The role of power-to-gas in the future Dutch energy system

Summary

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Abstract

This document contains a summary of the study on the possible future role of Power-to-Gas in the Dutch energy system, financed by the TKI Gas. The summary describes the main conclusions, the selected approach and main assumptions, as well as the recommendations derived from this study.

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Main conclusions

Deep CO_2 emission reductions are the main driver for P2G

1. In the future Dutch energy system, P2G plays a robust role as part of a technology mix that enables deep CO_2 emission reductions by means of far-reaching implementation of solar and wind energy

Wind and solar energy are generally the two most abundantly available sources of renewable energy. Given the increasingly progressive CO_2 emission reduction targets in the energy system, and the large uncertainty surrounding alternative CO_2 reduction options such as CO_2 capture and storage (*Carbon Capture and Storage, CCS*) there will be an increasing need for a conversion technology such as P2G[1], which facilitates the use of renewable electricity[2] through a different energy carrier (hydrogen, synthetic methane) in other parts of the energy system that are difficult to directly electrify. This for example concerns the end-user sectors that traditionally depend on fossil energy carriers.[3] The importance of P2G as a conversion technology holds if alternative scenarios or assumptions are used[4]. P2G can therefore be regarded as a robust part of the mix of energy technology options required to achieve deep CO_2 emission reduction targets in the energy system (-80% to 95% in 2050) at the lowest possible cost to society. Depending on the specific future scenario, the contribution of P2G in the system may vary from 2 to 20 GW_e in terms of installed electrolysis capacity, the availability and potential of biomass and CCS in the system being important factors.

The need for flexibility alone is an insufficient driver for P2G

2. P2G contributes to the integration of the fluctuating renewable supply from wind and solar-based electricity generation, but it is not the first option in terms of lowest societal costs

To achieve deep CO_2 emission reductions at the lowest possible cost to society, it is important to integrate a very large share of renewable electricity from wind and solar resources into our energy system. This implicitly leads to a growing need for flexibility in the *electricity* system to accommodate peak and off-peak electricity supply from wind and solar-based resources. The system needs to have sufficient means to accommodate the fluctuating contribution from wind and solar at all times throughout the year. Electrolysis can offer a solution by converting electricity into hydrogen or methane, but this need for flexibility alone is insufficient for a positive P2G business case. The required level of flexibility can also be achieved by a mix of alternative flexibility options. This mix is depends on aspects such as costs, flexible characteristics and the type of flexibility that is required. Assuming that deep CO_2 emission reductions need to be achieved at the lowest possible cost to society, then the mix of options that

[1] This includes the conversion from electricity to hydrogen (H_2) as well as the further combination of hydrogen with a carbon source (e.g. CO_2, or biomass carbon) to methane (CH_4, or: synthetic natural gas or 'syngas').

[2] P2G could also include the conversion from conventionally produced electricity to hydrogen.

[3] Think of the oil based fuels in the transport sector and the application of natural gas for the production of hydrogen and process heat in industry, demand for oil in the transport and industry sector, and the deployment of the demand for natural gas for heat production in the built environment.

[4] Multiple scenarios have been analysed with. varying availability and costs of alternative options for reduction of CO_2 emissions (such as the use of biomass, nuclear energy, and CO_2 capture and storage (CCS)) and varying costs of electrolysis and energy storage technologies.

together balance the fluctuating supply from wind and solar-based electricity consists of the following options (in random order):

- Temporary curtailment of variable sustainable electricity generation sources;
- Exchanging electricity surpluses or balancing deficits with other countries;
- More flexible utilization of part of the *electricity* demand (demand side response);
- Flexible electrification of *energy* demand;
- Use of dispatchable gas-based electricity generation units (using natural gas or biogas, possibly combined with CCS);
- Implementation of some type of electricity storage (such as Compressed Air Energy Storage (CAES) and batteries in electric vehicles);
- Deployment of electrolysis to convert electricity to a gaseous energy carrier (P2G) (which, from the electricity system perspective, can be regarded as flexible demand).

Due to the capital intensity of P2G and its inherent efficiency losses[5], deployment of P2G for the sake of providing electricity system flexibility alone is not sufficient for a positive business case. Even the low – or possibly even negative – electricity prices that may arise for short time periods as a result of an imbalance in the electricity market, caused by an abundant supply of electricity from intermittent sustainable sources, are insufficient to compensate for the relatively high capital cost per produced unit of hydrogen or synthetic methane.[6] However, when P2G is already deployed for realising deep CO_2 emission reductions, flexible operation of electrolysers can generate extra yield for P2G by offering flexibility services on the balancing market.

P2G is not required for the provision of *seasonal* flexibility in *heat* demand, but P2G may contribute to CO_2 emission reductions through admixing of hydrogen in the gas system. Other options that contribute to future heat supply include geothermal and electric heat pumps. Moreover, energy-saving measures will cause the energy demand for heat supply to further decline.

5 For all technologies, including P2G, a technological development pathway to 2050 is assumed with regard to costs and/or efficiency.

6 The results from this study show that – depending on the selected future scenario – approximately 5,000 to 6,000 operating hours a year are required for P2G to realize a positive business case.

Text box 1: Drastic CO_2 emission reductions are the main driver for a positive P2G business case, not the need for flexibility

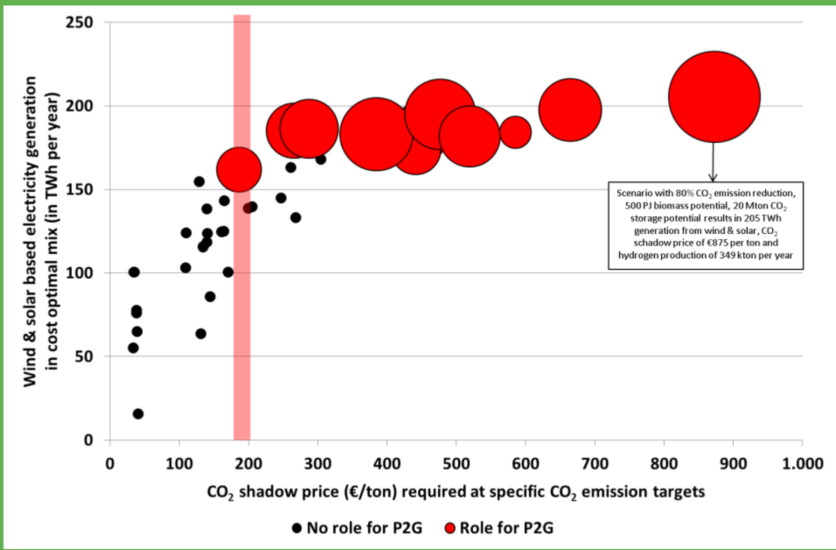

Figure 1: Relation between the amount of wind and solar-based electricity generation per year, the ambition level for CO_2 emission reductions (translated into CO_2 shadow prices per ton), and the role of P2G (in relative volume of hydrogen produced through electrolysis) in the cost-optimal mix of technologies

Figure 1 contains results obtained from the model analysis. Depending on the envisaged level of CO_2 emission reduction, which, for the purpose of mutual comparability of scenarios has been translated to the so-called CO_2 shadow price[7], and depending on the future scenario that is used, there is a specific need for wind and solar-based resources that contributes to the mix of energy technology options with the lowest cost to society. Each of the depicted data points indicate the contribution of wind and solar energy in the cost optimal mix of options. A black data point indicates that there is no role for P2G in the particular scenario, while a red data point indicates that there is indeed a role for P2G (in terms of units of hydrogen produced through electrolysis). The relative importance of P2G is reflected by the size of the (red) data point.

Firstly, the above figure shows that wind and solar energy potential are increasingly important for the realisation of CO_2 emission reduction targets for the Netherlands:

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[7] The CO_2 shadow price is the price of avoiding the last ton of CO_2 to realise the CO_2 reduction target and reflects the costs of the CO_2 emission reduction option that is deployed for this purpose. As the target becomes stricter or the CO_2 emission reduction options become more scarce, the CO_2 shadow price will increase accordingly. The CO_2 shadow price cannot be simply compared to the CO_2 price of the European Trading Scheme (ETS) as the ETS covers only a limited part of overall energy system demand. The CO_2 shadow price should rather be compared with the implicit cost of policies aimed at reducing CO_2 emissions in non-ETS sectors such as transport. For example, the Netherlands Court of Audit calculated that the implicit cost - in terms of CO_2 emissions avoided - of a specific fiscal scheme aimed at growth in sustainable energy demand in the transport sector was about €1,000 per ton.

the higher the CO_2 shadow price (as a result of effective climate policy), the larger the share of wind and solar energy in the energy mix with the lowest cost to society. Secondly, the figure shows that P2G primarily contributes to achieving deep emission reductions with an implied CO_2 shadow price of around €200 per ton and higher. Thirdly, the figure illustrates that P2G only plays a role when there is a relatively large amount of wind and solar energy penetrating the system. Up to that point, the flexibility that is needed to accommodate the variable contribution from variable sustainable sources in the electricity system is provided by other flexibility options at relatively lower cost to society.

P2G mainly concerns hydrogen, to a lesser extent synthetic methane

3. The role for P2G in the future Dutch energy system is mainly related to the production and subsequent use of hydrogen (*power-to-hydrogen*), and only to a lesser extent to the further conversion to – and use of – synthetic methane *(power-to-methane)*

In the wide array of options needed to achieve deep CO_2 emission reductions, the admixing of hydrogen in the gas system is relatively attractive because of the relatively limited distribution cost and the effect in terms of decarbonising (part of) the gas supply. The admixing of hydrogen could play a more significant role if current admixing restrictions can be successfully relieved or even removed. However, there are quite some challenges in terms of customizing the gas infrastructure and gas-based end-user applications, which have to be dealt with first[8]. This way, part of the final energy demand in households and in industry can be made more CO_2 neutral. Besides the admixing of hydrogen, the direct deployment of hydrogen in the transport and industry sector could be another viable option. However, this deployment depends on a large number of factors[9] and it is not yet possible to draw a robust conclusion based on the analysis in this study.

Methanation is an option to achieve a significant CO_2 emission reduction when the available capacity for CO_2 storage is fully utilized or when there is much societal resistance to CO_2 storage. Before deploying the methanation route, it is economically more efficient (from a social perspective) to fully deplete the available potential for CO_2 storage first . Once CO_2 (in the form of methane) is distributed it is very difficult to capture it in an economically viable way – if at all. It would imply that in order to compensate for the emission of this CO_2, relatively more expensive CO_2 emission reduction measures would need to be taken elsewhere in the system to achieve the targeted level of CO_2 emissions. From a private perspective, however, there could be a positive business case due to favourable local market conditions, mainly up until the point in time at which CO_2 emission reduction targets become severely restrictive (-85% and beyond).

[8] The costs for adjustment and/or replacement of assets and appliances in the current gas value chain have not been included in this study.

[9] Factors involved include the costs and availability of alternative CO_2 free options, the development of fuel prices, the possible cost of the development of a hydrogen distribution network, and the specified limit on hydrogen admixing.

From a social perspective P2G is not cost-effective in the short to medium term

4. Although P2G is not considered a cost-effective option from a public perspective in the short to medium term, a positive private business case for a specific, local niche application of P2G may still prove feasible

Although P2G is a robust part of a deeply decarbonized energy mix, the three performed case studies show that a solid positive business case is hard to realise in the short to medium term (2030). Yet it is not inconceivable that a positive business case is possible in specific situations with favourable local conditions, e.g. a combination of limited local capacity in the electricity network, the local / regional availability of a surplus of renewable electricity, and a sustainable, local demand for hydrogen (e.g. in industry or in local/regional public transport).

Approach and assumptions in this study

Approach and assumptions

The above conclusions were derived from a study based on a combined model and case study approach, using an integral energy system perspective with the Netherlands as system boundary[10]. The realisation of a strong decarbonisation of the Dutch energy system at the lowest social cost is an important reference point. The study uses a broad set of possible future scenarios to explore how a number of uncertain factors can affect the role of P2G in the future.

The integral Dutch energy system as research perspective

The energy system perspective stipulates that the analysis is not based on only one part of the energy system - e.g. the electricity or gas sector - but on the Dutch energy system as a whole. In an energy system that has to comply with increasingly strict CO_2 emission reduction targets, interaction among the different elements in the system will play an increasingly important role. In what part of the system can CO_2 emissions be reduced most cost-effectively? And: what does this imply for the use of energy sources and CO_2 free technologies in the energy mix? An approach that targets only part of the energy system would insufficiently take into account the complexity of interactions in reality, and thus lead to unreliable results– e.g. with regard to the role of P2G.

Achieving deep CO_2 emission reductions at the lowest possible cost for society

An important starting point in the analysis is that the current CO_2 emission level in the Netherlands will be further reduced by means of effective climate and sustainable energy policy, up to a target of 85% to 95% CO_2 emission reductions in 2050 (compared to the emission level in 1990). The model used in the study calculates which energy technology mix leads to a decarbonisation of the Dutch energy system at the lowest possible cost to society. For the actual realisation of a resulting mix with the lowest cost to society it is necessary that market and government create the correct market conditions, e.g. by providing the right market incentives for the actors in the system. In practice, however, this could be different, causing the business case for a certain technology to appear different than foreseen in an analysis based on social costs. In other words: the results are derived from an analysis from a social perspective that, in practice, need not necessarily correspond with the perspective of

[10] Including fuel import from the rest of the world (oil, gas, biomass, uranium, etc.) and the option to exchange electricity with neighbouring countries.

a private investor. A combination of policy and market circumstances could enable a private party to close a business case for a certain investment that, from a social point of view, is not profitable and possibly less desirable.

Scenarios as a means to analyse the effect of uncertain developments on the role of P2G

The future is uncertain and uncertain factors that could affect the future role of P2G in the Dutch energy system are numerous. To map the importance of these uncertainties, a broad set of possible future scenarios has been analysed. Uncertainties that were explored in separate scenarios include the cost development of electrolysis and storage technologies, the availability of / support for low carbon energy options (biomass, nuclear energy, CO_2 capture and storage), the limitations of mixing hydrogen in the gas system, the fossil fuel price, and the network capacity range within which electricity can be exchanged with the surrounding countries.

Table 1: Overview of performed model analyses

Scenario / sensitivity analysis	Explanation
Restrictions on biomass potential	Available biomass potential 40% lower (compared to. 500PJ in reference scenario)
Restrictions on CCS potential	Available potential CO_2 storage in NL 40% lower (compared to 50 Mton per year in reference scenario)
Restrictions on nuclear energy	Possible total capacity of nuclear energy in the future is 50% lower (compared to 5 GW_e in reference scenario)
Separate target wind & solar	Separate target for total capacity of wind (36,5 GW_e) and solar (45GW_e) in the system
High g potential H_2 admixing limit	Maximal admixing percentage of hydrogen in the gas network is 50% (instead of 10% in reference scenario)
Low potential H_2 admixing limit	Maximal admixing percentage of hydrogen in the gas network is 1% (instead of 10% in reference scenario)
Lower cost energy storage	Costs of energy storage are 50% lower than in reference scenario
Low cost P2G	Costs of electrolysis are 50% lower than in reference scenario
Low cost H_2 transport	Costs of H_2 transport options are 50% lower than in reference scenario
Low fuel prices	Fuel prices (oil, gas) are 50% lower than in reference scenario
High fuel prices	Fuel prices (oil, gas) are 100% higher than in reference scenario
Unlimited flexibility in electricity system	Exchange of electricity among countries is unlimited and free of charge
No P2G	Electrolysis technology is available for the energy system

Flexibility of energy technologies

The revenue that P2G can generate by delivering flexibility to the *electricity* system also depends on the characteristics of other flexibility options. Therefore the study explicitly focuses on the characteristics, availability and costs of flexibility options in various scenarios. As for the flexibility of conventional electricity plants, the fact that new generation coal and nuclear plants, from a technical viewpoint, will be more flexible than the current generation, has been taken into account. Whether these – or other – specific flexibility options will eventually be included in the mix of technologies with the lowest cost to society is an economic issue.[11]

Recommendations for a P2G road map

Recommendations

A Dutch P2G *road map* should prepare and organise the role of P2G in the long term
This study demonstrates the need for P2G in the long term, and the lack of positive business cases for the implementation of P2G in the short term. The P2G option is of such high importance in the long term that it seems important to stimulate further technology developments in the short to medium term. Without such stimulation, there is a risk that the necessary technology may not be readily available or sufficiently developed at that point in time when its implementation turns to be crucial. In different areas much thinking will need to be done about how to prepare the energy system and society for a distinct role for P2G. Both the government and the market will have to play an initiating role in this process. A P2G *road map* should answer the question 'How can P2G in the Netherlands be organized in such a way that the potential of this technology to realise significant CO_2 emission reductions can be optimally utilized?' and should indicate which development and implementation steps should be taken at which point in time and by which actors. The following areas will need to be considered in preparation of the future role of P2G:

- *Technology development:* which innovations are needed, and how can they best be stimulated? Further lowering of electrolysis cost is required (e.g. by scaling up the available capacities and introducing new materials). Moreover, innovations aimed at making electrolysis technology more flexible could improve market opportunities for P2G.
- *Gas value chain:* how can the current gas value chain be made (more) suitable for a future with a wider range of gas quality specifications, including hydrogen? What are the bottlenecks, how can they be addressed and when should action be taken by which parties?
- *Social implications:* how could sufficient support for the implementation of P2G (hydrogen) as a relatively new technology (energy carrier) be achieved?.
- *Business models & institutional aspects:* Which business models can support a positive business case for P2G in the future? The system integration aspect of P2G makes it even more challenging to successfully position this new technology in the market. Current law and regulations can be a limiting factor: which institutional adaptations are required for a successful implementation?

Getting the regulatory framework right is a necessary condition for a successful energy transition at the lowest possible social cost
P2G is a robust part of a future mix of energy technologies that realises the required high CO_2 emission reduction in the *energy system* at the lowest social cost, where P2G offers added value by also contributing to supplying part of the required flexibility in the *electricity* system. For the energy transition to actually follow the path with the

[11] The possible revenue from flexibility services that can be generated within the hour have not been included in determining the economic benefits of flexibility options such as P2G,

lowest cost to society, it is necessary that the government arranges the right regulatory framework.[12] For example:

- Implementation of effective climate policy– resulting in a sufficiently high CO_2 price – is required for a solid P2G business case. Without such policy there is no economic incentive to invest in P2G today. The ultimate role of P2G partly depends on how climate and renewable energy policy are detailed and on the actual value that is implicitly attached to 'green' hydrogen and/or methane in the various end user sectors as a result of these policies.
- To fulfil the growing need for flexibility at the lowest social cost, an accurate valuation for flexibility in the market is required. This can for example be covered in the design of the electricity market: operators of intermittent electricity generation units could be considered a programme responsibility party and be subjected to prices on the electricity balancing market.

Follow-up research required with regard to the role and impact of flexibility and low carbon options in the mix of energy technologies

This study shows that the availability of alternative low-carbon options as well as alternative flexibility options has an important impact on the role of P2G. Various scenarios explore how the role of P2G changes as the availability of alternative options varies, although these options have not been studied in great detail. Part of the required flexibility in the *electricity* system, for example, could potentially be achieved by making industrial production processes and part of the electricity demand (combined with electrification of the final energy demand) more flexible. A question triggered by this study is what the real potential is of these sources of flexibility and under which conditions this 'hidden' flexibility can be mobilised? And what are the effects on the role that other technologies can play (such as energy storage and P2G)?

An international perspective is required in analysing the Dutch energy system and P2G developments

The Dutch energy system does not stand alone in its challenge to reduce CO_2 emissions and integrate larger amounts of wind and solar PV. Moreover, developments within the Dutch energy system are co-dependent on developments in neighbouring energy systems. The international dimension is therefore the relevant dimension to apply when implementing the previous recommendations. A Dutch road map for P2G can benefit from, and should be aligned with, similar initiatives abroad. Furthermore, international coordination should lead to an effective regulatory framework for energy markets (such as the electricity and gas market). Finally, interactions with neighbouring energy systems should be taken into account in further research on the integration of wind and solar resources and the technologies that may assist therein.

[12] This condition does not specifically apply to the P2G option but applies to the entire array of options that can contribute to the reduction of CO_2 emissions or can cater for the needed flexibility.

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