

Remarks to the reader of the STORE&GO Roadmap for large-scale storage based PtG conversion in the EU up to 2050

The STORE&GO project started in 2016 and has been running up to February 2020. The content and conclusions in the Roadmap therefore reflect the results generated during this period. Since there have meanwhile been some fundamental developments at the EU political level, e.g. with the publication of “The European Green Deal” [1], EU strategies for energy system integration and hydrogen documents [2] [3] and the 2030 Climate Target Plan [4], the authors feel the need to give the reader some reflections on how they feel these new developments relate to the content of the STORE&GO document, and could have altered the conclusions.

With regard to the text of the STORE&GO Roadmap the more recent developments seem to generally underline the STORE&GO key point of the need for an urgent and progressive approach to “greening the molecules” and gas in particular. Some of the actions suggested in the European Green Deal are already addressing this, and one can therefore argue that they are in line with the roadmap recommendations.

In the European Green Deal 2030 Climate Target Plan a more ambitious mid-term mitigation target is mentioned, 55% rather than the prior target of 40% [4]. In our view this new target would not have altered the conclusions made in the Roadmap. It rather emphasises the need for a strategic and coordinated approach to guarantee a well-functioning energy market, efficient technologies, and sufficient supply of renewable gases in time as described in the roadmap ‘The energy picture of the EU by 2050’.

In the text of ‘Powering a climate-neutral economy: An EU Strategy for Energy System Integration’ [2] [5], the team also welcomes some suggested actions that are strongly in line with the roadmap recommendations:

1. Decarbonisation of the gas sector and promotion of smart integration across sectors is stated as one of eight focus areas in the corresponding factsheet “Clean Energy” that need to be addressed. This is further underlined with the first focus area mentioned - Interconnect energy systems. The team welcomes this as a clear plea for having Power-to-Gas to play a major role in integrating the future energy system.
2. The EU documents also mentions the promotion of renewable and low-carbon fuels, including hydrogen, for sectors that are hard to decarbonise [2] [6], which clearly is in line with the Roadmap text, as well as notions such as:
 - a. ‘Unlock the potential of sustainable biomass and biofuels, green hydrogen, and synthetic fuels’.
 - b. ‘Enable carbon capture, storage and use to support deep decarbonisation, for example in cement production’.
 - c. ‘Clearly define and classify different fuels to support market uptake and transparency’.
 - d. ‘Promote innovative projects based on low-carbon fuels, such as hydrogen-fuelled clean steel plants’.



Furthermore in the same series of documents, and equally in line with the Roadmap suggestions:

3. The adaption of energy markets and infrastructure to a more complex, integrated energy system with the following set of actions:
 - a. 'Ensure equal treatment for all energy carriers, making electricity and gas markets fit for decarbonisation, for example with respect to taxation'.
 - b. 'Support research and innovation to create new synergies in the energy system'.

In the text of the other recent EU publication 'Hydrogen Strategy for a climate neutral Europe' [3] [7], the reader will probably recognize various policy suggestions also mentioned in the Roadmap, although the EU text relates to hydrogen only, whereas the STORE&GO roadmap looks at all renewable energy gases with a key role for Synthetic Natural Gas.

EU and STORE&GO suggestions that are quite similar are, for instance:

4. Support for 6 GW of hydrogen electrolyzers until 2024 with a production of up to 1 million tonnes of renewable hydrogen (compare '10 demo projects until 2025' in the Roadmap)
5. Boost the demand for clean hydrogen coming from industrial applications and mobility technologies (Roadmap suggesting mandatory admixing or introducing quota for renewable gases), and
6. Promoting research and innovation in clean hydrogen technologies (where the Roadmap suggests the same for all renewable gases including methanation technologies in particular).

More generally, in the EU documents other renewable gases than hydrogen seem to be left a bit behind as well as actions on how to promote them. Boosting the role of carbon neutral hydrogen in the EU is absolutely important in the view of the team, but somewhat more focus on a level playing field in the promotion of all carbon neutral energy gases would have been desirable, if only because it probably is a less costly way forward. Because synergies in introducing different renewable energy gases seem possible, the team would rather suggest more attention for integrated approaches as a way forward.

References

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- [3] European Commission, "A hydrogen strategy for a climate-neutral Europe COM(2020) 301 final," Brussels, 08.07.2020.
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- [6] European Commission, "EU Energy System Integration Strategy," 08.07.2020.
- [7] European Commission, "A Hydrogen Strategy for a climate neutral Europe," 08.07.2020.

Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation

Roadmap for large-scale storage based PtG conversion in the EU up to 2050

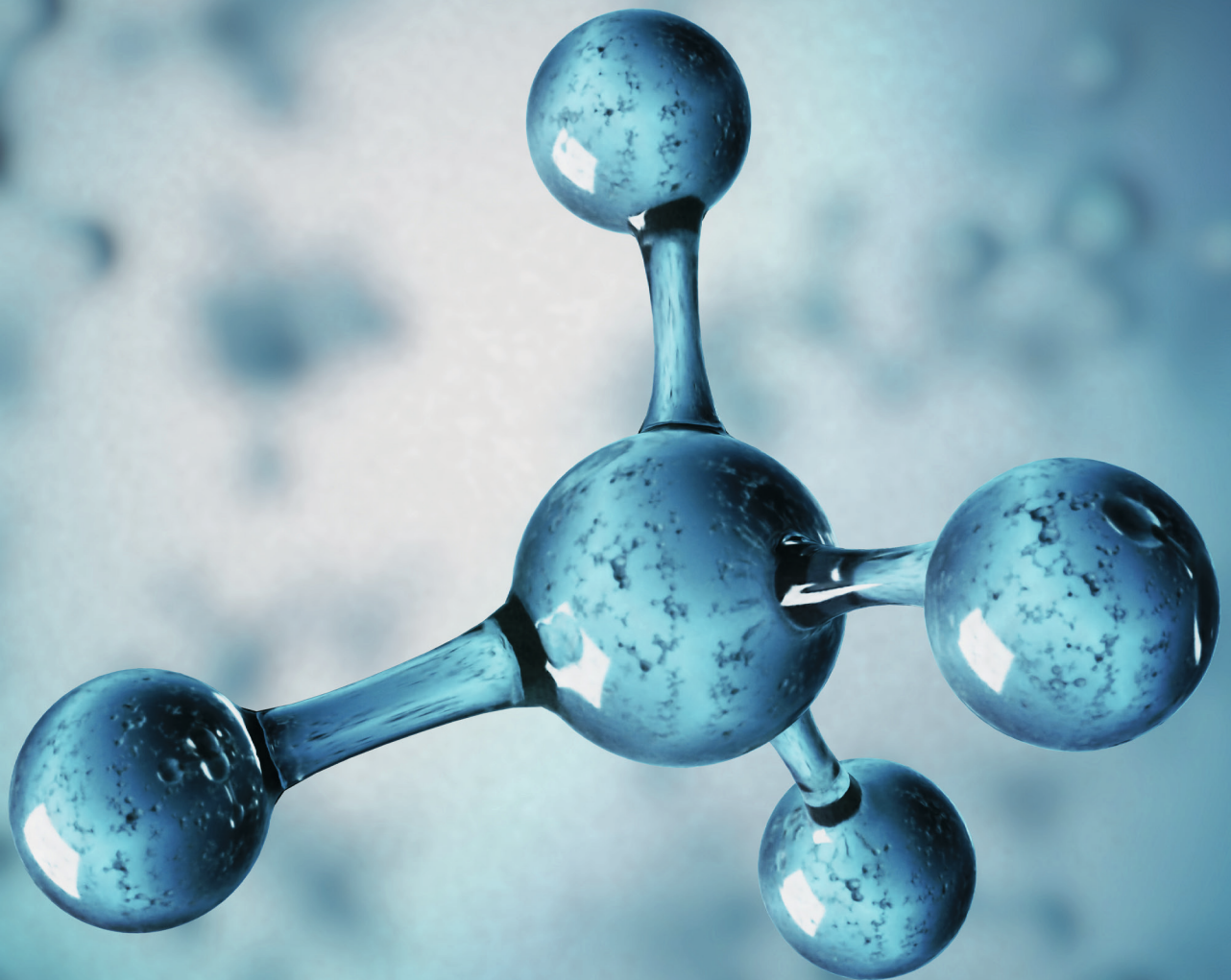


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Preface

The current European Energy Roadmap is aiming to cut the continent's greenhouse gas emissions by 80% to 95% by 2050. 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.

The vital role of gas and power-to-gas technology (PtG), in this context is undisputed. Complementary to green power (electrons), it will produce the green gases (molecules) needed to reach 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 electricity, industry, heating and cooling and mobility.

However, for PtG to achieve its potential in providing hydrogen and renewable methane as green carriers for the energy transition, regulatory hurdles have to be eliminated and the facilities have to be given equal access to the marketplace. To reach the goals of 2050 and related mitigation targets, power-to-gas will have to reach market maturity by 2025.

The STORE&GO project has been funded by the EU under the Horizon 2020 scheme and started almost five years ago in order to fathom the application of different power-to-gas technologies in three different European countries, acting as a reality lab. 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 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.

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 will only be possible if adequate pricing for gases is implemented, meaning that the ecological impact of gases from fossil sources has to be reflected in a much higher market price. A successful energy transition should end the constraints and burdens on innovative solutions such as the ones applied in the STORE&GO project and open a level playing field for them – thus unfolding the full potential of power-to-gas as the key enabler for decarbonisation.

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 biobased 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 leading the discussion on how to adequately approach these issues. What is obvious already at this point: The answers can only be found in combining renewable hydrogen, climate neutral 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 matured and climate-friendly gas-related technologies.

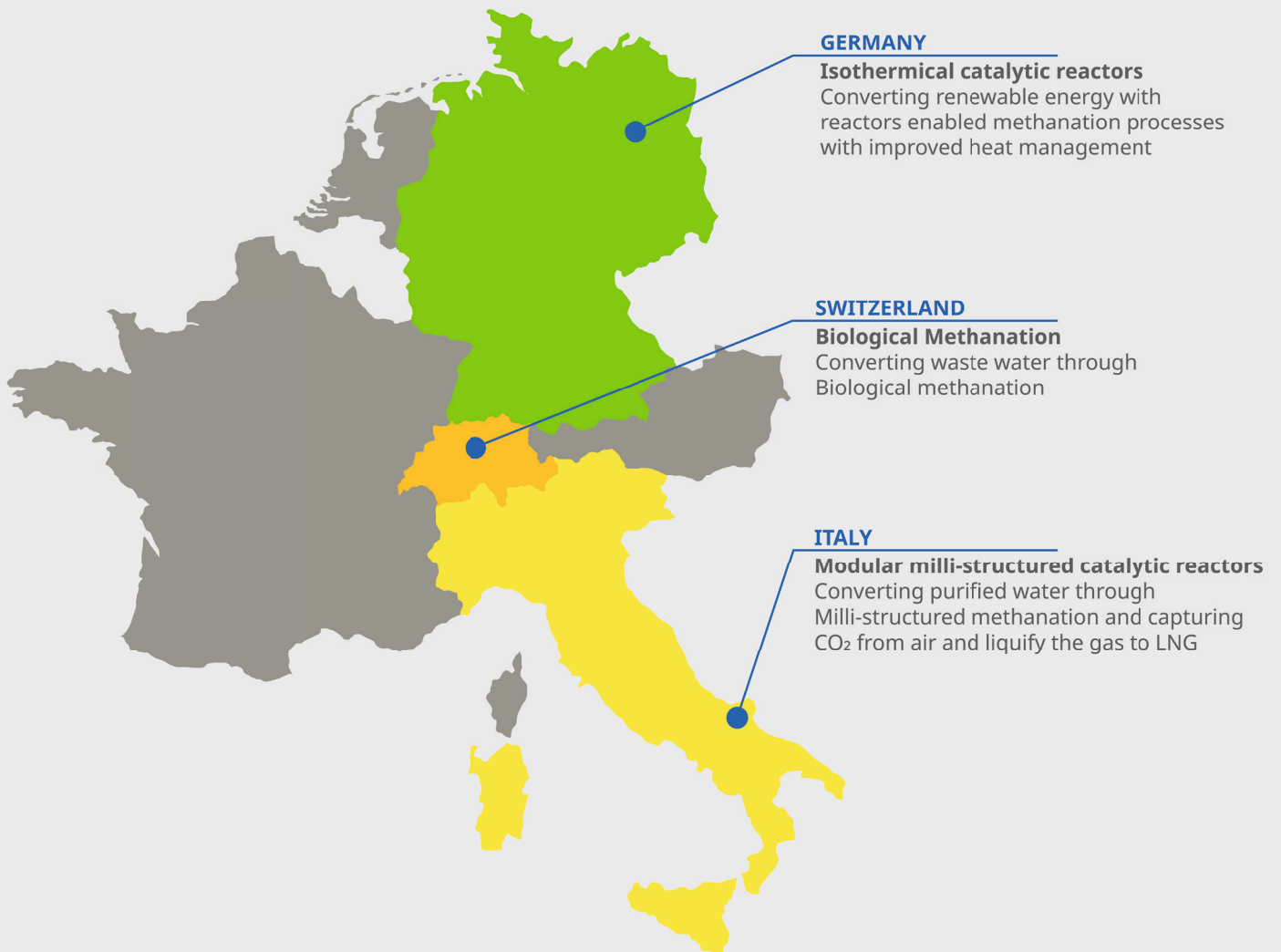


Figure 01: Map of the three demonstration sites and their characteristics

Executive Summary

In order to reach the 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.

The EU energy challenge: the importance of energy molecules for achieving the targets of 2050

Politics does not have a high focus on the potential of green gases, leaving aside that the EU Energy Roadmap itself projects a share of electrons of about 40% at most and even the electricity industry's association Eurelectric estimates a maximum of 60% of direct electrification [1]. Vice versa, these projections leave 60%–40% of the total energy uptake to energy molecules.

Currently, energy molecules form the backbone of the EU energy system (covering more than 70%) – not without reason thanks 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.

Green molecules and extensive sector coupling

Power-to-gas (PtG) enables the production of green energy (molecules) as hydrogen and renewable methane and is thus supporting carbon reduction paths not only in the electricity sector, but also for the transportation and industry sectors. Especially in long-distance maritime, road, and air transport, where electrification is not realistically possible. Also, in personal mobility further alternatives to electricity are needed to achieve carbon reduction.

About half of the EU's energy consumption goes into the heating in buildings and in the industry. Although the total amount of heating energy is expected to decrease due to building renovations and efficiency measures, a largescale 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.

In the industry sector, to achieve high temperatures the need for energy molecules as feedstock will remain [2]. 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 main sources of carbon for green energy molecules

Considering all the sectors within the energy system, it is likely that the need for gas will stay very high and the demand for green gases will grow significantly. Studies commissioned by the EU and dealing with the gas demand prediction estimate a range between 1,860 to 4,700 Terawatt hours (TWh).

The future gas demand will mainly have to be covered by carbon-neutral gases – such as biomethane, synthetic methane (synthetic natural gas, SNG) and green as well as blue hydrogen. The main source 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 blue hydrogen – hydrogen produced from natural gas and including Carbon Capture and Storage (CCS) technologies.

Green methane is obtained by adding a further methanation step to the green hydrogen gathered from PtG electrolysis and combining it with CO₂. There are basically two major sources providing green CO₂: biomass and direct capture from the air (DAC). The grey CO₂ from industrial processes like cement and steel production can be counted as the third source. The future share of these three sources will be a trade-off. Availability of biomass is limited, and it may be claimed for other uses. DAC is currently the costliest source. Industrial sources are expected to reduce in the future, even if some will remain at large scale. Instead of releasing the resulting CO₂ directly into the air, it is reused for methanation and subsequent gas applications.

The role of the gas infrastructure for the overall energy system

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, e.g. for green gases stored from renewable sources in times of surplus production – 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 acceptance of the public to large infrastructure projects very often is a risk for such projects. By contrast, necessary expansions of the natural gas network would also result in less topographical intervention in relation to the expansion of the electricity grid.

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

In general, 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 €/kW¹, 170 €/kW² and 270 €/kW³ 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.

There is only little difference in SNG production costs, depending on which technology is employed. Depending on the used 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

In order to achieve the 2050 goals, power-to-gas must be commercially competitive by 2025. 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:

Power-to-gas (PtG) 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. Simultaneously there needs to be a clear perspective for a functioning market on the other side of the valley. To overcome this valley of death and to establish a functioning market for renewable gas, support and funding schemes are needed for research and development as well as for investors. This could take the form of substantial demo-projects for large scale deployment of power-to-gas. The preferred tool to establish a fair market for renewable gas would be the introduction of an admixing quota system. A gradual approach would for example start with low shares in certain sectors, such as industry, and then gradually diversify the sectors and increase the obligatory quotas. This approach would both help to overcome the valley of death and be a legitimate tool to establish a functioning market. This needs to be accompanied by an operational system for guarantees of origin.

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. Unfair double network tariffs, unclear definitions of power-to-gas and eligible roles for different stakeholders need to be ruled out.

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.

¹ AEC ² PEMEC ³ SOEC

The STORE&GO Project

A reality lab for optimisation of large-scale power-to-gas conversion

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 is currently running three pilot plants with different innovative power-to-gas technologies. 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.

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 currently produces up to 1,400 m³ of Synthetic Natural Gas (SNG) per day, equivalent of approximately 14,500 kilowatt-hours (kWh) of energy.



Figure 02: Methanation plant in Falkenhagen

The second STORE&GO demonstration site is located in Solothurn (Switzerland). It employs a special methanation method. Microorganisms, the 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.

The third demonstration site has been built in Troia, Italy and shows that direct air capture of CO₂ can also represent a technical option. The plant combines a novel microreactor for methanation with an innovative liquefaction plant. The required CO₂ is captured from the ambient air. 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 they are 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 has been 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.

	Demonstration site Falkenhagen/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 area 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 03: Characteristics of the three demonstration sites (<https://www.storeandgo.info/demonstration-sites>)

1. The energy picture of the EU by 2050

The need for power-to-gas technology

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 we bring this vision to life?

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, including industry, heating/cooling systems and transportation. All studied projection scenarios show that gas and 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. Even in high electrification rate scenarios, 40-60% of final energy consumption needs to be satisfied with molecules.

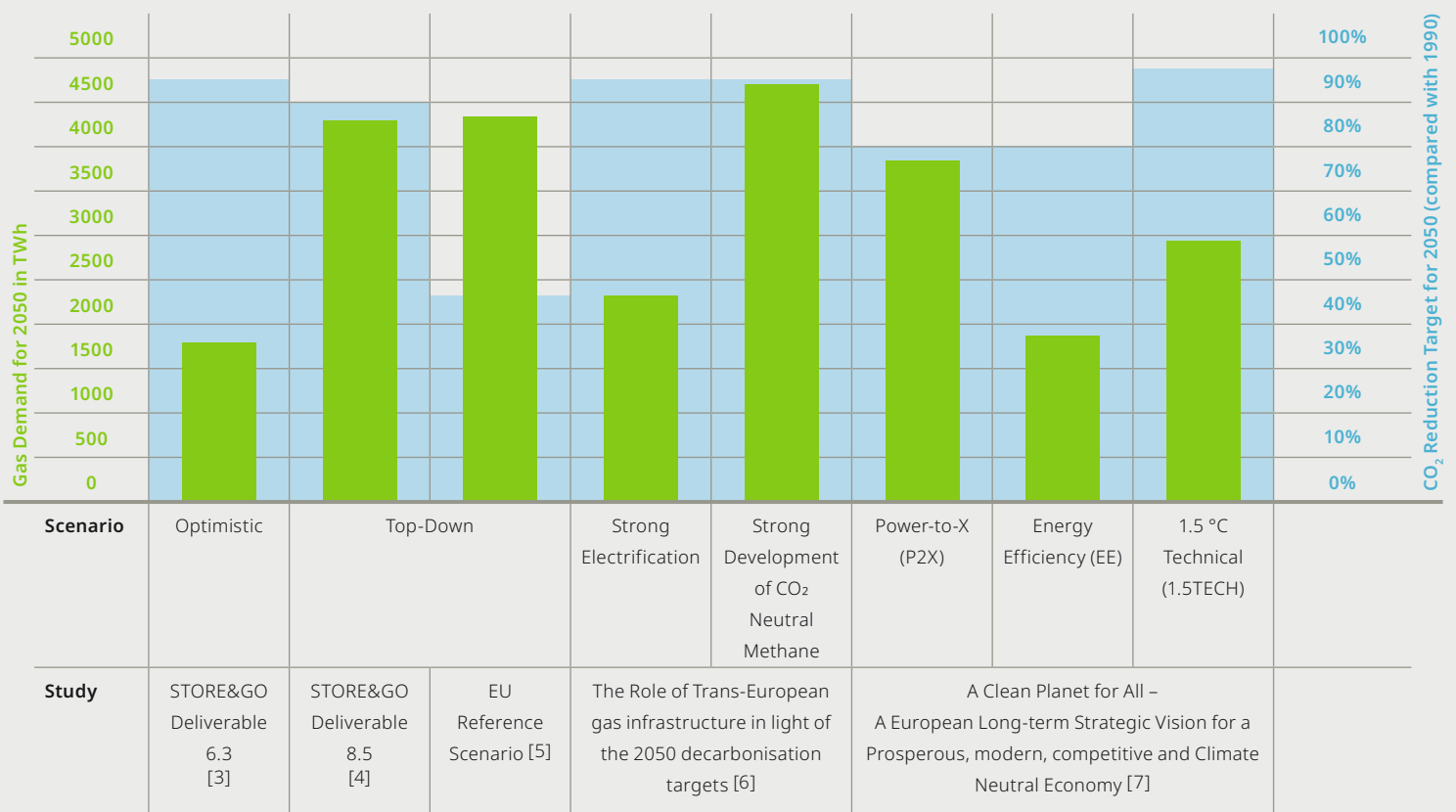


Figure 04: Estimates of the gas demand in 2050 vary between different studies and scenarios [3] [4] [5] [6] [7]

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.

A number of studies commissioned by the EU ([5], [6], [7]) estimate a range of 1,860 to 4,700 TWh for the total gas demand in 2050, 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 study on the short, medium and long-term perspective of various market segments for green gases carried out during the STORE&GO project, the future gas demand in 2050 is estimated to 4,373–4,443 TWh [8]. The leading 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 EU by 2050 [3].

In all sectors, but especially in branches without any or with insufficient technologies available for electrification, the only effective way for decarbonisation is to employ energy molecules, produced from climate-friendly renewable sources. This applies to heavy transport, marine and air traffic and concerns the industry sector, where gases are needed for energy as well as feedstock in production processes.

The electric sector is facing growing challenges to phase out coal fired power generation and simultaneous build-up of renewable energy generation. 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 CO₂ savings could be made, and by gradually greening the gas, further CO₂ savings could be achieved. Conventional gas and gas-CHP (CHP: combined heat and power) is the optimal partner for renewable volatile electricity (RVE) 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% [3] [4].

In the industry sector the top 5 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 higher 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. The net renewable gas demand in 2050 of the industry sector in

The sufficient supply of green gas...

... will be critical to satisfy both the EU climate targets and the demand for clean energy in the form of molecules. Today 70% of the European energy system rely on molecules as energy carriers. Projections toward 2050 indicate that this share will remain substantial and likely on the upper scale or even beyond current leading projections.

the top-down assessment is about 630 TWh. The share provided by power-to-gas is estimated to be about 10-65% [4].

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. The chemical/petrochemical sector is heavily reliant on mainly oil and gas as key feedstocks and produces non-energy products such as chemical fertilizers and plastics. The net renewable gas demand in 2050 of the industry sector in the top-down assessment is about 570 TWh. The share provided by power-to-gas is estimated to be about 30-60 % [4].

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 [4].

The heating of buildings and industry cumulates roughly to about half of the EU's energy consumption. Though 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 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% [4].

	Net gas demand 2050 acc. to top-down assessment	Share possibly provided by PtG
Electric sector	1200 TWh	0-5%
Industry (energy consumption)	628 TWh	10-65%
Industry (non-energy consumption)	570 TWh	30-60%
Heating Systems	756 TWh	30-60%
Mobility	1012 TWh	30-60%

Figure 05: Gas demand across the sectors. "Non-energy consumption" denotes usage as feedstock [4].

In mobility, electrical drives still struggle with acceptance issues as well as daily mileage and are available only as part of appliances, so gaseous and liquid e-fuels from power-to-gas applications could be a complementary fuel alternative for air, marine and heavy traffic. The net renewable gas demand in 2050 of the transport and mobility sector in the top-down assessment is estimated to about 1,012 TWh and therefrom about 30-60 % would be provided by power-to-gas [3] [4].

A critical cross-check of results: 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 [4].

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 [4].

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 alone, the sheer gas amounts which are needed clearly illustrate 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.

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 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.

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 [9].

A power system that heavily relies on renewable energy sources must cope with their intermittent supply. Uptake of renewables comes with some great challenges such as curtailment of renewable energy sources, flexibility issues and long-term storage [10]. 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.

In the development of hybrid networks...

...the natural gas infrastructure is a key component. Hybrid networks integrate changing mixes of power generation, transmission and distribution, delivery and control. Hybrid networks are able to connect different energy systems bidirectionally 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.

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.

The key advantage of energy storage in gases: energy can not only be stored and released locally and in the short term, but it also applies to converting large amounts of energy for long term storage. 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 the 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 can do [10]. Furthermore, the battery cost is expected to decrease in the next decades; however, even if the battery cost decreases to 60 €/kWh by 2050, it will still be more expensive to store the surplus renewable electricity for seasonal storage purposes compared to PtG [11].

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 might vary. Still it remains undisputed that with high penetration of renewable energy sources in the energy system, energy storage is required [12].

The current gas storage capacity (operational) in Europe (EU-28) is around 1,131 TWh according to Gas Infrastructure Europe (GIE) and these gas storage facilities can deliver up to 22 TWh natural gas per day. Moreover, this gas storage capacity is planned to increase to 1,300 TWh in the future [13].

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” [14].

Renewable methane from PtG and the supply of CO₂

In a scenario relying on large-scale methanation as common practice throughout the EU, notable quantities of CO₂ are required for the methanation process. Two major sources are providing green CO₂: biomass and direct capture from air. Industrial processes like cement and steel production are the source for so called grey CO₂. The future share of these three sources will be a trade-off. The availability of biomass is limited, and it may be claimed for other purposes.

However, stricter CO₂ reduction targets, will lead to even further replacement of industrial CO₂ sources by alternative technologies. Accordingly, less CO₂ from these sources will be available.

Two scenarios of limited or balanced CO₂ availability were created for a potential impact analysis. The limited CO₂ availability scenario describes a 95 % reduction of the industrial CO₂ compared to 2015 levels by 2050, whereas the balanced CO₂ availability scenario achieves a CO₂ reduction of 90 % in the same time frame. As a result, the CO₂ from industrial sources provides for about 130 to 260 TWh of methane respectively, as the analysis in STORE&GO shows [15].

As for biomass, estimates of the technical potential across Europe differ widely, from 1,000 to 8,300 TWh [16]. Assuming that one third of this biomass can be used for biogas production the total potential amount of methane from green sources reaches values between 1190 – 1390 TWh/a, by far outperforming the industrial methanation potentials estimated for 2050. Producing methane from green CO₂ and grey CO₂ from industry applications could cover between 1,320 and 1,650 TWh for the limited and balanced CO₂ availability scenarios respectively. This corresponds to 35 to 70 % of the total gas demand [15].

A further alternative option investigated in STORE&GO is direct air capture. Direct air capture (DAC) is currently the most expensive technology, though in principle unlimited. Industrial sources should be reduced in the future, but some will most likely remain at large scale. Instead of releasing this CO₂ directly into the air, its reuse in methanation and subsequent gas applications offers a better solution.

Around 1100 Terawatt hours...

... 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. Existing storage infrastructure is estimated to be 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, holding huge storage capacities, could serve for this purpose – without building up additional infrastructure [13].

Towards an EU 2050 roadmap

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 we bring this vision to life?

The EU Reference Scenario [5] and other EU studies [6] [7] sketch out a scenario, in which some 1,200 GW wind and some 2,000 GW solar generate around 5,000 TWh per year, with further 2,500 TWh coming from EU hydro and nuclear capacities [4]. If the final energy consumption will be around 11,000 TWh in the EU in 2050 (projections in EU-related studies vary by around 2,000 TWh), then the described domestic EU carbon-neutral power supply could deliver about three quarters of the 2050 EU energy uptake [5] [7]. 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 [1].

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. In the electric and mobility sector renewable gas demand are the highest, estimated to go beyond 1,000 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%. An 'electrification scenario' without enough energy molecules would pose major problems,

particularly regarding energy transport and storage infrastructures – leading to considerable costs.

Annual extra costs for EU taxpayers in an 'electric scenario' might sum up to over 200 billion Euros, compared to a system based on molecules which would play a significantly larger role by combining the existing gas grid with power-to-gas technologies [2] [11] [17]. This alternative scenario already includes a substantial build-up of the required capacities for biomethane and blue hydrogen production as well as power-to-gas conversion and would allow for extensive sector coupling – meaning the integration of all energy consuming segments with the power generation sector.

All studied projection scenarios show that gas and power-to-gas must play a major role with an estimated total gas demand between 1,860 to 4,700 TWh. 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.

This demand for green molecules alone presents a major argument for the build-up of substantial PtG capacities. Methane production using green and grey CO₂ could cover 40-140% of the total gas demand. 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.

Moreover, the systemic benefits of power-to-gas in the electrical system illustrates another argument. Seasonal storage facilities for electricity of 1,000-1,100 TWh would be required annually to balance the system. The existing gas storage infrastructure as it stands at the moment would already be able to cover this. Furthermore, additional services for energy transport and grid balancing might be provided with the same technology.

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.

200 billion Euros...

... are the annual extra costs for EU taxpayers of an almost exclusively 'electric scenario'. The alternative is a scenario in which molecules play a significantly larger role by combining the existing gas grid with PtG technologies. This alternative would include a serious extension of the biomethane and blue hydrogen production beyond 2030, but most of all of massive conversion of power-to-gas.

2. Technological characteristics and market requirements

High Technology readiness and high potentials for further optimisation

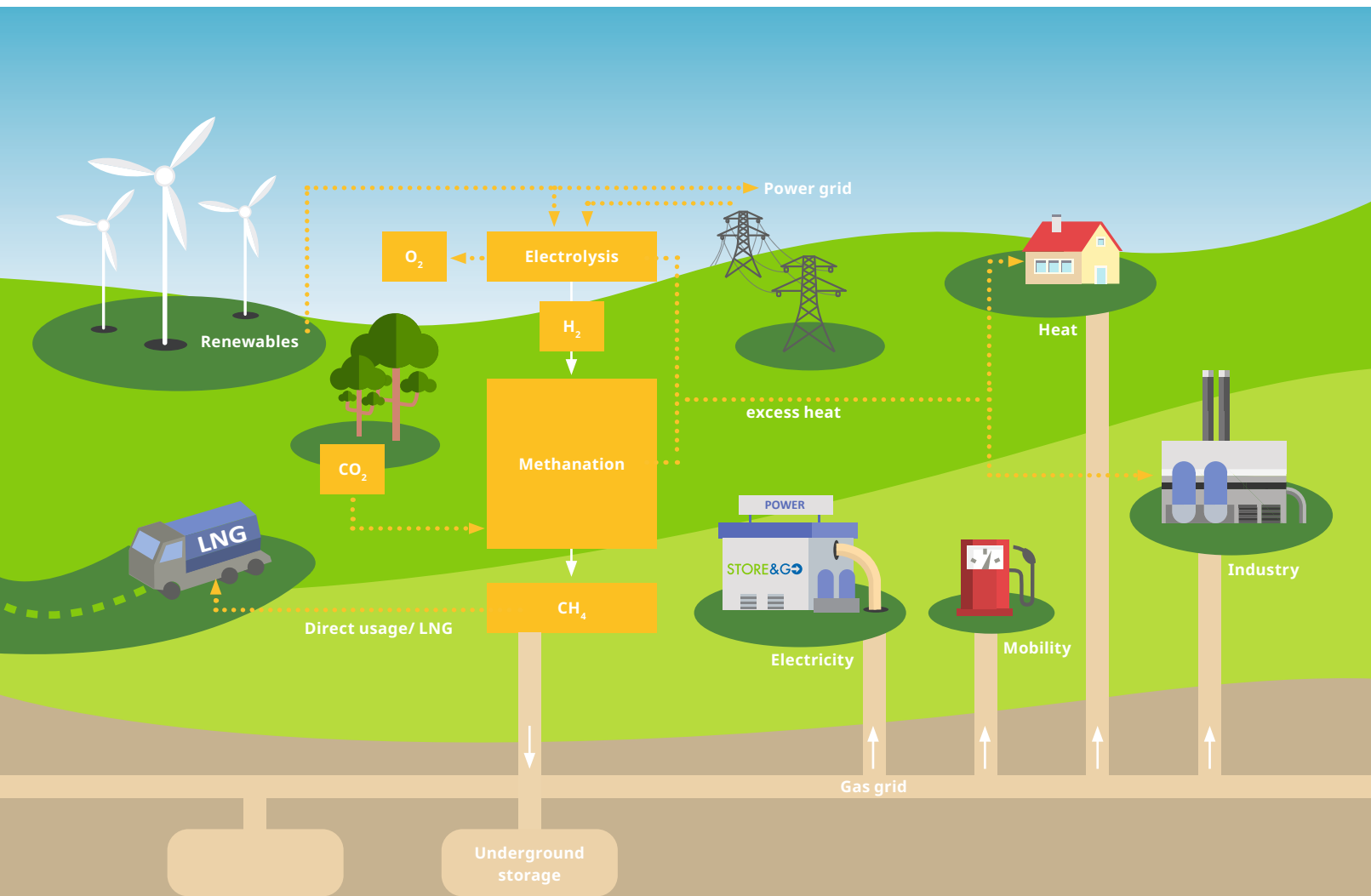
Operating power-to-gas in conjunction with innovative technologies and processes, is one of the achievements of the STORE&GO project. With its three demonstration plants in three different European countries, the project has shown technological maturity of power-to-gas. The main conclusions from the experience of the pilot projects can be summarised by the following statements:

- The power-to-gas technology at the STORE&GO sites demonstrates the high level of technology readiness for the market and an ongoing rapid development.
- A full range of technologies are 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 electrolysis 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 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

The outdated regulatory frameworks are currently acting as restraints and need to be reformed so the resulting market distortions can be eliminated. 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.

Figure 06: Process chain of PtG within the project STORE&GO (Source: Energieinstitut an der JKU Linz)



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.

1. 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 offering 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.

a) Electrolysers today and potential further development

The 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). It is already being applied with larger installations of 10 MW and higher. The efficiency of the system is about 75% with a lifetime of about 60,000 hours of operation. The cold start duration is about one hour [18].

The PEMEC technology is mature, complete and qualified (TRL 8). The commercialisation of large systems is only in its beginning stage. The efficiency ranges between 70-75%, with a lifetime of about 45,000 hours of operation. The cold start duration time is quite low: just around 10 minutes, offering a highly dynamic application [19].

The SOEC technology has been demonstrated in an industrial environment (TRL 6) and is considered as potentially disruptive. It offers impressively high efficiency levels (93%) already today and substantial cost reduction potentials in the future. Although it provides high capacity and very high efficiency, the lifetime of the electrolyser is about 25,000 hours of operation [18].

As renewable hydrogen has gained increasing attention due to the potential it holds for a low carbon energy system, electrolysis technologies have significantly and positively evolved in recent years. For several characteristics, like stack and system capacity, stack lifetime and degradation, the development so far outperforms the values forecasted 10 years ago. This highlights the efforts put into the technology and shows its relevance for future energy systems.

b) 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 possible component of STORE&GO 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 [20], so the underlying processes are mature. Therefore, most recent developments have tackled the optimisation of reactor technologies, upsizing, and cost reduction [20] [21] [22] [23]. 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 one hand and chemical, or catalytic, methanation on the other.

Catalytic methanation occurs with the aid of catalysts at high temperature (200-700°C) and under high pressure (1-100 bar). The technology is commercially available (TRL 8) and already in industrial use. System efficiency is about 80%. When implementing strong heat recovery, even higher efficiencies of up to 95% can be reached. While modern electrolysers can be operated with a very high load flexibility, the catalytic process of methanation does not yet meet this requirement [24] [25].

Biological methanation is carried out at comparatively low temperatures (30-70°) and pressures. The conversion of hydrogen and carbon dioxide is done by microorganisms. Biological methanation is currently being tested at a pilot and demonstration scale and is not commercially available yet (TRL 7). The system provides an efficiency of 80%. As the methane conversion rate is relatively low, a higher number of reactors, or reactors of bigger volume are needed [24] [25].

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.

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

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.

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 through further development. Furthermore, significant cost reductions can be expected based on learning curve effects.

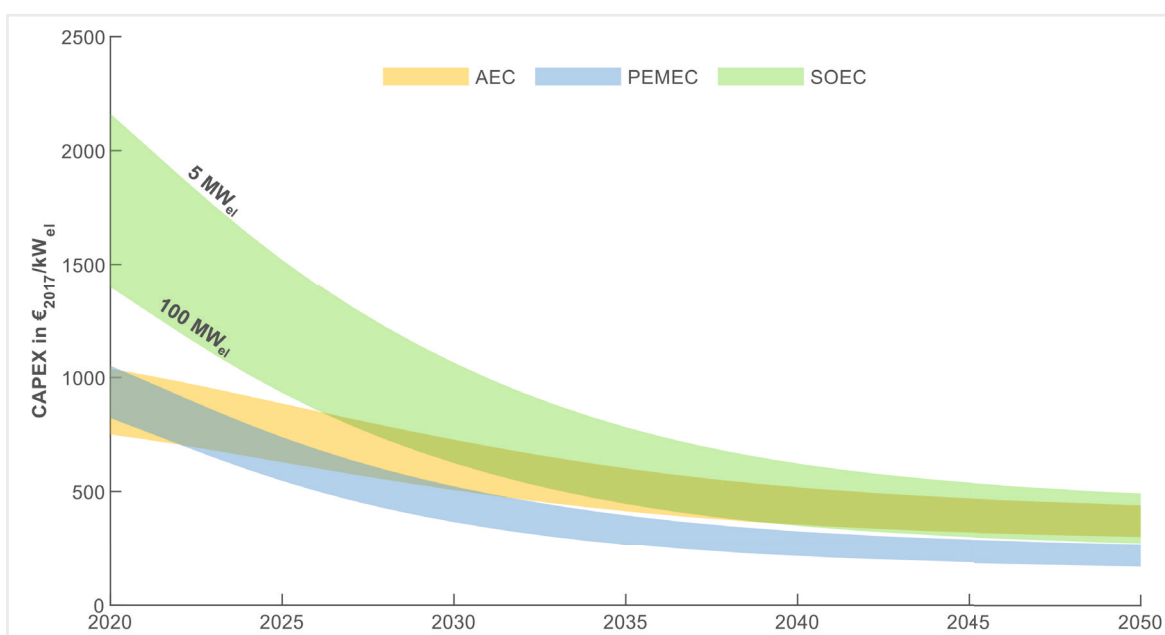


Figure 07: Cost development of electrolysis systems related to scaling effects and technological learning

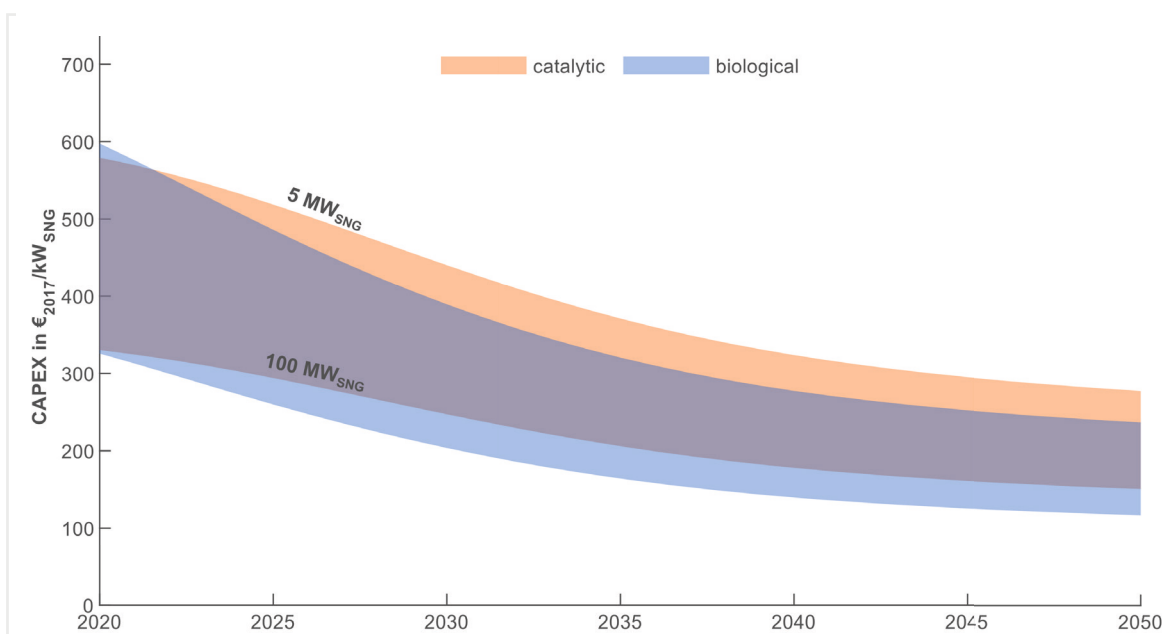


Figure 08: Cost development of methanation systems related to scaling effects and technological learning

3. Auxiliary technologies for specific options

a) Carbon capture

Besides hydrogen, carbon dioxide is the second necessary feedstock to produce green methane or SNG. It comes mainly from three different sources: CO₂ 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 [26]. Defining the cost precisely is challenging as it highly depends on the concentration of the CO₂ in the source stream. Thus, CO₂ from ammonia production is less expensive than from a natural gas operated power plant. Cost values from research literature for a ton of CO₂ vary between 12 €/ton and 101 €/ton [19].

Carbon dioxide from biogenic sources is the furthest developed carbon capture technology with a TRL of 9 [26]. The cost for the technology ranges between 0 €/ton (as by-product of a biogas plant) and 111 €/ton CO₂ [19]. 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 CO₂ concentration in the air and due to the maturity level of the technology (TRL 7–9) [26]. The costs for this technology lie between 80 €/ton and 475 €/ton [19]. Theoretically, the amount of derived heat from the methanation process is enough to be used for direct air capture technology because the direct air capture technology requires heat [24].

b) Liquefied Natural Gas (LNG)

When cooling natural gas down to around -162°C it liquefies. In its liquid form, natural gas needs 600 times less volume and thanks to thermal insulation of vessels, LNG can be transported very efficiently via ships, trucks or trains – a good alternative wherever a gas pipeline is not available. Additionally, it can be stored in LNG-hubs and used for peak-shaving.

Liquefaction technology is fully commercial and is already available for large scale application. The infrastructure is ready and can be used for liquefied renewable gas without any modifications (LRG).

4. 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 European energy supply must be transformed due to energy-related, social, economic, and environmental/climatic factors.

The use of green gases based on 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. Therefore, since the market launch and development of 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 has been undertaken based on the calculation of the specific production costs for SNG in 2020, 2030, and 2050 for a power-to-gas plant (PtG) with 100 MW electrical input for three different fields of application (PtG plant powered by a photovoltaic power plant (PtG-PV); a PtG plant powered by a wind farm (PtG-Wind); and a PtG plant powered by the public grid (PtG-Grid) as well as for different PtG technologies, which are combinations of an AEC, PEMEC, and SOEC, with a catalytic or biological methanation unit.

Figure 09 summarises the results of all the calculations performed, providing a range of costs for each use case.

The full-load hours for reasonable PtG plant operation (gas production, SNG production costs, and grid suitability) are regarded to be in the range of 3,000 to 5,000, incurring costs of about 5.5 to 7.5 Cent/kWh in 2050 in an optimal case. 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.

5. 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 PtG technology [3]. The potential future investment cost reduction of the main components of the PtG 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 similar to the energy picture of the EU by 2050 presented in Chapter 1.

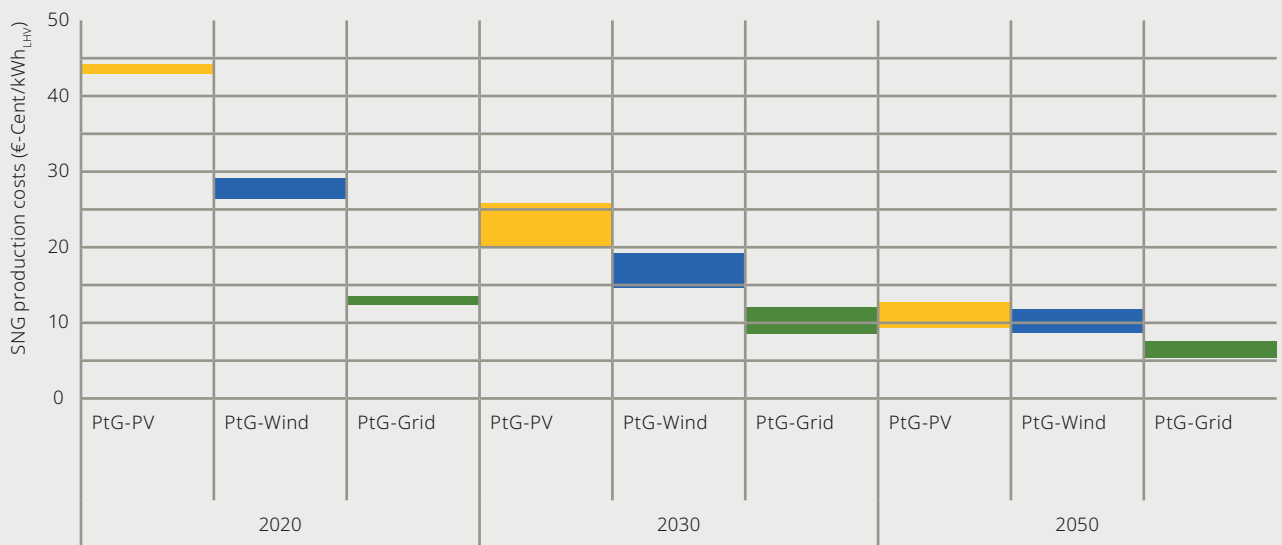


Figure 09: Range of SNG production costs of a 100 MW plant in 2020, 2030 and 2050 for different scenarios

Consequently, 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.

3. Solutions for further implementation of power-to-gas and policy recommendations

Administrative frameworks and public policies have to catch up with technological innovations

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 (PtG) 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 (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 likelihood that “investments in power-to-gas are lower than socially optimal” [27].

To bridge the valley of death, additional policy support for power-to-gas will be needed to allow power-to-gas to contribute to meet the ambitious energy and climate goals within the EU. One of the key questions will be, what policy framework will be needed, and which policy approaches are available. Within the STORE&GO project, four groups of policy approaches have been identified that would support the market uptake of PtG.

The STORE&GO project has identified four interconnected barriers which need to be overcome. Bridging the valley of death as first priority enables a necessary transition from basic research funding to a commercially viable market penetration. This transition is a time-limited process, as are the measures that need to be taken. At the same time, overcoming the valley of death conditions the establishment of a functioning market for green gases as second barrier identified in the project. This is to provide incentives for investors early during the product development stage, as well as to ascertain fair market conditions once the initial measures for overcoming the valley of death are phased out. If not done simultaneously, there will be no real market to penetrate and any measure to bridge the valley of death would have to be extended indefinitely. From an economic perspective this would not be desirable, as the market conditions are key to minimise the overall costs for governments to implement power-to-gas solutions and to decarbonise the molecular branch of the energy sector. The third barrier relates to internalising any current positive externalities of the power-to-gas technology, given that its introduction to the energy system brings benefits beyond producing green gas. This should be reflected accordingly in incentives for investors and operators. Finally, there are different cross-cutting individual issues obstructing the uptake of a well-functioning power-to-gas market.

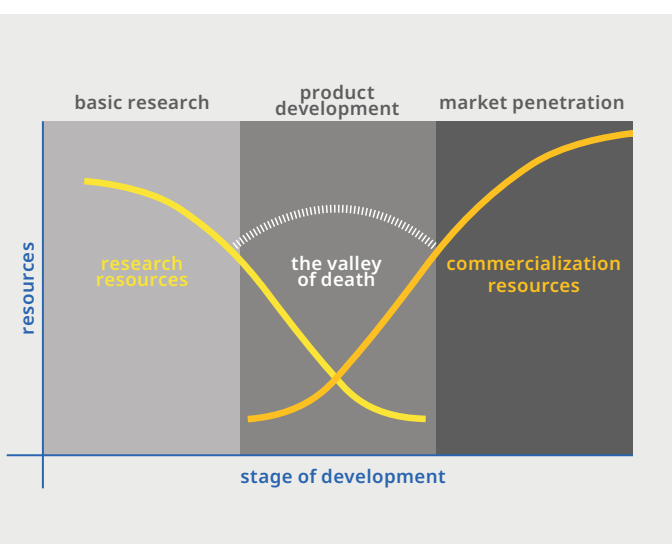


Figure 10: Illustration of the technology valley of death that needs to be bridged

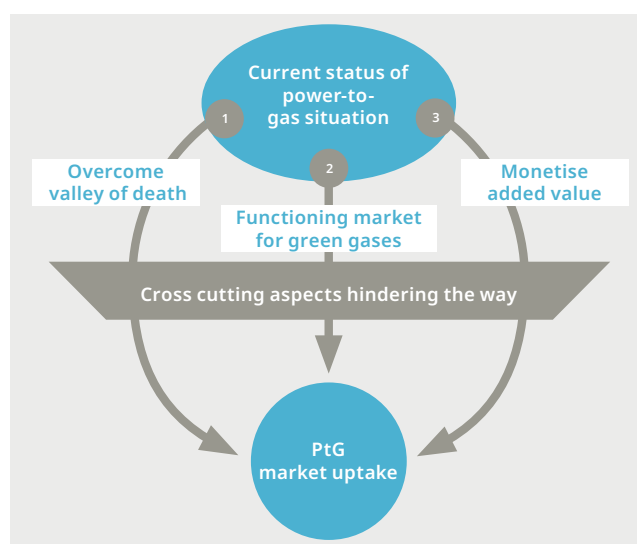


Figure 11: Illustrating the corresponding four groups of policy approaches to support PtG market uptake

1. Measures to overcome the valley of death

a) Investment subsidy

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 in the form of governmental investment funding would lead to a reduction of CAPEX, which would then reduce the production costs of hydrogen and SNG, thus helping to overcome the valley of death.

b) 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 is therefore an exemplary cross-cutting measure (see 4.a) "Support for continuous support and further development of PtG" for a more detailed discussion). However, some types of support dedicated to high TRLs are viewed as especially helpful to overcome a valley of death situation.

A regulatory sandbox enables companies to operate their business models temporarily and spatially limited, without already being subjected to all legal precautions and compliances [28]. 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 legislative change and implement it in this case, or to include an existing project-related exception as a rule beyond the project [29].

c) Feed in tariff for green gas

Possible support instruments under the Renewable Energy Directive 2018 are feed-in tariffs or premium payments. They can be designed in a way that plant operators either receive a fixed tariff for a certain time period, or a premium on top of the obtained gas price. If the designed support scheme proves to be beneficial to the business perspective of power-to-gas, it would also have the potential to leverage the integration of green gases (including power-to-gas) into the market and to bridge the valley of death [30].

Discussion

Innovation subsidies are a tried and tested policy mechanism to provide support to specific technologies. Within the EU, the EU ETS (EU emissions trading system) could serve as a mechanism to generate funding for PtG activities. Currently, power-to-gas does not belong to the typical scope of the EU ETS system and GHG savings generated by PtG plants cannot be monetized yet. However, the EU ETS can be used to generate funds to support PtG investments.

One of the main rationales to link PtG deployment to the EU ETS is because of the positive externality PtG deployment has on the overall GHG emissions of the energy system. This strong cause-effect relationship supports a solid political argument to justify amendments / changes to the EU ETS regime.

2. The creation of a functioning market for green gases

a) Quota for renewable gas

One important instrument for achieving climate targets is the introduction of a mandatory quota for green gases. The conventional approach would be a requirement to supply end-users with a gradually increasing percentage of renewable gases related to their total gas supply (e.g. starting with a supply share of 5% of renewable gases⁴ by 2025 and 10% by 2030). Alternatively, obligations for gas suppliers to meet a certain GHG emission performance for their gas supply portfolio can be introduced (e.g. max. 15 g CO₂-eq. of life cycle emissions per average unit of gas supplied to market) [31].

Both alternatives aim at suppliers having to diversify their supply portfolio with a determined share of gas from renewable origin. 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.

b) Financial penalty for CO₂

A financial penalty for emitting CO₂ can take the form of a CO₂ tax or the form of a market-based cap-and-trade scheme, like the EU ETS [32]. Both measures aim to establish a cost for the emission of CO₂, providing incentives for consumers to switch to renewable gases rather than fossil gases and thereby establishing a market for renewable gas.

This project's findings suggest that a market-based solution would be the favourable approach in line with the EU open market policy. However, the EU ETS currently covers neither the transport nor other sectors where CO₂ is emitted during the combustion of fossil fuels [33].

⁴ The term „renewable gas“ here refers to any type of non-fossil gases, such as biogas, biomethane, hydrogen from PtG, or methane from PtG (i. e. SNG).

Discussion

A portfolio obligation for renewable gases would affect all suppliers of both renewable and non-renewable gases within the EU. Two basic options for a portfolio obligation can be identified.

1. Introduce a mixing or blending obligation for renewable gases for gas suppliers
 - (e.g. 5% share of renewable gases supplied to market by 2025, gradually increasing over time)
2. Implementing a portfolio GHG emission standard for supplying (renewable) gases
 - (e.g. 15g CO₂-eq. of life cycle emissions per average unit of gas supplied to market)

The EU Biofuels Directive (2003/30/EC) introduced the mandatory blending of renewable fuels for transport. Such an obligation could also be introduced for the gas sector, which implies that a certain percentage of renewable hydrogen/SNG as part of the total gas supplies has to be supplied to end-users. The alternative to this is to introduce an obligation for gas suppliers to meet a certain GHG emission performance for their gas supply portfolio. This means that for the average unit of gas supplied to the market a certain level of GHG emissions is accepted.

Regulatory-based approaches in the form of a CO₂ tax or similar government imposed financial sanctions might be another option to provide the government more direct control over appropriate taxation. Such an approach would provide less uncertainty for investors. It would however face the same challenges as a cap-and-trade scheme: to reach the desired effect in market behaviour, a tax would need to be disproportionately high, making it less likely to gain acceptance or to be implemented at all.

c) Establishment of a system of guarantees of origin

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. Guarantees of origin would also create pull effects from consumers as gas from fossil sources and gases from renewables become clearly distinguishable. With the help of guarantees of origin, imported gases can also be credited. This enables producers to produce where it is most cost-effective [34].

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

a) Need to coordinate the specific provisions of the various sectors covered by

As power-to-gas combines several sectors, its 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.

Not clarifying how power-to-gas can be applied across all sectors, including a simplification of who is allowed to operate the facility, hinders the power-to-gas technology's system benefit to release its full potential.

b) Reflecting externalities in electricity pricing – harmonised in Europe

The production costs of green gases change fundamentally if not only the direct costs are considered, but also the externalities such as incorporating the damages by using fossil molecules into their market price. Moreover, power-to-gas systems contribute to the reduction of infrastructure expansion. 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 [35]. 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 [36]. This gap must be closed or rather even inverted to create business cases for power-to-gas.

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.

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. 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.

Discussion

With ongoing energy network integration (gas, electricity and heat), there will be an increasing pressure on energy network operators to develop novel and cost-effective strategies to balance the energy grids.

By considering PtG plants as part of the energy network infrastructure, and by acknowledging their service to safeguard the security of supply, network operators must be able to include the investment and operational costs for PtG plants in transmission and distribution tariffs for gas and/or electricity (e.g. through Commission Regulation (EU) 2017/460 on gas transmission tariffs).

This 'third' policy approach implies that the costs for PtG are socialised through the grid tariffs that are charged to all households and industries and connected to the public grids. As such, this approach has quite different distributional implications relative to the innovation subsidy that 'only' charges ETS industries. This approach is already used in many different EU countries to generate funds for the feed-in subsidy schemes for renewable energy (e.g. like the German "Umlage" for the EEG). However, one key policy design question will be how the PtG costs will be allocated to both the electricity and/or gas grid. Will the electrolyser costs be allocated to the electricity grid, and the costs for methanation to the gas grid?

No G-charges have to be paid in any of the three countries for injecting gas into the network. 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 because it provides increased flexibility by making the energy available in the currently needed form. Especially considering the system services that power-to-gas can provide, Italy and Switzerland should therefore consider exempting power-to-gas from paying L-charges even when there is no reconversion to electricity. Germany should moreover exempt power-to-gas plants from the EEG charge (EEG Umlage) which every electricity consumer is obligated to pay.

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

a) 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 enhance the performance of next generation power-to-gas plants.

The STORE&GO project has for example identified untapped potentials regarding the optimal integration of power-to-gas technology concepts into the energy system. Further material research could potentially increase efficiency of hydrogen production, significantly lowering costs, decreasing CAPEX, and reducing sensitivity to impurities in feed water. There are many areas where research can further optimise the technology and its deployment. Continued R&D is essential for achieving the cost reduction curves projected in chapter 4 on the technological characteristics and market requirements of PtG.

b) Clarification of the position of SNG under the Renewable Energy Directive

Although an amendment from 2015 to the Renewable Energy Directive has introduced the term "renewable liquid and gaseous transport fuels of non-biological origin" 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 [30].

The current gas legislation in Germany and Italy applies to SNG. Also, the scope of the Federal Pipeline Ordinance in Switzerland covers 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 biomethane. However, conditions for electricity and the carbon source are undefined. Clarification especially concerning the required carbon source would be helpful and necessary [37].

c) 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 in gas and the access to the gas grid from 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.

d) 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 and should be pursued [30] [37].

e) 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. 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 pertinent for power-to-gas concerning the Environmental Impact Assessment. Power-to-gas may fall under Annex I, which requires an EIA, or under Annex II, which leaves this to the discretion of the member states. A clarification in this respect and of other existing ambiguities should take place.

f) Promotion of trainings and further education and awareness raising

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 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.

Since consumers currently cannot distinguish between fossil fuels and power-to-x products, information on power-to-gas has to be provided to the public and raise awareness of the value of renewable gases and power-to-gas. The continuation of funding for further research on both technical and technological aspects as well as on the connection to the energy economy and the requirements of the respective market situation is crucial for tapping further cost reduction potentials.

g) 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 entails the construction of major renewable energy production plants. However, while overall public opinion is positive, when it comes to the actual realisation of the project, lower levels of acceptance or even a strong local opposition may emerge. Identifying factors with an impact on social acceptance can be crucial for the sustainable success of energy transition [38]. The analysis of the STORE&GO project shows that both solar farms and power-to-gas infrastructure increase social acceptance of local energy communities, while wind farms remain ambiguous. The introduction of gas power plants and power lines lowers acceptance. Opinions of governmental bodies on the EU, national or local level can shape acceptance levels to different extents. Other parameters like place attachment, residing near power plants or income level, however, did not show any impact on acceptance levels of renewable energy infrastructures in the sample. Sociodemographic characteristics such as gender, education and employment further revealed a persisting impact on a household's acceptance of PtG and its alternatives [38].

4. Conclusions from the project

Administrative frameworks and public policies have to catch up with technological innovations

The presented insights from the STORE&GO project and the derived conclusions may serve as contribution to the discussion on how to support the realisation of Europe's future energy system, with its high focus on carbon reduction. By indicating some possible routes to take, they contribute with the technology experts' perspective on potential future policy measures for the enhancement of power-to-gas implementation.

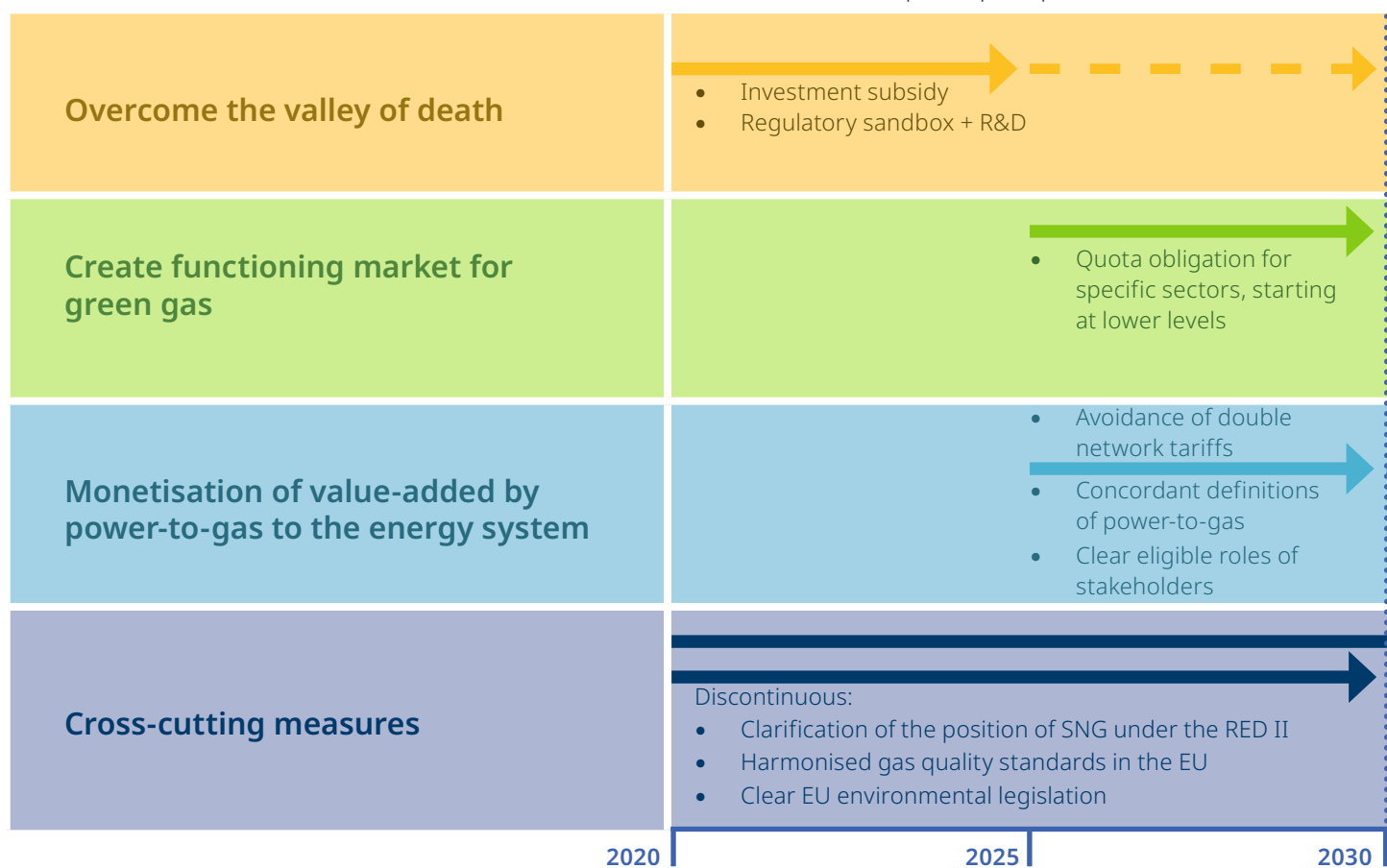
1. Renewable gas has an indisputable role to play in the future energy system. Power-to-gas is the key technology to meet that demand, as it provides the solution to produce the required large amounts of green molecules – be it as hydrogen (H₂) or methane (CH₄).
2. Furthermore, power-to-gas in combination with the already existing European gas infrastructure is essential for seasonal shift of renewable energy, energy transport & distribution as well as providing balancing services to the power grid.

3. Power-to-gas as technology is fit to enter the market. Innovative technologies and processes could be demonstrated within STORE&GO.

4. Therefore, it is crucial to drive forth PtG in time to enable the availability of sufficient green energy molecules (H₂ as well as CH₄) for feedstock and energy purposes. Most experts seem to agree that specific policies and measures are required.

5. At some point in the future – assuming power prices will further come down as well as electrolyser CAPEX-levels – PtG will become commercially feasible. However, this will likely take too long without accompanying policy measures. In that scenario, it is doubtful that the EU will be able to realise its 2050 mitigation targets.

6. In order to achieve the 2050 goals, power-to-gas must become commercially competitive by 2025 so that it can compete on a market for renewable gas that needs to be established by 2030. The following mix of policies may serve as a means to speed up the process:



a) First, it will be a priority to set up a number of **substantial demonstration projects** at short notice (pre-2030) to collectively cover the feasible technology ranges of PtG. This will require a dedicated support scheme at the EU level for some **10 demo projects**, each requiring **~100 million Euros** of public funds. This can be supported as R&D projects and/or with investment subsidies. Preferably also as “sandbox-projects” to simultaneously gain experience for the higher development stage.

I. A second set of **policy measures** is required to establish a credibility to potential investors in PtG 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**.

The **feedstock market** could be the first market segment to set this in motion, especially given that so far it is completely dominated by the uptake of grey hydrogen and grey carbon, both having a considerable carbon footprint. Policies and measures to rule out the use of grey hydrogen for these purposes – on a mandatory basis and within a clear timeframe – would immediately drive the estimated demand for carbon neutral gas and potentially increase investments and support the learning curve. **An obligatory quota for renewable gases** is suggested to be implemented already by 2025. To reach the **total energy market** for gas, the **obligatory admixing of renewable gases** to the EU gas system seems to be a valid way to continue. It might start at **5% by 2025** with an obligation to be based on a **guarantees of origin** system. Imported gases into the EU should be subject to the same rules.

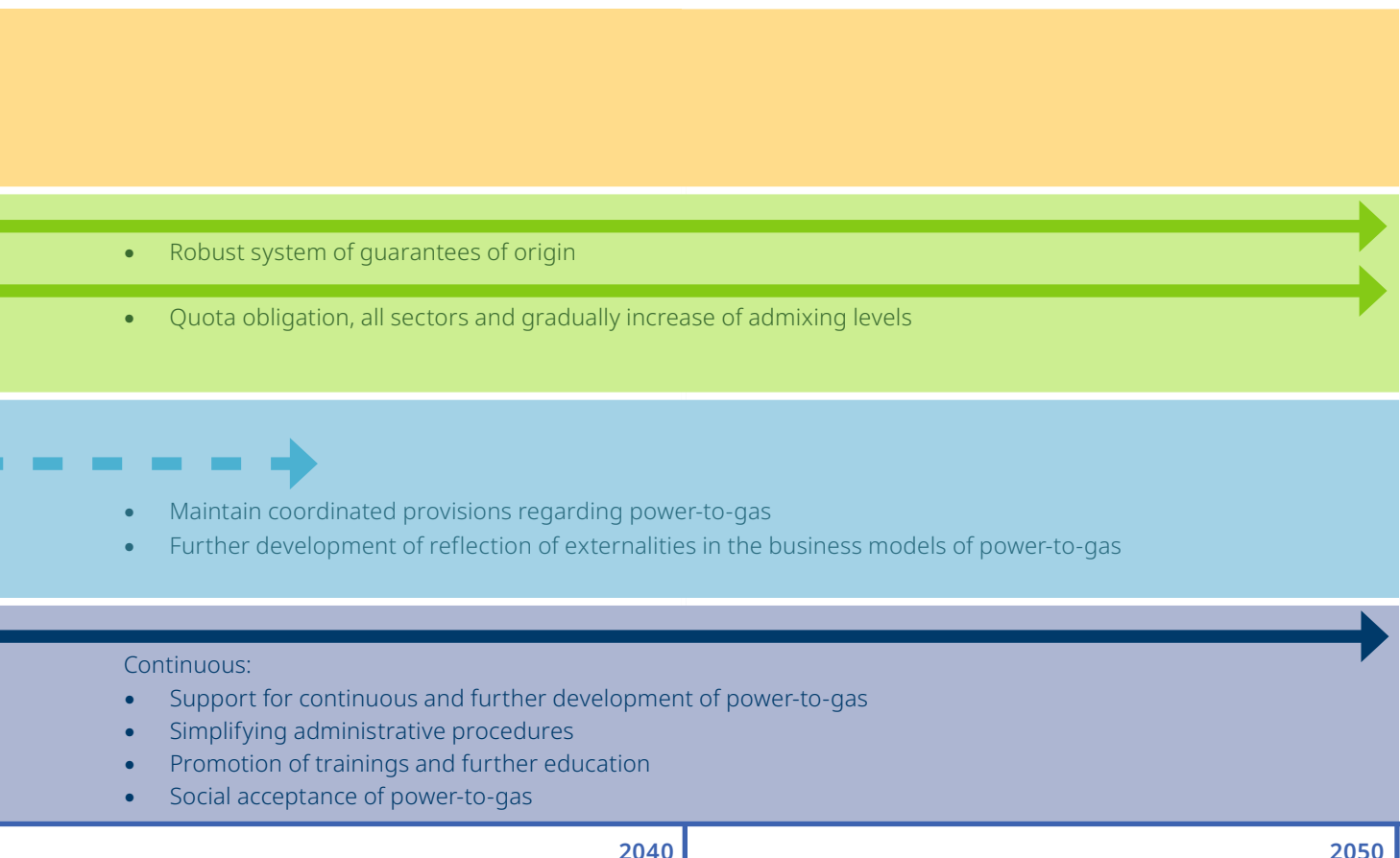
II. If the common European approach of a “**quota obligation**” is not possible in the designated timeframe, “**feed-in tariffs**” for renewable gas on the national level are suggested as an **optional way** to proceed with a proven potential of impact. Considering the gradually evolving market and sinking costs of technology, **this measure can also serve** as an alternative to support a market for renewable gas for an **extended period**.

b) Assure that the overall **benefits of power-to-gas to the energy system** and the environment are **reflected in possible business models by coordinating the provisions and definitions of power-to-gas across all sectors** and applications. Priorities should also be on how to **avoid unfair double network tariffs**, and what **roles different stakeholders** are eligible to take.

c) **Clear the path** for power-to-gas by eliminating all current detailed issues unnecessarily hindering the development of power-to-gas such as: “**Clarification of the position of SNG in the RED II**”, “**Harmonised gas quality standards in the EU**” etc.

d) **Finally, create incentives** to continue further **PtG development** by appropriately considering power-to-gas in the **research programmes**.

A timeline shows the different types of policy measures as introduced in the policy recommendations.



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 may be considered as part of the supply as well as, given its carbon capture and storage capacities.

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 CO₂. The air flows through a filter where CO₂ is removed. The captured CO₂ 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 (CH₄), 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: CO₂ 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 catalyser is needed. Alternatively, biological methanation, employing microorganisms, can also be used as methanation method.

Methane: A colourless, flammable, odourless 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 CO₂ emissions if the electrical energy comes from a renewable energy source. Green methane can be generated by combining green hydrogen with CO₂. 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)

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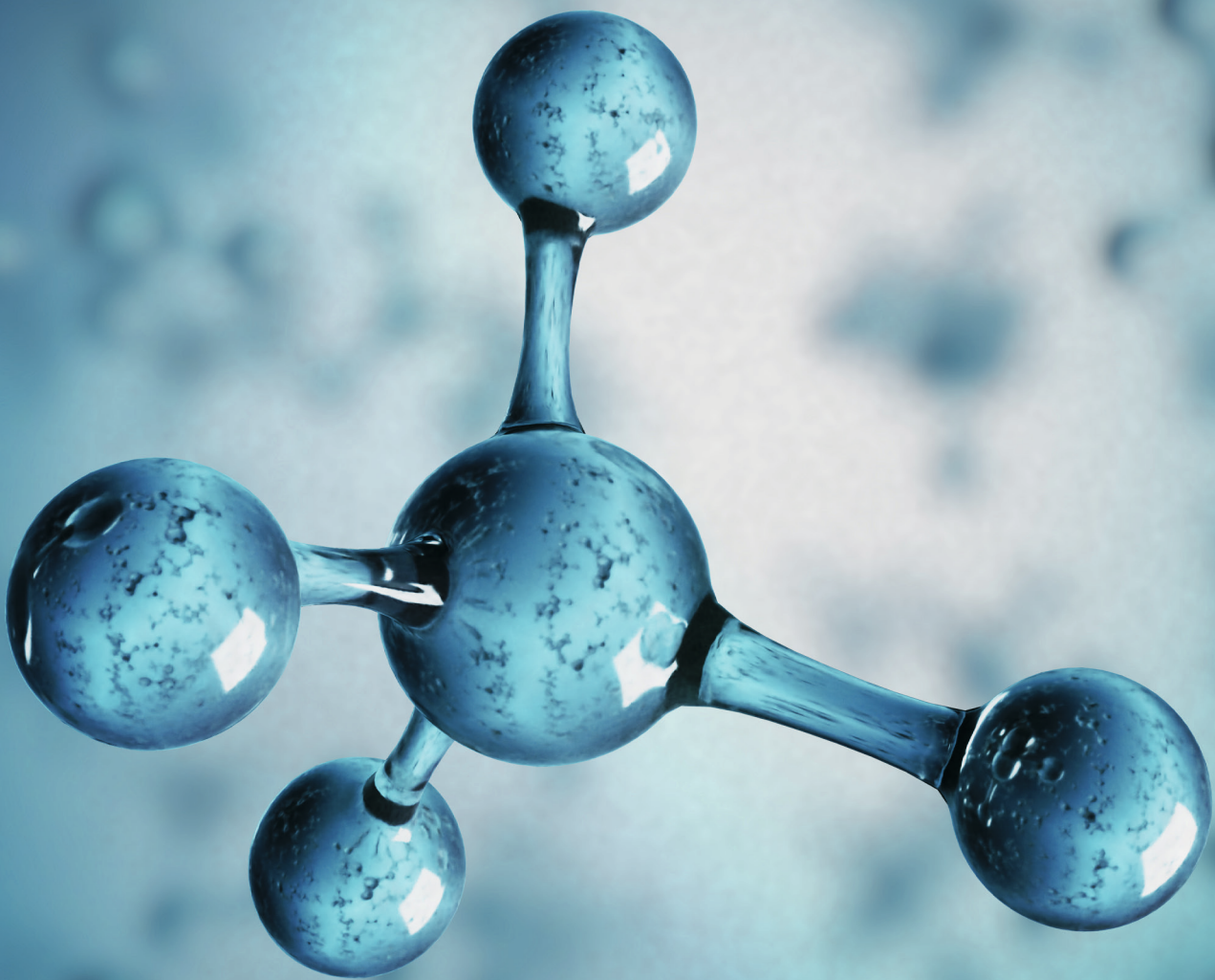
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