently charge power-to-gas facilities twice: as consumer (L-charges) and producer connected to the network (G-charges). The 2019 Electricity Directive allows the European Commission to adopt specific guidelines for network tariffs for energy storage. This would provide a specific tariffication regime that recognises the contributions of energy storage, power-to-gas to decarbonisation and security of supply, in the same spirit as the recently adopted tariff regime for gas storage facilities [58].

Concerning the demo site countries: Currently Germany is the only one of the three demo site countries that provides an exemption from paying L-charges related to the purchase of electricity even when there is no reconversion to electricity (according to the predominant opinion). In Italy and Switzerland, the exemption of paying L-charges is limited to reconversion to electricity. There is no exemption for cross-sectoral storage technologies. For injecting gas into the network, in none of the three countries G-charges have to be paid. Although the exemption of paying L-charges in the power-to-power scenario is a good step towards promoting power-to-gas, the greatest potential is seen in the cross-sectoral use. Amongst other reasons, because PtG provides increased flexibility, since the energy can be made available and used in the form in which it is currently needed. Thus (especially considering the system services that power-to-gas can provide), Italy and Switzerland should consider to exempt power-to-gas from paying L-charges even when there is no reconversion to electricity [59].[33]

[33] Further information on the network charges that may affect power-to-gas in the respective demo site countries are outlined in Annex I.

6.5 Cross-cutting measures to cancel out hindering specific aspects and ease a smooth implementation

What are possible cross-cutting regulation elements that help to cancel out hindering specific aspects and ease a smooth implementation? In this chapter, the measures connected to this realm will be introduced, and it will be shown how they can contribute to a power-to-gas market uptake.

6.5.1 Support for continuous and further development of power-to-gas

To support the further development of PtG technologies and technology advancements, a continuous R&D and innovation program remains necessary to ensure enhanced performance of next generations of power-to-gas plants.

There is still a need for action with regard to analyses for optimum system integration (optimum integration of the power-to-gas technology concept into the energy system). Research and development must therefore be accelerated that focuses on the optimal integration of the system or the power-to-gas technology into the energy system or the national economy. In addition, there is a need for action to develop new forms of financing beyond the direct economic component, which includes the essential benefit of power-to-gas for the entire energy system and for the national economy. This integrates economic and legal research into the development of new forms of financing in order to implement further economic development.

Alongside with existing electrolyser technologies, the investigations in Deliverable D7.7 have shown that further research on the material side could result in significant reductions in hydrogen production costs due to increased efficiency, decreased CAPEX, and reduced sensitivity to impurities in feed water. Furthermore, new water electrolysis concepts, like membrane-less cells and plasma electrolysis, will provide low-cost alternatives [35].

6.5.2 Clarification of the position of SNG under the Renewable Energy Directive

Although the term “renewable liquid and gaseous transport fuels of non-biological origin” is used in the Renewable Energy Directive 2018, which may cover SNG, this only applies to transport. As SNG can also be used in other sectors such as heating/cooling or electricity production, this term should be expanded [58].

Concerning the demo site countries: The current gas legislation in Germany and Italy applies to SNG. Also the scope of the Federal Pipeline Ordinance in Switzerland seems to cover SNG as hydrocarbon. In Germany, SNG can be classified as biogas when at least 80% of the electricity fed into the electrolyser and the carbon used for methanation come from renewable sources. In Italy it can be classified as bio methane. However, conditions for electricity and carbon source are undefined. Clarification especially concerning the required source of the carbon would be helpful and necessary. In Switzerland, SNG is only defined as renewable gas under SVGW Directive G13. Electricity must then originate 100% from a renewable source and the carbon may not be intentionally produced for the methanation process. What is covered by “renewable energy source” should be defined in Swiss energy legislation. It was found that Germany can be identified as a “best-practice country”, as it has introduced various privileges which should promote the injection of SNG as biogas into the gas network [59].[34]

[34] Further information on the classification of SNG under Natural Gas legislation in the demo-site countries is explained in Annex I.

6.5.3 Harmonised gas quality standards in the European Union

At the moment, there are different gas quality standards across the EU. Since this may be a barrier to cross-border trade of gas, and to accessing the gas grid with renewable sources, the harmonisation of gas quality standards in the EU must be pursued. Furthermore, uniform international technical norms and standards for equipment and products should be sought. Since harmonisation efforts concerning gas quality standards have not resulted in a consensus on a common Wobbe Index or hydrogen limit, there are different gas quality standards in the EU. This may form a barrier to cross-border trade in gas, and to accessing the grid with gases from renewable sources. Therefore, a harmonisation of gas quality standards in the EU is very important [58]. In the context of harmonisation, it would be desirable to allow higher percentages of hydrogen to be fed into the grid. Hydrogen limits vary in the respective countries. In some countries, there are higher limits (e.g. in Germany up to 10%), in other countries there are pretty narrow ones, as it is in Italy, where only 0,5% are allowed. Since gas grids would tolerate a lot more (with partial adaptation of power supply units) [67], a higher limit of hydrogen in the gas grid would be worth aspiring to. In addition, uniform international technical norms and standards for equipment and products should be aimed at. Concerning the demo site countries: The gas quality standards of the three countries differ from each other. Due to the lack of harmonised gas quality standards, these remain in place. Concerning hydrogen, the foreseen content limit in Germany is 10%, in Italy 0,5%, and in Switzerland 2% [59].[35]

6.5.4 Simplifying administrative procedures

Among the demo site countries, only Italy has introduced a comprehensive streamlined authorisation, which also applies to power-to-gas installations. Municipalities create a single desk (Sportello unico per le attività produttive – SUAP) in order to provide the applicant with a uniform and timely electronic response. Comparable procedures are lacking in Germany and Switzerland, but also in some EU member states or the EU as a whole and should be pursued [58] [59].

6.5.5 Clear EU environmental legislation

The production of hydrogen and SNG, including the construction and operation of a power-to-gas plant, is regulated under EU legislation related to the protection of the environment and human health. The Environmental Impact Assessment Directive (Directive 2011/92/EU) (hereafter “EIA Directive”) makes a distinction between projects which are assumed to have a definite significant effect, and those which likely, but not necessarily, have a significant effect. Projects falling under the first category are listed under Annex I to the EIA Directive and always need to be subjected to an assessment.[36] For certain activities under Annex I a quantitative threshold is provided. For projects falling under the second category, under Annex II, Member States have the discretion to determine whether a project shall be made subject to an assessment.[37] However, as the relevant legislative instruments contain no direct reference to power-to-gas, their applicability remains partially open to interpretation. It stays unclear which regulation is suitable for power-to-gas concerning the Environmental Impact Assessment. Power-to-gas may fall under Annex I, which requires an environmental impact assessment, or under Annex II, which leaves this to the discretion of the member states. A clarification in this respect should take place [58].

6.5.6 Promotion of trainings and further education

The STORE&GO project has initiated trainings and education. The availability of human resources which can be facilitated through targeted training measures is of particular importance for the future research and development of power-to-gas technologies. Training measures for the development of

[35] Further information concerning the different technical specifications for the Injection of SNG in Germany, Italy and Switzerland are presented in Annex I.
[36] Article 4(1) of the Environmental Impact Assessment Directive (2011/92/EU).
[37] Article 4(2) of the Environmental Impact Assessment Directive (2011/92/EU).

the technologies themselves and for handling the power-to-gas system are therefore necessary. In addition, the interconnection between different disciplines should be promoted within the framework of training.

6.5.7 Social acceptance of power-to-gas

Following Directive (EU) 2018/2001 of the European Parliament and of the Council of the European Parliament, European countries look for possibilities to increase renewable energy production. This also means construction of major renewable energy production plants. However, while overall public opinion to such changes can be positive, when it comes to actual project realisation a low level of acceptance or even a strong local opposition may arise. So identifying factors that have an impact on social acceptance can be crucial for persistent success of the further energy transition [68].

Results from the analysis carried out during STORE&GO show that solar farms and power-to-gas infrastructure increase acceptance of local energy communities, while wind farms have an ambiguous effect, and introduction of gas power plants and power lines decreases acceptance. Acceptance levels are prone to be influenced differently by the opinions of EU and national governmental bodies and the opinions of local politicians in the countries involved in the project. Other investigated parameters like place attachment, residing near power plants or income level did not show an impact on acceptance of renewable energy infrastructures in our sample. Socio-demographic characteristics like gender, education and employment revealed persistent impact on households' acceptance of PtG and alternatives [68].

There are some arguments and some misbelief that the energy transition will cause a lot of job losses and recession in the economy. However, the facts show the opposite direction. Between the years 1990 and 2016, use of energy was decreased around 2% and the GHG emissions were decreased by 22%; while the GDP has grown by 54% [3]. Keeping the level of disruption low by utilising existing infrastructure and job skills as far as possible, assuring that societal cost of the overall energy system as such is low, as well as keeping the efficiency of the measures to achieve the climate targets high, seems to be key to maintain high acceptance for the energy transition in general. Power-to-gas enables this in several ways.

6.6 Conclusions & Discussion

The current and mid-term outlook for large-scale power-to-gas deployment in the EU is faced with low net present values. Despite that the technology is often contributing to a broad range of positive externalities, the current state of affairs is likely to result in underinvestment in power-to-gas. Power-to-gas currently finds itself in the technology valley of death, where public support is required to meet the R&D and technology scale-up needs for the technology to grow into a commercially viable and mature energy market solution (see Figure 10).

The existence of externalities is a clear sign of market failure. In the case of power-to-gas investments, the positive externalities do generally not accrue to the investor under the current market regime. This results both in low net present values (NPV) for power-to-gas plants as well as a high likeliness that "investments in power-to-gas are lower than socially optimal" [69].

To bridge the 'valley of death' but also for the creation of a functioning market for green gases, additional policy support for power-to-gas will be needed to allow the technology to contribute to the ambitious EU energy and climate goals. One of the key questions is what policy framework will be needed for this and may be available and acceptable. In this chapter, it is described and explored which portfolio of policy instruments can provide (additional) support to power-to-gas in its different technology and market development stages. Following is a discussion for a subset of policy instruments, the key issues and design features in relation to providing support to power-to-gas. Also a short discussion on possible policy mixes for power-to-gas is provided, because a coherent and synergetic policy framework will be needed to not only support the production of green gases, but also to enable their transmission, distribution, storage, supply and end-use. Unlike e.g. just a power-to-gas dedicated feed-in premium or an additional CO_2-penalty for grey gases, such a mix supports power-to-gas throughout the entire value chain.

6.6.1 Suggestion for Roadmap & Policy Recommendations

Starting points for power-to-gas

1. Green gas has an indisputable role to play in the future energy system. Power-to-gas is the key low-carbon technology to meet that demand, as it provides the solution to produce the required large amounts of green molecules – be it as hydrogen (H_2) or methane (CH_4).

2. Furthermore, power-to-gas in combination with the already existing European gas infrastructure is essential for dealing with the seasonal shift of energy transport & distribution as well as providing balancing services to the power grid.

3. Power-to-gas technology is promising and indispensable to generate the required volumes of green gases, but economically not yet fit to enter the market for large-scale production.

4. Therefore, it is crucial to stimulate PtG in time to enable the timely availability of sufficient green energy molecules (H_2 as well as CH_4) for feedstock and energy purposes. Most experts seem to agree that dedicated additional policies and measures are required for this.

5. At some point in the future – assuming power prices will further come down as well as electrolyser CAPEX-levels – PtG is likely to become commercially feasible. It is deemed crucial to get the technology to this point within the next ten or even five years. However, there is risk this will take too long. In that scenario it is doubtful if the EU will be capable of realising its 2050 mitigation targets. Adequate measures need to be undertaken to avoid this.

On policies and policy mixes

The above starting points clearly suggest that there is a great need to speed up and scale up the implementation of power-to-gas technology in the EU energy market. However, in trying to accelerate investment in power-to-gas technologies (incl. methanation), it is important to realize that most of this technology, although commonly known, is still in its pilot phase. The kind of (public) support for a technology in the pilot phase is clearly different from support for more mature technologies, but can be equally urgent. Given power-to-gas technologies' high capital intensity and long lead times, it seems sensible to now already design a policy framework for both the early stages as well as the subsequent market exploitation and maturity phases.

Early stage support for power-to-gas (pre-2030)

One of the current major needs is to establish a first batch of serious power-to-gas demonstration plants. These projects should ideally cover the complete hydrogen (and derived product) value chain at short notice to collectively cover the feasible technology ranges of power-to-gas. This will require a dedicated support scheme at the EU level of approximately a few billion euros (assuming more than 10 demo projects are needed, each requiring several 100 million euros of public funds). Methanation should be included in this set of demonstration projects. This would substantially help power-to-gas to overcome the first part of the valley of death. It can be questioned if the more generic EU Innovation Fund (6.2.1) will be sufficient to fund this: despite its size of about 10 billion EUR, the Fund targets a wide range of renewable energy low-carbon technologies, of which power-to-gas technologies are just one category. A combination of the measures "Investment subsidy" (6.2.1) and "Regulatory sandboxes and expenditures for R&D" (6.2.2) could be a suitable form.

In order to fast-track the development of a market for renewable gas and power-to-gas, it is desirable to create a pull effect for significant volumes of green gases. The hydrogen feedstock market could be targeted as the first market segment to be set in motion with the help of policies and measures. This segment represents a substantial and often concentrated demand volume that can quickly absorb the volumes produced by large-scale power-to-gas demonstration projects. Moreover, because this market segment uptake so far is completely dominated by grey hydrogen and carbon, both with a considerable footprint, such policies and measures can fast-track the decarbonisation of the EU industry. The short-term introduction of policies and measures to (gradually) phase out the use of grey hydrogen feedstock for the industry – on a mandatory basis and within a clear timeframe – would immediately drive up demand for carbon neutral gas, increase investment in power-to-gas, and support its learning curve. For reasons of maintaining a level playing field, the EU clearly would need to play a role in this process. The corresponding measure would be "Quota obligation for renewable gas", and it can be gradually extended to also include further market segments and admixing rates to establish a permanent and stable market (see further in "Supporting power-to-gas in a more mature development stage (post-2030)").

If this pan European approach does not succeed with in the desired timeframe, it is suggested to resort to the measure of "Feed in tariff for green gas" on national level as an alternative. This measure has proven to be very potent for introducing new technologies in a short period of time. But caution is needed to adapt to the gradually evolving market and sinking costs of technology to reach the desired effect to the lowest public cost. Originally, therefore categorised as a tool purely to overcome the valley of death, if applied with the right boundaries, it could also serve as an alternative to support a market for renewable gas for an extended period of time (see further in next subsection "Supporting power-to-gas in a more mature development stage (post-2030)").

Within this time period, starting now and until 2030, it would be important to clear the specific provisions of the various sectors covered by power-to-gas, and to establish a system for reflecting externalities that is harmonised in Europe. One approach could concern the energy network tariff regulations (like the Commission Regulation (EU) 2017/460 on gas transmission tariffs). These require some revision to determine which costs associated with power-to-gas development and implementation could (or should) be embedded in the network tariffs. While there is logic to include any costs for gas grid refurbishment (to be able to absorb higher shares of hydrogen) in the network tariffs, there can also be arguments for including (parts of) the costs power-to-gas plants in the asset base of TSOs or DSOs as the technology could provide a public (and cost-effective) balancing service. There are already precedents projects in the EU where the full costs of a grid balancing technology (i.e. the green gas booster project in the Netherlands) are fully embedded in the network tariffs [52].

Many of the cross-cutting measures, especially those that are discontinuous (i.e. once they are executed the desired state is reached), need to be concluded pre-2030. Such as: "Clarification of the position of SNG under the Renewable Energy Directive", "Harmonised gas quality standards in the EU" and "Clear EU environmental legislation"

Supporting power-to-gas in a more mature development stage (post-2030)

After a fast learning curve development of between 5–10 years from now; so by 2025–2030 the energy system and power-to-gas technology would need to be ready for EU-wide scaling up. At this point, classical investment support schemes, like R&D funds or investment subsidies (e.g. via the EU Innovation Fund), will no longer suffice as key support schemes. In such a more mature development stage, the public support generally transfers from investment support (i.e. to reduce CAPEX costs) to operational support (to cover additional OPEX costs). Quota obligation schemes (see 6.3.1), or a dedicated penalty on CO_2 emissions either via a CO_2 tax or emissions trading scheme (see 6.3.2), are the kind of instruments that have an impact on OPEX costs of power-to-gas investments. Still further evolved feed-in premium schemes (see 6.2.1) can remain adequate, While the EU ETS serves quite well as a vehicle to generate capital for the EU Innovation Fund, one can question whether the scheme can be adequate to support investment in (green) power-to-gas activities. First of all, the free allocation of emission allowances to renewable-gas producers would need to be cancelled. Second, simple calculations show that even if renewable-gas producers would have to buy 100% of their EU emission allowances, the ETS price would have to skyrocket to unprecedented levels (i.e. 100–200 EUR per ton CO_2 range) in the post-2025 period in order to ensure that green gases can compete with their fossil counterparts (see 6.3.2). Compared to the EU ETS, most of the current feed-in premium schemes for renewable energy in the EU provide much stronger financial support (when converted into per tonne of CO_2-eq. saved), but such schemes do require considerable public funding and therefore claims on the taxpayer or end-user.

So, for providing direct (OPEX) support to power-to-gas, introducing a quota obligation scheme (for admixing a certain share of green gases with conventional gases) seems to be more compatible with the ambitions of the EU internal energy market. In order to prevent issues related to large-scale physical admixing, such a quota obligation scheme would have to allow for administrative trade in green gases. This means the system for guarantees of origin also needs to be adopted correspondingly. Both measures need to be agreed upon at the EU level in order to ensure a level playing field.

A quota obligation scheme could cover green gases from power-to-gas only or consist of green (and/or blue) hydrogen and other gases with a certain level of carbon-neutrality, and can relate to a certain share of gases and be gradually introduced, e.g. starting with 5% by 2025 and 10% by 2030. A quota obligation scheme should allow for cross-border administrative trade in green gases that can be enabled by a system of guarantees of origin for green gas, so that physical admixing is not always necessary. Imported gases into the EU should ideally also be subject to the same rules, so that the required greening could take place either inside or outside the EU.

If EU wide support for a quota obligation scheme would not (timely) materialise, EU member states could consider alternative support schemes, e.g. by extending their feed-in premium schemes to also cover green gases. For investors, a feed-in premium scheme may have some advantages over a quota obligation scheme, as the premium scheme ensures a guaranteed income for a fixed period of time, whereas a quota obligation scheme does not give a similar guarantee because the price of the tradeable Guarantees of Origin certificates can vary (especially when the certificate trading market is not highly liquid or mature)

Alongside with this, whatever type or mix of support instruments chosen for green gases in the EU (e.g. feed-in premium, quota obligation scheme or CO_2-penalty), there will be a great need to track and trace the feed-in, transfer of ownership (trade) and end-use of green gases (see section 6.3.3). A robust, transparent Guarantees of Origin certification scheme for green gases at the EU level will allow the EU and its member states to better monitor and support power-to-gas developments, while it can avoid double counting and double-subsidization. Such robust and EU-wide system for Guarantees of Origin certification for green gases (that also incorporates power-to-gas and perhaps also blue and grey gases) should be implemented before 2030 at the very latest (i.e. the expected nature of the pre-2030 support structures for power-to-gas could still run effectively without such a scheme).

Additionally, it must be possible for the power-to-gas investors and operators to get a fair financial share for services and benefits their facilities bring to the energy system and society as a whole. Thus, measures from the category ‘monetisation of value added from power-to-gas to the energy system’ should be developed pre 2030 so that they are adopted alongside to the establishment of the “market conditions for green gases”, and are well established post 2030.

An overview over the different types and mixes of policy measures that were reflected in this section is illustrated on a timescale in Figure 16.

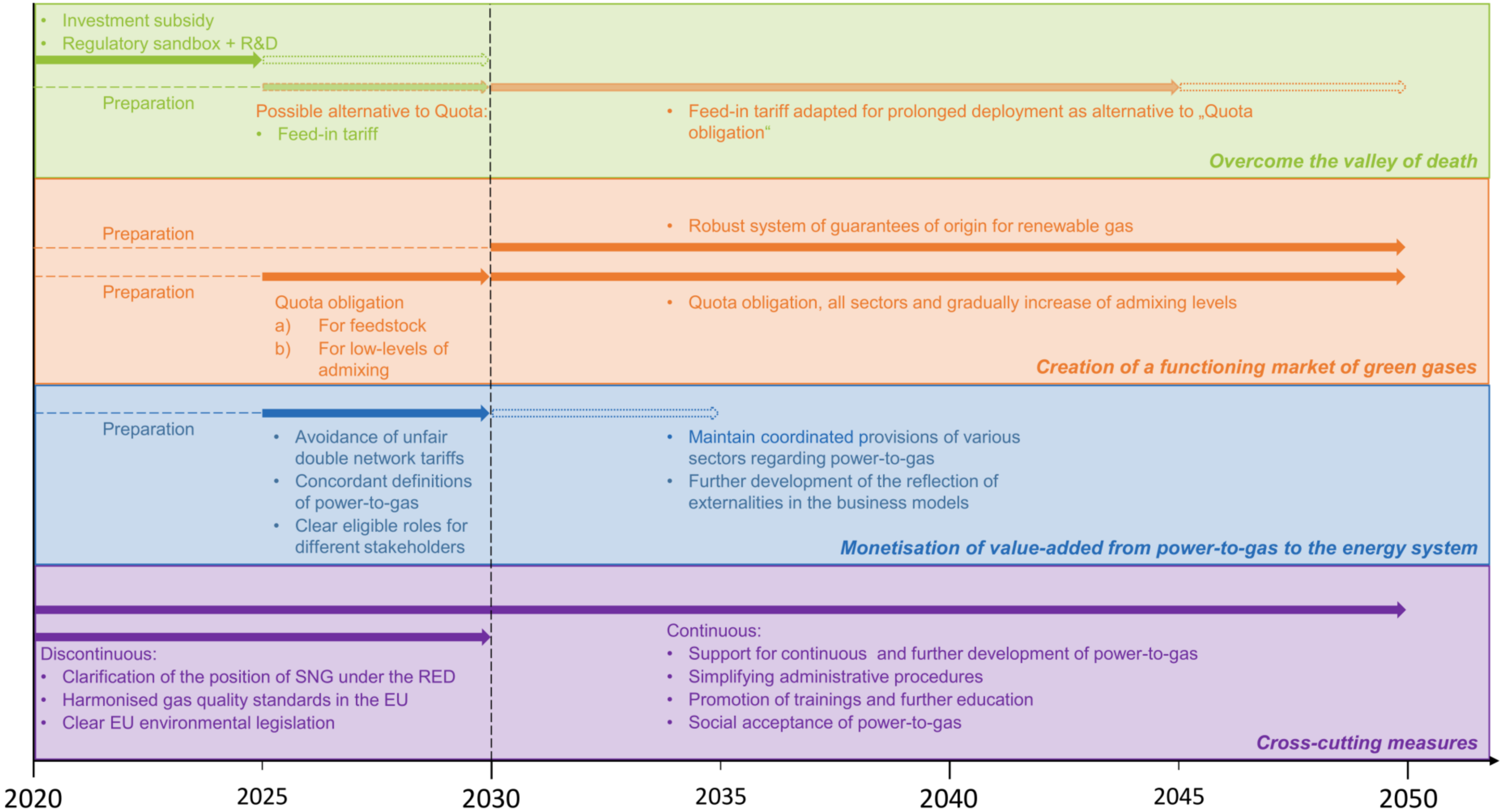

Figure 16: Timeline of the different types of policy measures for the establishment of power-to-gas in the energy system

7 Summary and Conclusions

In order to reach the EU's climate 2050 targets, greening of electrons (power) so far seems on track. Greening of molecules (gases) however is lagging far behind with only a few percentages of green-only and little perspective on serious progress towards 2030 targets and thereafter.

Currently, energy molecules form the backbone of the EU energy system (covering more than 70%) – not without reason, due to the high energy density of molecules. Transport and storage of energy molecules is easier and less costly compared to electricity. For exploring the potential of energy molecules as part of the European energy transition, power-to-gas as a key enabling technology needed further research and demonstration.

Europe's gas grid has seen enormous investments in the past decades, which created a widely branched high-tech infrastructure assuring the security of supply. The existing gas network could absorb very large volumes of green gases from renewable sources, without expanding.

Current electricity surpluses, which are increasingly occurring from wind power, are transported either directly to the consumers or to conventional electricity storage facilities such as battery systems or pump storages. Still, the latter can only be made available for limited amounts of energy and limited periods of time. Therefore, major investments in the expansion of the European power grid would be necessary in the future. However, the missing acceptance of the public for large infrastructure projects very often is a risk for such projects. By contrast, expansions of the natural gas network would also result in less topographical intervention in relation to the expansion of the electricity grid.

The methodology to create this roadmap was divided into two phases. It builds on the expert judgement and consensus of the scientific roadmap team and a supervisory group (subset), as well as the analysis and data assessment of the data generated during the STORE&GO project.

The overall scope of the roadmap is set by the energy transition including and considering the obligations of COP21. The sufficient greenhouse gas (GHG) reduction to meet the 1,5 °C maximum mean temperature increase until 2050 is a mandatory goal of this roadmap. Further, there is a focus on renewable synthetic methane from power-to-gas and four key areas of application, being sector integration, energy storage, power grid stability and energy transport.

There are three central parts that compose this roadmap. The first part is the energy picture of the EU by 2050. The second are the technological characteristics and potential technical and economic development of the power-to-gas technologies. The last part are measures and policy recommendations in order to support the further development of legislation on power-to-gas.

The energy picture of the EU by 2050

The energy picture of the EU by 2050 developed in this roadmap is based on scenarios that several studies of the EU and of the STORE&GO project have sketched [3] [17] [18] [19] [20]. These studies indicate a wide range of 1860 TWh to 4700 TWh for the total gas demand in 2050, while also having a wide range of CO_2 reduction targets. This gas demand has to be covered predominantly by green gases. Our research did not show a low future gas demand, even with a high CO_2 reduction target. Even high electrification scenarios estimate a 40–60% need of molecules in 2050, so the 1860 TWh serve as the absolute lowest estimation. Already here the conclusion can be made that there is a substantial need for green gas, as even the lower value of the two implies this. The further investigations in a top-down analysis conducted within STORE&GO takes a look on the complete European continent, sector by sector, and finds a future gas demand of around 4400 TWh.

- The electric sector needs to phase out of coal, and simultaneously build-up a renewable energy generation. With growing share of renewable energies, the need for curtailment rises, and here gas and gas-combined heat and power (CHP) are the optimal partners for a renewable volatile electricity production. The net renewable gas demand in 2050 of the electric sector is estimated to be around 1200 TWh, and the share provided by power-to-gas about 0–5% [20].

- In the industry sector, the need for energy molecules as feedstock will remain to achieve high temperatures [8]. Thus, enhancing green molecules across all sectors, electricity, mobility and industry is probably by far the largest EU energy transition challenge for the next decade. The net renewable gas demand in 2050 of the industry sector's final energy consumption is estimated to be about 630 TWh, and 570 TWh for the final non-energy consumption. The respective shares provided by power-to-gas are estimated to be about 10–65% for final energy consumption and 30–60% final non-energy consumption [20].

- About half of the EU's energy consumption goes into heating in buildings and in industry. Although the total amount of heating energy is expected to decrease due to building renovations and efficiency measures, a large-scale replacement of molecule-based heating systems by electricity-based ones is unlikely in the following decades. This generates a demand for a replacement of fossil energy molecules by green molecules. The net renewable gas demand of the heating sector in 2050 is estimated to be about 750 TWh, and the share of power-to-gas about 30–60% [20].

- The mobility sector faces the challenge that it will grow significantly, while still the GHG emissions need to decline. Gaseous and liquid e-fuels from power-to-gas should be complementary to electric mobility, since full electrification of the sector, especially in long-distance maritime transport, freight transport and aviation, seems unrealistic due to the high energy density demands in these areas. The net renewable gas demand in 2050 of the transport and mobility sector is estimated to about 1000 TWh, and therefrom about 30–60% would be provided by power-to-gas [20].

The bottom-up analysis per country on this indicates that the future gas demand is more likely in the upper than lower range, especially in countries with a high fossil energy supply today. Even if the overall demand of gas in the EU declines, the demand for green gases will grow.

The main source for renewable gas is projected to be provided by power-to-gas – either in the form of hydrogen or, as studied in the STORE&GO project, in the form of methane. A further option for large-scale decarbonisation is to consider carbon-neutral hydrogen – hydrogen produced from natural gas and including Carbon Capture and Storage (CCS) technologies.

Additional demand for power-to-gas arises from further energy system benefits. There is an existing energy storage capacity of 1100 TWh that green gases can utilise. The gas grid can complement the electric grid in terms of energy transport. Furthermore, the electric grid can be balanced due to the flexible load capacity of power-to-gas and the flexible supply of combined heat and power plants.

As the range of system benefits of power-to-gas is unique and indisputable, this remains a valid argument for policy to support its introduction to the market. The overarching and more fundamental argument when it comes to the order of magnitude and value to society as a whole, however, is the need to provide green gas in itself.

With regard to the possibility to continue the power-to-gas-process beyond hydrogen and going to 100% natural-gas-compatible methane, the future share of the three sources of CO_2 (biomass, direct capture from air (DAC) and grey CO_2 from industrial processes) was investigated. Availability of biomass is limited, and it may be claimed for other uses. Thus it is assumed that there will be a future trade-off between the different possible sources for CO_2. Industrial sources are expected to reduce in the future, even if some will remain at large scale. DAC is currently the costliest source, but the availability is "unlimited". The range of available CO_2 for methanation production from biomass alone is 1190–1390 TWh/a, and 1320–1650 TWh/a if combined with grey CO_2, covering 35 to 70% of the estimated future total demand of gas in this study.

What combination of CO_2 sources will be implemented in the end highly depends on the costs for each option. These were investigated in the second part of the roadmap. While the current costs for capturing CO_2 range between 5 and 110 €/ton for biomass and industrial sources, the costs for DAC are rather in the range of 81 to 475 €/ton [38]. However, the DAC technology is still in its early stages and further cost decreases are expected.

Cost and technological characteristics of the power-to-gas technology

The second part of this roadmap is dealing with the technological characteristics and the potential technical and economic development of the power-to-gas technologies. The STORE&GO projects demonstrates the power-to-gas technology in conjunction with innovative technologies and processes. The three demonstration plants in three European countries show the high level of maturity of the technology. Rapid development is ongoing in PtG technologies. The main components of the PtG technology – electrolyser and methanation systems – show significant cost reduction potentials thanks to scaling effects and technological learning. Depending on the chosen electrolyser application, the specific investment costs for large scale systems could decrease respectively to around 300 €/kW[38], 170 €/kW[39] and 270 €/kW[40] in 2050 for different technologies. Large-scale methanation systems are expected to reach specific investment costs of about 120–125 €/kW. In addition, there are also potentials for improvement of technological characteristics like efficiency, lifetime and start-up time. In general, there was a positive development of water electrolysis over the last 10 years. For several characteristics, like stack and system capacity and stack lifetime and degradation, the development so far outperforms the values proposed 10 years ago. Systems have significantly improved, especially in terms of PEM electrolysis. For example, the maximum available system and stack production capacities are currently far beyond the values proposed only a few years ago. The estimations of potential cost reductions and efficiency increases correspond to the future demands for power-to-gas according to "The energy picture of the EU by 2050". To tap the full potential of further technological developments, installed capacities have to increase. From the technological point of view, power-to-gas can act as the key enabling technology for the energy transition. The opportunities for Europe as a technological pioneer seem very favourable and exceed the chances of a perspective limited to Europe alone.

In 2020, the SNG production costs have a wide range from electricity from the grid, and electricity from wind and PV. This range will be smaller in 2030 and 2050. There is only little difference in SNG production costs, depending on which technology is employed. Depending on the use case, SNG production costs in the range of 5,5–12,6 Cent/kWh can be achieved in 2050 with large plants in Europe, depending on the electricity source used for SNG-production.

Legal uncertainties and market distortion are a burden to power-to-gas implementation

The third part of this roadmap are measures and policy recommendations to support the further development of legislation on power-to-gas. In order to achieve the 2050 goals, power-to-gas must

[38] AEC
[39] PEMEC
[40] SOEC

be commercially competitive by 2025 so that it can compete on a market for renewable gas that needs to be established by 2030. It can be expected that upscaling effects and learning curves will continue to enhance efficiency and keep bringing the costs further down – but this will depend on a successful introduction of power-to-gas in the market to achieve higher production volumes. There are four approaches that can be defined as main fields of action: Overcome "The Valley of Death", create a functioning market for green gases, monetisation of value added from power-to-gas to the energy system, and cross-cutting measures to cancel out hindering specific aspects and ease a smooth implementation illustrated in Figure 17.

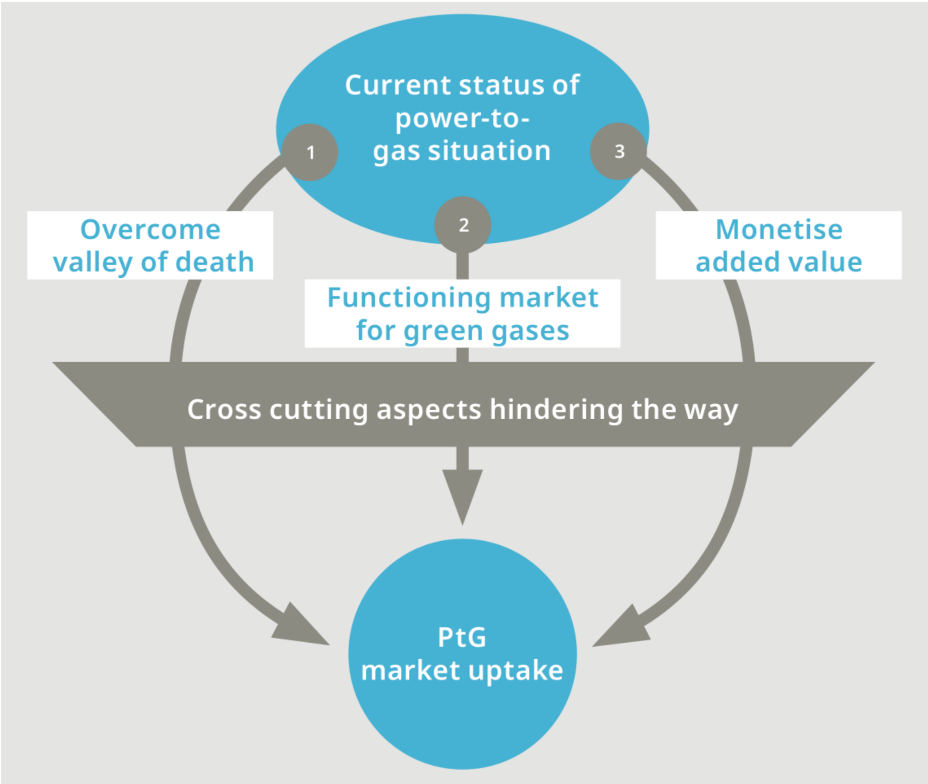

Figure 17: Three possible policy approaches for large-scale PtG deployment in the EU and the cross-cutting aspects to achieve an uptake of PtG in the market.

Power-to-gas currently finds itself in the technology valley of death, where public support is required to meet the R&D and scaling needs for the technology to grow into a commercially viable and mature energy market solution. This category of measures are characterised by being time-limited support that are not desirable to sustain on the long run; typically, financial supports on the provider side of the market. This can be done by creating specific support and subsidy schemes for both research and development as well as for investors, by granting feed-in remuneration for operators and by reforming regulation policies. By the investments and R&D to take place in "regulatory sandboxes", not only the valley of death issues are addressed but at the same time valuable experiences can be gained when it comes to the second category of measures: "Create a functioning market for green gases" as well as the third category "Monetisation of value added by power-to-gas to the energy system".

In order to be able to draw back the support tools specifically for overcoming the valley of death, there must be market boundaries established so that the further development of power-to-gas can take place with gradually less and less governmental support. Establishing a functioning market for green gases is therefore a crucial element when paving the way for power-to-gas implementation. This category of measures are characterised by being support that is fit for endless deployment (or gradually increasing); typically, market conditions or costs that affect all market players fair according to the goals without causing direct costs in the budget of governments. Instruments such as a mandatory admixing quota with cross sectoral impact, penalizing CO_2 emissions financially and providing a framework of guarantees of origin for renewable gases can be the options of choice.

Further rational measures can be derived from the value added that power-to-gas offers to the energy system – through the reflection of externalities in the monetisation system and the coordination of regulations in the electricity and gas markets. This category is about the question of who can operate a power-to-gas facility under which circumstances, and if the different provisions concerning the different sectors of application are aligned. But it also addresses the issue that additional value added to the energy system should be tangible for the investor/operator of the power-to-gas facility. The issue of network tariffs currently charging power-to-gas facilities twice: as consumer (L-charges) and producer connected to the network (G-charges) is especially highlighted here.

In addition, further measures concerning various specific aspects which contribute to the energy transition across all sectors must be approached. They include clarifying the position of synthetic natural gas (SNG) under the Renewable Energy Directive and regarding EU environmental legislation, harmonising gas quality standards, simplifying administrative procedures and further enhancing awareness and education for experts as well as for the public.

A realistic and effective strategy to assure a successful introduction of power-to-gas could be:

1. **Substantial demonstration projects** at short notice (pre-2030) to collectively cover the feasible technology ranges of PtG i.e. some **10 demo projects requiring ~100 million Euros** of public funds each. This can be supported as R&D projects and/or with investment subsidies. Preferably also as “sandbox-projects” to simultaneous gain experience for the higher development stage.

2. **Introduce policy measures** to establish the credibility in PtG to potential investors that there will be a serious **market for renewable and carbon neutral gases** (post-2030) as well as derived products **both** in the **feedstock** and **energy market**.

    a. The **feedstock market** could be the first market segment with policies and measures on a mandatory basis and within a clear timeframe – i.e. **obligatory quota for renewable gases** is suggested to be implemented already by 2025**.**

    b. To reach the **total energy market** for gas, the **obligatory admixing of renewable gases** to the EU gas system seems to be a profound way forward. It might start at **5% by 2025** and needed to base on a **guarantees of origin** system. Imported gases into the EU should be subject to the same rules.

    c. **If the common European approach of “quota obligation” should not be possible** in the designated timeframe, **“feed-in tariffs” for renewable gas** on national level is suggested as an **optional way forward** with proven potential of impact. With due caution to adapt to the gradually evolving market and sinking costs of technology to reach the desired effect to the lowest public cost, **this measure can also be made fit** to serve as an alternative to support a market for renewable gas for an **extended period of time**.

3. Assure that the overall **benefit of power-to-gas to the energy system** and environment in total are **reflected in possible business models** and **by coordinating the provisions of power-to-gas across all sectors** and applications. Priorities should be on the **avoidance of unfair double network tariffs, definitions of power-to-gas and eligible roles for different stakeholders**.

4. **Clear the path** for power-to-gas be eliminating all detailed current detailed issues all unnecessarily hindering the development of power-to-gas such as: **"Clarification of the position of SNG in the RED", "Harmonised gas quality standards in the EU"** etc.

5. **Finally, create incentives** for further **continuous PtG development** via appropriate consideration of power-to-gas in the **research programmes.**

In conclusion, in the future perspective, the gas system will not only be confronted with one type of gas. In a PtG process, one option available is to use the hydrogen directly from the electrolyser. The other option is to continue the process and produce methane. Besides these two options there are several routes of other bio-based methane as well as hydrogen from natural gas that is made climate neutral by means of Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU). Furthermore, today a substantial part of the supply for the EU demand for "energy molecules" is imported. Scientists and technological experts are still discussing on how to adequately approach these issues. What is obvious already at this point: The answers can only be found in combining renewable hydrogen as well as renewable methane in the natural gas mix, utilising existing infrastructures, and by incorporating both energy imports and EU domestic generation. These questions are subject of and highly influenced by national and European interests. The scope of STORE&GO focuses on the aspects of the production of methane in a European production perspective. However, the technologies, market conditions and the regulatory framework needed for a positive development of renewable synthetic methane from power-to-gas are also estimated to have positive concurrent effects on other renewable gases in the energy system if the conclusions from the project and the measures presented in this roadmap are deployed. The decarbonisation of European energy can be considered as an opportunity to further strengthen European leadership in innovative energy technologies, energy-related transport technologies and services, as well as the application and implementation of mature and climate-friendly gas-related technologies. The results of this roadmap underline this and show how power-to-gas could and should become a part of this future.

8 Glossary

Biomethane: Biomethane is produced from an anaerobic digestion process of biodegradable materials. The energetic value of biomethane is processed to match the quality and purity of natural gas. This allows for limitless injection of biomethane into the natural gas network. Blue hydrogen is gained from fossil natural gas with the climate-impacting carbon being captured and stored safely. To be able to meet the overall gas demand in the future, carbon-neutral blue hydrogen should be considered as part of the supply as well as, given its carbon capture and storage capacities.

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CNG (Compressed Natural Gas): To obtain CNG, natural gas is compressed to a pressure at or above 200 bar and stored in high-pressure containers. It is mainly used as a fuel for natural gas-powered vehicles.

Curtailment: Wind turbines often are shut down when their continuous production (e.g. in the case of strong wind) could endanger the grid's balance due to a surplus of electricity. Curtailment results in a loss of large amounts of renewable energy production.

DAC (Direct Air Capture) is a technology in its early development stage for capturing carbon dioxide from the ambient air and generating a concentrated stream of CO_2. The air flows through a filter where CO_2 is removed. The captured CO_2 can serve as feedstock source for power-to-gas.

Dark Doldrum: Dark Doldrum is the energy industry's term for low electricity production from renewable sources (mainly wind and solar power plants) due to weak winds and phases of darkness or very little daylight. Dark Doldrums occur particularly in the winter season.

Electrolyser: Unit where the electrochemical process of breaking water into hydrogen and oxygen takes place. The three available methods of electrolysis are: alkaline electrolyser (AEC), proton exchange membrane electrolyser (PEMEC), and solid oxide electrolyser (SOEC).

AEC and PEMEC are low temperature electrolysis methods, while **SOEC** can be performed at high temperatures. Besides the operating temperature, the three electrolysis methods differ in further individual characteristics such as energy input, pressure, and start-up times.

Green hydrogen is generated via power-to-gas in a carbon-neutral way, using renewable energy sources such as solar or wind for the electrolytic process. **Grey hydrogen** is hydrogen produced using fossil fuels such as natural gas, and thus has a negative climate impact.

Green methane: Green hydrogen can be chemically transformed into flammable methane (CH_4), which subsequently can be fed into the gas grid as Synthetic Natural Gas (SNG). This process is called methanation. In Germany, synthetic methane (or SNG) can be classified as biogas when at least 80% of the electricity fed into the electrolyser and the carbon used for methanation come from renewable sources.

Grey carbon: CO_2 coming as a by-product from industrial processes like cement and steel production, which for their main purpose use fossil fuels.

LNG (Liquefied natural gas): LNG is a non-toxic liquid fuel, which is produced through pressure and by cooling natural gas down to -161 °C to -167 °C. Through the cooling process, the volume of LNG is 600 times less compared to natural gas. This is significantly simplifying transport and making transport more efficient. Additionally, LNG can be easily and efficiently stored in hubs. Liquefaction technology is fully commercial and already available for large scale application. Its infrastructure is ready and can be used for liquefied renewable gas (**LRG**) without any modifications.

L-charges and G-charges: Those who are connected to a transmission or distribution network may be required to pay a tariff for the access or connection to this network. Tariffs can be divided into G-charges and L-charges. While G-charges have to be paid by producers connected to the network, L-charges are those for loads, or end-users.

Methanation: In the process of methanation, hydrogen is combined with carbon dioxide and transformed into methane. For the catalytic methanation method, a metallic catalyzer is needed. Alternatively, biological methanation, employing micro-organisms, can also be used as methanation method.

Methane: A colorless, flammable, odorless gas which is the major component of natural gas and an important source of hydrogen in various industrial processes.

Power-to-Gas (PtG): Power-to-gas denominates the transformation of renewable energy through electrolysis into hydrogen or, combined with a further step, to methane. Power-to-gas technology can produce ultra-pure hydrogen without CO_2 emissions if the electrical energy comes from a renewable energy source. Green methane can be generated by combining green hydrogen with CO_2. Globally, there are more than sufficient natural solar and wind resources to produce all the hydrogen needed for industry and transport. Additionally, when transformed into methane, electricity from wind and solar power plants can be stored in large amounts.

Sector coupling: Comprehensive sector coupling is the central idea of an energy system whose gas, electricity, heating and mobility infrastructures are technologically interlinked, and the energy consuming sectors are integrated with the power-producing sector. In a sector coupling scenario, an important part of renewable power could be converted into green gases that can be transported and stored much cheaper and easier than electricity.

SNG (Synthetic Natural Gas) / Synthetic Methane: Another Term for → Green methane.

SUAP (Sportello Unico per le attività produttive): The “One-Stop Desk for Productive Activities” is implemented in all Italian municipalities as the centralised point of contact between companies and authorities for all the public procedures related to the opening and management of a company.

TRL (Technology Readiness Level): Scale for measuring the development status of innovative technologies based on systematic analysis. It indicates in nine stages how far developed an assessed technology is. The first TRL scheme was developed by NASA. The Horizon 2020 programme uses the following adaption:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

9 Bibliography

[1] European Commission, „Energy Roadmap 2050," Publications Office of the European Union, Belgium, 2012.

[2] European Commission, „ec.europa.eu," European Union, 2019. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Zugriff am 21 01 2020].

[3] European Commission, "A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy," Brussels, 28 November 2018.

[4] M. R. Allen, O. P. Dube, W. Solecki, F. Aragón-Durand , W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu and K. Zickfeld, "Global Warming of 1.5 ºC," October 2018.

[5] European Commission, „A European Strategy for Low-Emission Mobility," 2016.

[6] European Commission, „EU Energy in figures - Statistical Pocketbook 2019," August 2019. [Online]. Available: https://publications.europa.eu/en/publication-detail/-/publication/e0544b72-db53-11e9-9c4e-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=37085&WT.ria_f=3608&WT.ria_ev=search. [Zugriff am 07 Oktober 2019].

[7] Navigant, "Gas for Climate - The Optimal Role for Gas in a Net-zero Emissions Energy System," March 2019.

[8] ERIG - European Research Institute for Gas and Energy Innovation, "The Scope of Internet of Energy - The potential of connecting electrons and molecules," 2018.

[9] EUROGAS, "The Sustainable Credentials of Gas - A Study of Scenarios to 2050 by Using PRIMES," 2018.

[10] International Energy Agency IEA, „Energy Technology Roadmaps - a guide to development and implementation," Paris, 2010.

[11] European Power to Gas (DNV GL), „White Paper - Power-to-Gas in a Decarbonized European Energy System Based on Renewable Energy Sources".

[12] DVGW, „Bewertung von Quellen und Abtrennungsverfahren zur Bereitstellung von CO2 für PtG-Prozesse," 2019.

[13] European Commission, „SET Plan 10 Key Actions," SETIS - Strategic Energy Technologies Information System , [Online]. Available: https://setis.ec.europa.eu/. [Zugriff am April 2019].

[14] IRENA and European Union, „Renewable Energy Prospects for the European Union," February 2018.

[15] FVV - Forschungsvereinigung Verbrennungskraftmaschine E.V (Research Association for Combustion Engines), „Renewables in Transport 2050 - Empowering a Sustainable Mobility Future with Zero Emission Fuels from Renewable Electricity - Europe and Germany," January 2016.

[16] Eurelectric, „Decarbonization Pathways," 2018.

[17] Cécile and H. Blanco, "STORE&GO D6.3 - Impact analysis and scenarios design," 31 May 2018.

[18] P. Capros, A. De Vita, N. Tasios, P. Siskos, M. Kannavou, A. Petropoulos, S. Evangelopoulou, M. Zampara, D. Papadopoulos, C. Nakos, L. Paroussos, K. Fragiadakis, S. Tsani, P. Karkatsoulis, P. Fragkos, N. Kouvaritakis, L. Höglund-Isaksson, W. Winiwarter, P. Purohit, A. Gomez-Sanabria, S. Frank, N. Forsell, M. Gusti, P. Havlík, M. Obersteiner, H. P. Witzke and

M. Kesting, "EU Reference Scenario 2016 - Energy, transport and GHG Emissions Trends to 2050," Imprimerie Centrale in Luxembourg, Luxembourg, 2016.

[19] European Commission, DG ENER, "The Role of Trans-European Gas Infrastructure in the Light of the 2050 Decarbonisation Targets," November 2018.

[20] C. Jepma, E. Spijker und O. den Boon, „STORE&GO D8.5 - The short, medium and long term perspectives of various dedicated market segments for 'green gases',“ 31 October 2018.

[21] European Parliament's Committee on Industry, Research and Energy, "Sector Coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?," November 2018.

[22] Bloomberg New Energy Finance, „An Integrated Perspective on the Future of Mobility,“ October 2016. [Online]. Available: https://data.bloomberglp.com/bnef/sites/14/2016/10/BNEF_McKinsey_The-Future-of-Mobility_11-10-16_ExecSum.pdf. [Zugriff am August 2019].

[23] European Environment Agency (EEA), „Evaluating 15 Years of Transport and Environmental Policy Integration - TERM 2015: Transport Indicators Tracking Progress Towards Environmental Targets Europe,“ Publications Office of the European Union, Luxembourg, 2015.

[24] European Environment Agency, „Greenhouse gas emissions from transport in Europe,“ [Online].

[25] European Environment Agency (EEA), „Transition Towards a More Sustainable Mobility System - TERM 2016: Transport Indicatiors Tracking Progress Towards Environmental Targets in Europe,“ Publications Office of the European Union, Luxembourg, 2016.

[26] DVGW, "Gasmobilität (PKW, LKW, BUS) - Umweltauswirkungen, Technologie und Wirtschaftlichkeit gasbasierter Mobilität," [Online]. Available: https://www.dvgw.de/medien/dvgw/leistungen/publikationen/daten-fakten-gasmobilitaet.pdf. [Accessed Juni 2019].

[27] A. Moser, M. Zdrallek, H. Krause und F. Graf, „Nutzen der Power-to-Gas-Technologie zur Entlastung der 110-kV-Stromverteilungsnetze,“ DVGW Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, 2015.

[28] H. Blanco and A. Faaij, "A review at the role of storage in energy systems with a focus on Power-to-Gas and long-term storage," Elsevier, August 2017.

[29] J. Huettenrauch und J. Glandien, „STORE&GO Deliverable D5.10 - Report on economic analysis of test cases,“ 2020.

[30] Gas Infrastructure Europe, "Gas Infrastructure Europe - Storage Database," December 2018. [Online]. Available: https://www.gie.eu/index.php/gie-publications/databases/storage-database.

[31] ENTSO-E & ENTSO-G, "Ten-Year Network Development Plan 2018 - Scenario Report," 2018.

[32] J. Schaffert, H. Cigarida, D. Coquette, J. Leukefeld, M. Lange, R. Albus, F. Burmeister und K. Görner, „STORE&GO Deliverable D8.9 - Report on an EU-wide potential analysis of Power-to-Gas locations coupled to local CO2 and renewable energy sources,“ Gas- und Wärme-Institut Essen e.V., Essen, 2020.

[33] A. P. C. Faaij, "Securing sustainable resource availability of biomass for energy applications in Europe; review of recent literature," University of Groningen - The Netherlands, November 2018.

[34] D. Thrän und F. Müller-Langer, Biogas, Chapter 2, Potenziale in Deutschland und Europa, F. Graf und S. Bajohr, Hrsg., München: Oldenbourg Industrieverlag GmbH, 2011.

[35] F. Mörs, R. Schlautmann, J. Gorre und R. Leonhard, „STORE&GO Deliverable 5.9 Final report on evaluation of technologies and processes,“ 2020.

[36] RWTH Aachen University & Frontier Economics, "The value of gas infrastructure in a climate neutral Europe - A study based on eight European countries," 2019.

[37] A. Zauner, H. Böhm, D. C. Rosenfeld und R. Tichler, „STORE&GO D7.7 - Analysis on future technology options and on techno-economic optimization," 2019.

[38] H. Böhm, A. Zauner, S. Goers, R. Tichler and P. Kroon, "STORE&GO D7.5 - Report on experience curves and economies of scale," 31 October 2018.

[39] T. Smolinka, N. Wiebe, P. Sterchele, A. Palzer, F. Lehner, M. Jansen, S. Kiemel, R. Miehe, S. Wahren and F. Zimmermann, "Studie IndWEDe-Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme," Berlin, September 2018.

[40] S. Rönsch, J. Schneider, S. Matthischke, M. Schlüter, M. Götz, J. Lefebvre, P. Prabhakaran und S. Bajohr, „Review on methanation – From fundamentals to current projects," Fuel, 2016.

[41] F. Graf, A. Krajete und U. Schmack, „Techno-ökonomische Studie zur biologischen Methanisierung bei Power-to-Gas-Konzepten," Deutscher Verein des Gas- und Wasserfaches e.V. (DVGW), 2014.

[42] B. Lecker, L. Illi, A. Lemmer und H. Oechsner, „Biological hydrogen methanation - A review," Bioresource technology, 2017.

[43] L. Grond, P. Schulze und J. Holstein, „Systems Analyses Power to Gas - Deliverable 1: Technology Review - Final Report," DNV KEMA Energy & Sustainability, 2013.

[44] J. Perner, M. Unteutsch and A. Lövenich, "Agora Verkehrswende, Agora Energiewende and Frontier Economics: The Future Cost of Electricity-Based Synthetic Fuels," September 2018.

[45] J. de Bucy, „ENEA Consulting - The Potential of Power-to-Gas," January 2016.

[46] Deutsche Energie Agentur (DENA), "Roadmap Power to Gas," Berlin, November 2017.

[47] J. Schäffer, F. Ortloff, U. Lubenau, J. Senner and C. Imberg, "Bewertung von Quellen und Abtrennungsverfahren zur Bereitstellung von CO2 für PtG-Prozesse," DVGW-Forschung (DVGW-Förderkennzeichen G 1-04-16), April 2019.

[48] European Commission, "Liquefied Natural Gas," [Online]. Available: https://ec.europa.eu/energy/en/topics/oil-gas-and-coal/liquefied-natural-gas-lng. [Accessed August 2019].

[49] S. Feldpausch-Jägers, N. Lefort, D. M. Lange, A. Mozgovoy, F. Burmeister, M. Henel, A. Wehling, E. Schuhmann, R. Erler, J. Ruf, W. Köppel, D. D. Gerstein and F. Brandes, "Potenzialanalyse LNG - Einsatz von LNG in der Mobilität, Schwerpunkte und Handlungsempfehlungen für die technische Umsetzung," DVGW - Förderzeichen G7/01/15, Essen, October 2016.

[50] B. Merrifield, „Obsolescence of Core Competencies versus Corporate Renewal.," *Technology Management,* Bd. 2(2), pp. 73-83, 1995.

[51] P. Abraham und H. Gundimeda, „Barriers to the Deployment of Low Carbon Technolo-gies: Case Study of ArunTM 160 Solar Concentrator for Industrial Process Heat.," *Low Carbon Economy,* Bd. 5, pp. 117-125, 2014.

[52] C. Jepma, E. Hofman und E. Spijker, „STORE&GO D8.8 - The societal business case for power-to-gas: valuing positive and negative externalities," 2019.

[53] H. Blanco, „Report on assessment of the environmental impacts depending on the reference energy system employed (D5.1)," STORE&GO project, 2017.

[54] H. Blanco, J. Gorre, S. Verleger, H. Föcker, A. Lochbrunner, A. Diego, A. Rossi, A. Zauner, F. Marcehal und R. Tichler, „Report on the life cycle environmental impact assessment model for power to gas systems (D5.4)," STORE&GO project, 2018.

[55] H. Blanco, „Assessment of the net environmental impacts of deploying Power-to-Gas technologies," STORE&GO project, 2019a.

[56] T. Gronemann, „Die „Regulatory Sandbox" – Ein Modell auch für das deutsche Bankaufsichtsrecht?," 10 07 2018. [Online]. Available: https://www.fc-heidelberg.de/die-regulatory-sandbox-ein-modell-auch-fuer-das-deutsche-bankaufsichtsrecht/. [Zugriff am 28 09 2019].

[57] ISGAN, „Innovative Regulatory Approaches with Focus on Experimental Sandboxes," 2019.

[58] G. Kreeft, „STORE&GO Deliverable 7.2 - European Legislative and Regulatory Framework on Power-to-Gas," 2017.

[59] G. Kreeft, „STORE&GO Deliverable 7.3 Legislative and Regulatory Framework for Power-to-Gas in Germany, Italy and Switzerland," 2018.

[60] European Commission, „EU Emissions Trading System (EU ETS)," [Online]. Available: https://ec.europa.eu/clima/policies/ets_en. [Zugriff am 25 09 2019].

[61] D. F. C. Matthes, „ Ein Emissionshandelssystem für die nicht vom EU ETS erfassten Bereiche: Praktische Umsetzungsthemen und zeitliche Erfordernisse.," 2019.

[62] J. L. Moraga, M. Mulder und P. Perey, „Future Markets for Renewable Gases&Hydrogen," CERRE, 2019.

[63] A. Marcu, E. Alberola, J.-Y. Caneill und M. e. a. Mazzoni, „2019 State of the EU ETS Report," 2019.

[64] H. Nymoen, S. C. Sendler, R. Steffen und R. Pfeiffer, „Kurzstudie "Quote erneuerbare und dekarbonisierte Gase"," Berlin, 2019.

[65] E. e. a. Spijker, „A level playing field for the European biogas and biomethane markets, case of the Netherlands and Germany: policy environment, key differences and harmonisation issues," 2015.

[66] YCharts, „European Union Natural Gas Import Price," [Online]. Available: https://ycharts.com/indicators/europe_natural_gas_price. [Zugriff am October 2019].

[67] DVGW, „DVGW-Regeln für klimafreundliche Energieinfrastruktur - Mehr Wasserstoff technisch sicher verankern," 2019.

[68] V. Azarova, J. Cohen, C. Friedl und J. Reichl, „STORE&GO D7.8 - Report on social and public acceptance determinants in selected EU-countries," 2019.

[69] A. De Nooij, A. Van der Welle und H. Mozzafarian, „STORE&GO D7.6 Full CBA analysis of power-to-gas in the context of various reference scenarios," 2018.

[70] B. b. B. V. V. BDEW, „Hemmnisse für Energiespeicher," 2016.

[71] European Commission, "Our Vision for a Clean Planet for All: Social Transition," [Online]. Available: https://ec.europa.eu/clima/sites/clima/files/docs/pages/vision_3_social.pdf. [Accessed August 2019].

Annex 1

Concerning chapter 6.4.1:

- Germany:
  Power-to-gas as storage: the EnWG contains different terminologies to refer to technologies which aim to store electricity. In absence of clear definitions on "*Stromspeicher*" or "*Anlagen zur Speicherung elektrischer Energie*", there remains uncertainty as to which storage technologies and applications fall under these concepts. This makes it essential to examine on a case-by-case basis from the context of a particular provision whether or not this applies to power-to-gas, especially when no reconversion into electricity is intended to take place [59].
  Power-to-gas as producer: The power-to-gas conversion is considered gas production. Whether power-to-gas-to-power is considered electricity production is not clear for the moment and should therefore be clarified by the German legislator [59].

  Ownership regimes (the same counts for Italy)**:** The operation of power-to-gas (as gas production) by transmission system and distributions system operators is not allowed, as power-to-gas is perceived as gas production [59].

- Italy:
  Power-to-gas as storage: systems for the storage of electrical energy" (*sistemi di accumulo di energia elettrica*) are defined as: *A "storage system" is a set of devices, equipment and management and control logics, functional for the absorption and release of electricity, designed to operate continuously in parallel with the network with a third party access obligation. The storage system can be integrated or not with a production plant (if present)*[41] [59].
  Power-to-gas as producer: Power-to-gas conversion is considered gas production. Power-to-gas-to power is also considered electricity production [59].
  Ownership regimes: see above for Germany [59].

- Switzerland:
  Power-to-gas as storage: Article 6(1) of the Federal Energy Act explicitly mentions that the energy supply chain includes storage. The article refers to "*Speicherung*" which refers to the storage of electricity.[42] A definition of what constitutes storage in the electricity context is, however, lacking. For the moment, the Federal Council expressed its opinion that only technologies which charge *and* discharge electricity should be treated as storage in a similar fashion as pumped hydro storage.[43] As such, the treatment of power-to-gas by the Swiss authorities as storage technology will depend on its deployment, i.e. whether the power-to-gas conversion, the storage, and the reconversion to electricity take place at one location [59].
  Power-to-gas as producer: Power-to-gas conversion is considered gas production. Power-to-gas-to-power is also considered electricity production [59].
  Ownership regimes: Concerning the transmission level the federal Pipeline Act (Rohrleitungsgesetz) contains no provision on the unbundling of gas system operators or a requirement for the non-discriminatory operation of gas networks. The Federal Council in 2014 announced the drafting of a Gas Supply Act (*Gasversorgungsgesetz*). In 2017, the SFOE announced that it would sent out a draft for consultation of this Gas Supply Act which, according to the SFOE, complies as far as possible with the norms of EU law under the 2009 Gas regulation (No. 715/2009) and 2009 Gas Directive (2009/73/EC). Although it is not yet known how the unbundling rules under the new Gas Supply Act will take shape, it is unlikely that these will allow gas system operators to operate power-to-gas facilities which are deployed in the commercial segment of the gas sector. Taking note of the statement by the SFOE that the new Gas Supply Act

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[41] Article 2(m) of the AEEG/ARERA Resolution 547/2014/R/EEL.
[42] *See* applied wording under the Nuclear Energy Act of 21 March 2003, No. 732.1 and the Federal Energy Act of 30 September 2016.
[43] Position by the Federal Council of 25 May 2016 on Motion 16.3265, "Equal treatment of storage technologies in network charges".

will comply with EU rules, and considering the spirit of the gas industry agreement, system operation will most likely need to be separated from other activities. At the distribution level it is allowed for regional energy companies to simultaneously operate a gas producing power-to-gas installation and an electricity and/or gas distribution network. So the bundling of competitive and regulated activities is allowed in Switzerland at the distribution level [59].

Concerning chapter 6.4.2:

- Germany: The current situation in Germany is that energy storage (the purchase of electricity from the public grid for the purpose of conversion into gas) is considered to be an end-use activity. The definition of final consumers is as follows: „natural or legal persons purchasing energy for their own use“. There is no exclusion for power-to-x-to-power storage or power-to-gas. Although there are increasing voices to remove the classification as final consumer, these efforts have so far not led to any change in the law [59] [70].

  Concerning the network tariffs Article 118(6) EnWG 2017 establishes that installations for the storage of electrical energy are, for a period of 20 years after becoming operational, exempted from paying L-charges (charges for loads or final consumers) related to the purchase of electricity which feeds into the installation. Power-to-gas installations are thus exempt from L-charges. This exemption also applies when there is no reconversion to electricity (according to the predominant opinion) [59].

- Italy: Final consumers are defined as „natural or legal persons purchasing energy for their own use“. Independent of whether reconversion occurs or not, a power-to-gas installation is to be considered as a final consumer of electricity. Final consumers of electricity in Italy pay L-charges. Operators of pumped hydro storage plants are exempted from the obligation to pay transmission and distribution network tariffs for electricity. This exemption is extended to other systems for the storage of electricity. However, an exemption from network charges for cross-sectoral storage technologies does not exist in Italy. Italy has no system of G-charges for producers of (renewable) gas who are feeding into the network [59].

- Switzerland: Article 4(1) of the Electricity Supply Act defines a “final consumer” (*Endverbraucher*) as a “*customer who purchases electricity for its own use. Excluded therefrom is the purchase of electricity for (…) the propulsion of the pumps in pumped storage power plants”*. Whether other storage technologies are similarly excluded from the definition of final consumer is not clarified under the Electricity Supply Act. However, at least in the context of electricity network tariffs, the Swiss authorities award equal treatment to storage technologies which discharge the stored energy as electricity into a public network. On the question whether the power-to-gas plant operator is a final consumer when the SNG is not reconverted, the Federal Council has stated: *“from the point of view of the Electricity Supply Act, a power-to-gas plant which does not inject electricity back into the electricity grid is an end consumer”.*[44] L-charges for the electricity fed to the electrolyser are not to be paid when the electricity is withdrawn from a directly connected wind or solar installation behind a connection point with the public network. L-charges for the electricity fed to the electrolyser are also not to be paid when the electricity is withdrawn from the network, stored, and reinjected as electricity at a later point in time. L-charges need to be paid, however, when a Power-to-Gas installation converts electricity into a gas without the reconversion to electricity taking place at a later point in time. The injection of gas (including renewable gas) by producers is not subjected to G-charges [59].

Concerning chapter 6.5.2:

[44] Response by the Federal Council to Motion 16.3265 of 4 November 2011 by the Commission for Environment, Spatial Planning and Energy.

- Germany: Hydrogen and SNG produced through Power-to-Gas are definitely a “gas” in the context of the EnWG and GasNZV. When both the electricity and carbon come predominantly from renewable sources, these gases are also to be considered “biogas”. The German legislator has clarified that at least 80% of the electricity fed into the electrolyser *and* the carbon used for methanation must come from renewable sources[45] [59].

- Italy: The Letta Decree No 164/2000 applies in a non-discriminatory manner *“to biogas and gas derived from biomass or other types of gases, to the extent that these gases can be injected into the natural gas system and transported through that system without posing technical or safety problems to the system“.* The Italian legislation allows SNG to be treated as a gas of a renewable character, namely as biomethane (*biometano*). The definition of biomethane is not limited to biomass-based gases, but seems to apply to *all* gases produced from renewable sources which are of a similar gas quality as natural gas and can therefore be injected into the gas grid. There is no guidance available as to the exact application of the definition on biomethane to nonbiomass based gases from renewable origin such as SNG. Although it can be deduced from the wording of the definition that at least the electricity, as the energetic component, must be of a renewable origin, the question whether this is the same for the carbon source is left open. What can be concluded, however, is that the definition is broad enough to include SNG produced through Power-to-Gas when both the electricity and carbon are of a renewable origin [59].

- Switzerland: The Federal Pipeline Act applies to pipelines for the transportation of petroleum, natural gas, or other liquid or gaseous fuels designated by the Federal Council[46]. In fulfilment of this task, the Federal Council adopted the Federal Pipeline Ordinance which applies to pipelines for the transportation of liquid or gaseous fuels, hydrocarbons or hydrocarbon mixtures such as crude oil, natural gas, refinery gases, petroleum distillates or liquid residues of petroleum refining.[47] This scope is broad enough to cover hydrocarbons from a renewable origin such as SNG. A definition of SNG or other gases from renewable origin such as biogas is provided under Directive G13 on the *“Injection of Renewable Gases*” issued by the SVGW. This Directive sets the technical and chemical conditions for the feed-in of renewable gases from biomass or other renewable energy sources.[48] The term “renewable gas” (*Erneuerbare Gase)* encompasses biogas, renewable hydrogen, and renewable methane.[49] As “Renewable hydrogen” (*Erneuerbarer Wasserstoff*) is considered hydrogen produced from biomass or other “renewable energy carriers”.[50] Finally, “renewable methane” (*Erneuerbares Methan*) is defined as synthetic gas produced through the methanation of renewable hydrogen.[51] What is understood as a “renewable energy source” is not explicitly defined under Swiss energy legislation. The following renewable sources are, however, listed under the Federal Energy Act in the context of incentives for the feed-in of electricity from renewable energy sources: hydropower, solar energy, wind energy, geothermal energy, and biomass[52] [59].

Concerning chapter 6.5.3:

- Germany: Article 36(1) of the GasNZV requires that in-feeders of biogas ensure that the gas at the entry-point and during injection complies with the gas quality specifications in worksheets G 260 and G 262 of 2007 issued by the German Association for Gas and Water (Deutscher Verein

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[45] BT-Drs. 17/6072, S. 50.
[46] Article 1 of the Federal Pipeline Act of 4 October 1963, No. 746.1.
[47] Article 1 of the Federal Pipeline Ordinance of 2 February 2000, No. 746.11.
[48] Paragraph 1 of the SVGW Directive G13d on the “Injection of Renewable Gases”.
[49] Paragraph 3 of the SVGW Directive G13d on the “Injection of Renewable Gases”.
[50] Paragraph 3 of the SVGW Directive G13d on the “Injection of Renewable Gases”.
[51] Paragraph 3 of the SVGW Directive G13d on the “Injection of Renewable Gases”.
[52] Article 19(1) of the Federal Energy Act of 30 September 2016.

des Gas- und Wasserfaches, hereafter "DVGW").[53] The amount of hydrogen which can be injected will depend on the local network conditions (e.g. capacity, availability and quality of other gases, pressure, and nearby end-users). Due to the existence of such varying local conditions, DVGW worksheet G 262 only gives the advice that, as a starting point, a hydrogen limit of up to 10% is general technically possible, but admixing needs to consider local boundaries [59].

- Italy: There is sufficient basis to argue that SNG, in so far as it conforms with the requirements of UNI EN 16723-1, UNI/TR 11537 and the Ministerial Decrees of 2007 and 2013 (amongst others a hydrogen limit of 0,5%), is now allowed to be injected into the Italian public gas network. First, although SNG is treated as biomethane in Italy, its chemical composition is more similar to natural gas than to biomass-based gases. Second, all components present in SNG (methane, carbon dioxide, and hydrogen) are now specified under the different technical regulations and standards. As such, not allowing SNG to be injected would likely be in breach of the non-discrimination principle under Article 2-bis of the Letta Decree, which requires the equal treatment of gases which can technically and safely be injected into the natural gas network. The injection of non-compliant gases is only allowed for natural gas producers [59].

- Switzerland: Technical specifications on the required gas composition for the injection of gas into the network are provided by the Swiss Gas and Water Industry Association (*Schweizerische Verein des Gas- und Wasserfaches,* hereafter "SVGW"). Relevant for SNG are SVGW Directives G18 (gas quality in the natural gas grid), G13 (injection of renewable gases), and G11 (Odorisation). It is possible to inject gases which are not compliant with SVGW Directives G18 and G13 by admixing these to the gas which flows through the gas network. As a minimum requirement, the injected gas must consist at least for 50% out of combustible components. Furthermore, the injected gas must be able to mix into the available gas stream so that the gas is compliant at the first exit point of a consumer.[54] The maximum amount of renewable gas to be injected is then thus determined by the composition of the gas mixture after the entry point and before the first consumer exit point[55] [59].

[53] Both worksheets are available in the online shop of the DVGW: https://shop.wvgw.de.
[54] Paragraph 7.9 of SVGW Directive G13.
[55] Paragraph 7.9.2 of SVGW Directive G13.