Smart sector integration – an assessment of the economic and environmental benefits of Power-to-Gas

A study for Amprion GmbH and Open Grid Europe GmbH

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Key results at a glance:

1) **Flexibility advantages** of Power-to-Gas (i.e. storage and use of existing infrastructures) outweigh the efficiency disadvantages (i.e. conversion losses), particularly in the transport and industry sectors.
2) Utilisation of gas storage capacities for **seasonal energy storage** via Power-to-Gas is inevitable for achieving the ambitious climate policy goals - reduction of CO_2 emissions by 95% compared to 1990 levels by 2050 – in an economically efficient way, complementing short-term power storage in stationary batteries.
3) In the long-term, i.e. beyond a share of approx. 400-450 TWh of renewable electricity production, Power-to-Gas can meaningfully **complement the power grid expansion based on the German grid development plan for electricity** (Netzentwicklungsplan Strom – NEP-Strom).
4) Power-to-Gas has **negative CO_2 avoidance costs** in comparison to an "all-electric" world due to lower overall investment needs for achieving the same CO_2 emission reduction targets. Therefore it represents an economically reasonable way to achieve the climate policy goals from the system perspective.
5) **End-use applications are an essential cost driver** towards CO_2 avoidance.
6) The more ambitious the climate policy targets by 2050 the more advantageous will be Power-to-Gas in comparison to an "all-electric" world.

BACKGROUND AND OBJECTIVE:
What are the advantages of Power-to-Gas (PtG) in comparison to an "all-electric" world?

Renewable electricity is regarded as the most important energy carrier of the German "Energiewende". Next to traditional applications in the power sector, electricity will also be needed in the future to supply all other end-user sectors such as transport and heating (households and industry) sectors as well as for the production of synthetic fuels as industrial feedstock. As a consequence, it is expected that today's electricity demand will more than double by 2050.

In the context of this study, sector integration is defined as coupling of electricity and gas grids to efficiently integrate renewable energies into different end-use sectors. Even if the expansion of the electricity grid until 2030 were implemented successfully according to the German grid development plan for electricity (NEP-Strom 2030 version 2017), the electricity grid alone might be not able to cope with the transmission and distribution of further increasing feed-in of renewable power. In the context of the sector integration, the electricity network expansion until 2050 could be complemented in an-efficient way by utilisation of energy transport and storage capacities of the existing gas grid.

In the spring of 2017, Amprion GmbH and Open Grid Europe GmbH jointly commissioned Ludwig-Bölkow- Systemtechnik GmbH (LBST) to analyse in sector-specific detail the economic and environmental effects of a broad introduction of Power-to-Gas (PtG) in comparison to an "all-electric" world for Germany by 2050. In this context, the assessment included the modelling of the entire power sector with all system flexibility options, however excluding electricity distribution network.

The introduction of PtG was considered for three selected energy sectors (transport, residential heating and substitution of fossil hydrogen production in chemical industry) assuming integration of additional quantities of renewable electricity beyond the NEP-Strom both on the supply and demand side. The total costs comparison between an energy system design including PtG, differentiating between Power-to-Hydrogen (PtH_2) and Power-to-Methane ($PtCH_4$), and the "all-electric" world was calculated for two CO_2 emission reduction scenarios (-80% and -95% versus 1990 by 2050, respectively). The cost-minimising modelling of the German energy system comprised a spatial (4 regions) and a temporal (on an hourly basis) dimension.

KEY FINDINGS:
Flexibility advantages of PtG outweigh its efficiency disadvantages

In general, the total system costs examined in this study include five different components: costs from (1) intermittent renewable and flexible dispatchable electricity generation, (2) energy storage by selected technologies (e.g. batteries, hydrogen or methane storage), (3) additional flexibility options (e.g. energy import/export or demand side management), (4) energy transport via electricity and gas grids, and (5) costs related to the end-use applications, e.g. for vehicles and corresponding refuelling stations or heating systems. In this context, the PtG technology has the disadvantage of higher energy demand due to conversion losses (more distinct for $PtCH_4$ than for PtH_2), however, it also benefits from the fact that the universal energy carriers hydrogen (PtH_2) and synthetic methane ($PtCH_4$) can be more easily stored and transported. In addition, both PtG technologies in this study are assumed to have cheaper end-user applications.

In particular under the assumption that all energy sectors are supplied by renewable electricity in the future, the analysis shows that both system designs with PtG are economically better off than the "all-electric" world. From the system perspective, PtG has a cost advantage in particular in the industry and transport sectors. In comparison to the "all-electric" world, the cost savings from the use of electrolysis and the H_2 or CH_4 storage as system flexibility options in both sectors and all scenarios are larger than the additional costs from extra primary energy supply due to conversion losses. The reasons for this are that in the "all-electric" world only comparatively expensive stationary batteries are available for direct electricity storage and other flexibility options, such as electricity import or export or demand side management, are limited. This effect is further supported by the lower costs for end-use applications of PtG.

Energy end-use costs are an important cost driver

The analysis also shows that, from an economic point of view, the end-use costs have a dominant share of the total system costs in all sectors (here particularly in mobility) for all system designs and scenarios, possibly even exceeding the energy costs in the long-term. $PtCH_4$ turns out to be the most cost-efficient energy option in the transport and heating sectors in the short-term as a consequence of the existing gas infrastructure and in the sort-term comparatively cheap combustion engines and conventional heating appliances. It is followed by PtH_2 becoming the preferred option in the long-term as it can draw from its efficiency advantages e.g. from the technological leap towards fuel cells. The costs for the additional transport infrastructure only represent a small share of the overall system costs. Hence, the infrastructure costs alone are not sufficient to determine whether PtG can become competitive.

Utilisation of the gas storage capacities is inevitable for achieving the 95% target

In the "all-electric" world the costs for stationary batteries providing system flexibility are by far the most important cost driver whereas for PtG the capital expenditures in electrolysis or methanation plants play an important role. Depending on the scenario and the assumptions until 2050, it was found that high electrolysis capacities are needed for single end-use sectors. However for a future commercially successful operation of PtG plants, it is essential that their utilisation is as high as possible. This can be achieved especially by taking into account different end-use application simultaneously in the sense of the sector integration.

Regarding the climate policy targets, the study illustrates a “tipping point” between the CO_2 emission reduction goals of -80% and -95%. For a CO_2 reduction of 95%, not only short-term power storage but also large scale seasonal energy storage is required, which is prohibitively expensive in a strictly “all-electric” world building only upon stationary batteries. Also the use of natural gas for substituting CO_2-intensive coal-fired power plants for regional power supply, e.g. in southern Germany, will then become more restricted.

In the long-term, PtG can meaningfully complement the power grid expansion

The analysis of the energy infrastructures reveals that an electricity grid expansion beyond the NEP-Strom levels is not necessary until 2035 in the reference scenario (-80% CO_2) and until 2030 in the more ambitious climate protection scenario (-95%) even in an “all-electric” world as the flexibility of the power system still suffices under the given CO_2 restrictions. However, this changes when the renewable power generation increases above a level of 400 to 450 TWh/a. Due to higher energy efficiencies particularly in the heating sector resulting e.g. from improved thermal insulation and due to general electrification trend through e.g. applying electric heat pumps the overall need for transport and distribution of natural gas is expected to decline. Consequently based on the results of this study, the expansion of the existing gas grid is not required for the $PtCH_4$ and in the PtH_2 case only an upgrade of the existing gas pipelines to cope with hydrogen becomes necessary.

PtG has negative CO_2 avoidance costs in comparison to the “all-electric” world

The advantage of PtG in comparison to the “all-electric” world also becomes evident in the relative CO_2 avoidance costs, calculated by the division of total system costs by overall avoided CO_2 emissions. Since all energy system designs must achieve the same emission reduction level in a given scenario and PtG have lower total system costs in comparison to the “all-electric” world they are consequently characterized also by lower relative CO_2 avoidance costs. Hence defining the “all-electric” case as a benchmark, it can be shown that both PtG options (PtH_2 and $PtCH_4$) have negative CO_2 avoidance costs.

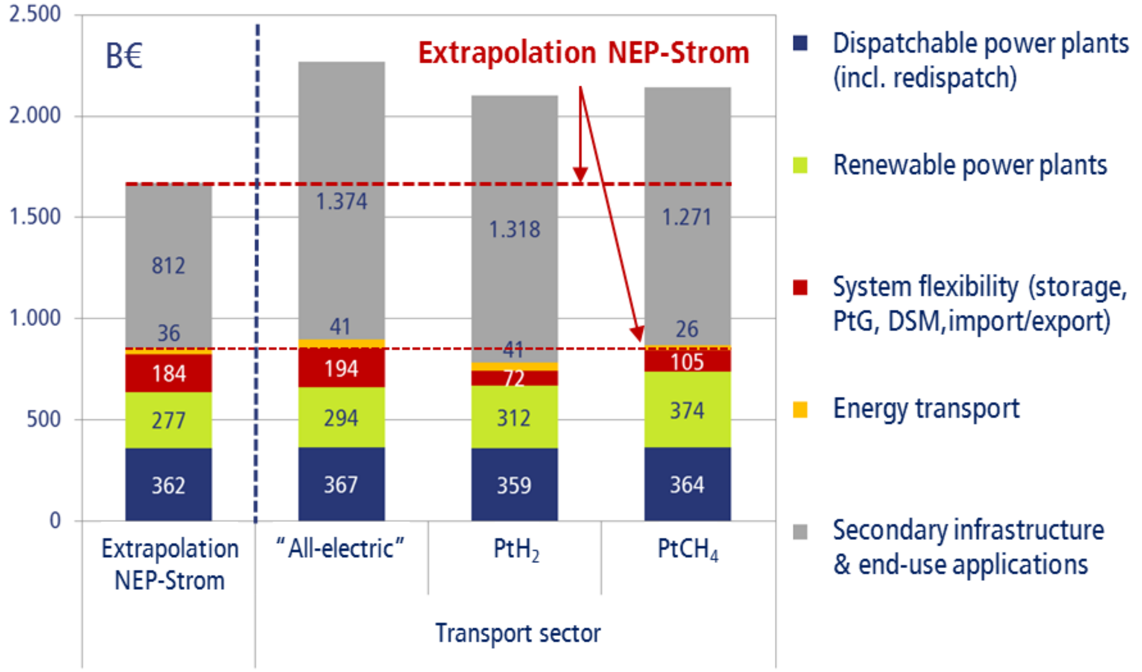
STRATEGIC APPRAISAL OF RESULTS:
Advantages of PtG distinct in particular in respect of ambitious climate policy targets until 2050

In the future energy system, renewable electricity is foreseen to play a dominant role as an energy carrier. However, the results of this study underline that from an economic perspective the efficiency disadvantages of the PtG technologies are overcompensated by their advantage of utilising the existing gas grid, cost-efficient energy storage capacities and cheap end-use applications in comparison to the “all-electric” world. While the $PtCH_4$ technology can benefit from already existing infrastructures and end-use application technologies in the short- and medium-term, the advantages of the PtH_2 technology will kick-in in the medium- and long-term resulting from smaller overall conversion losses. In conclusion, both PtG technologies can fully play to their systemic strengths from a cost (particularly storage) and social acceptance (infrastructure expansion) perspective in particular in respect of ambitious climate policy targets.

The market introduction of PtG technologies will require an early technology development, testing and market establishment of the core technologies at a relevant scale. With challenges lying ahead from the need to involve a multitude of actors this process should be started in the short-term in order to achieve the ambitious climate policy goals timely and in the most cost-efficient way.

ANNEX:
Cumulative total costs until 2050 in the reference scenario (transport sector)

The figure below depicts the cumulative total costs of the energy system until 2050 as an example for the transport sector in the reference scenario. The presented figures do not only include the capital expenditures for new assets on an annuity basis but also the annual operating expenditures (e.g. maintenance costs or expenditures for fossil primary energies). It is important to mention that these costs represent gross system costs, most of which will occur anyway even if the energy system will be not adapted to renewable energies. This means that a part of the investments, e.g. in new vehicles, power plants, networks, etc., will be needed in any case, independent from the selected technology. The extrapolation of the NEP-Strom (version 2017 scenario B2030) serves as a benchmark.



In this context following conclusions can be drawn:

- The total costs for all energy system designs are of the same order of magnitude. Nevertheless, the $PtCH_4$ case is most cost-efficient in the short- and medium-term (followed by the PtH_2 case), whereas in the long-term PtH_2 is the cheapest option.
- In the long-term, the costs for the secondary infrastructure (e.g. refuelling stations) and the end-use applications (e.g. vehicles) exceed the energy costs many times over (in particular in the "all-electric" world), and hence have a significant impact on the overall costs.
- The electricity demand (in absolute numbers and its time-dependent profile) is another major cost driver.
- The energy costs are determined by a trade-off between storage needs, increase in intermittent power supply, utilisation of flexible power plants and other additional flexibility options.
- PtH_2 and $PtCH_4$ system designs benefit from synergy effects and both technologies represent an important pillar of the future energy system.
- Although both Power-to-Gas technologies support the electricity grid, the transport of energy alone is not sufficient to demonstrate the advantages of PtG.