Exploring the role for power-to-gas in the future Dutch energy system

Final report of the TKI power-to-gas system analysis project

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July 2014
ECN-E--14-026

Acknowledgement

This paper reports on the key messages of the TKI gas project 'P2G system analysis study'. This project has been executed by ECN and DNV GL[1] between December 2012 and March 2014. This project is partly financed with subsidy from the Dutch Ministry of Economic Affairs, as part of the TKI Gas and commissioned by *Rijksdienst voor Ondernemend* Nederland (RVO). Apart from RVO, the following supporting partners are gratefully acknowledged for their valuable contribution to this project, both financially and content wise:

- Alliander: Michiel Geurds, Esther Hardi
- EBN: Ruud Schulte
- Energy Valley: Patrick Cnubben
- Gasunie: Piet Nienhuis, Koen Wiersma, Adriaan de Bakker
- Enexis: Michiel van Dam, Robert de Groot
- Nuon / Vattenfall: Jeffrey Haspels, Albert Bloem, Tim Besseling
- Rotterdam Climate Initiative (RCI): Monique de Moel
- Siemens: Jaap Bolhuis
- TAQA: Bas Froon
- Tennet: Gert van der Lee, Hans van Hooijdonk
- TKI gas: Jörg Gigler.

Other project deliverables that may be consulted are:

- DNV KEMA (2013). L. Grond, P. Schulze, J. Holstein. Systems analyses Power to Gas: A technology review.
- ECN (2014). J. de Joode. The role of power-to-gas in the future Dutch energy system: Summary. (Available at www.ecn.nl).
- ECN (2014). J. de Joode. De rol van power-to-gas in het toekomstige Nederlandse energiesysteem: Samenvatting. (Available at www.ecn.nl).

We like to thank Michiel Hekkenberg and Marcel Weeda for reviewing the project deliverables and Manuela Loos and Marlies Kamp for their assistance in editing the deliverables.

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[1] During the course of this project partner DNV KEMA changed its name into DNV GL.

Abstract

P2G - the conversion of (renewable) electricity into a gas (hydrogen, methane) - is considered an attractive option to both accommodate intermittent electricity supply from wind and solar resources and decarbonise fossil fuel dependent end-use sectors (e.g. transport, built environment). But what is the actual role that could be played by this technology? What are the drivers and bottlenecks for the P2G business case from an energy system perspective? This report presents the results of a model-based, energy system analysis and case study analysis.

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Management summary

Goal of the study

This power-to-gas(P2G) system analysis study aims to identify the future role and viability of the P2G concept in the Dutch energy system (within the context of the European energy market). The complexity of the energy system requires an integrated approach in which the entire electricity and gas value chains are incorporated. The final goal is to draw conclusions on the viability of P2G in the future Dutch energy system.

Approach

The future role for P2G in the Dutch energy system is assessed using both a top-down and bottom-up approach. The top-down approach involves a scenario-based modelling analysis in which a model of the integral Dutch energy system is used to simulate a future mix of technologies that achieves decarbonisation goals at the lowest cost for society. The bottom-up approach involves an analysis of three case study applications of P2G in three distinctive regions in the Dutch energy system. Both analyses aim to uncover specific determinants that may affect the role for P2G, where the modelling analysis has a focus on system factors and the case study analysis has a focus on local factors.

Conclusions

The findings from the model-based analysis and the case study analysis are consistent with one another and give rise to the following main conclusions:

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;
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;
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 synthetic methane (power-to-methane);
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.

Recommendations

Based on the results of this study the following recommendations are made:

1. A Dutch P2G road map should prepare and organise the role of P2G in the long term;
2. Getting the regulatory framework right is a necessary condition for a successful energy transition at the lowest possible social cost;
3. Follow-up research required with regard to the role and impact of flexibility and low carbon options in the mix of energy technologies;
4. An international perspective is required in analysing the Dutch energy system and P2G developments.

1

Introduction

1.1 Motivation and background of research

Climate and renewable energy policy goals
The Netherlands has committed to increasingly strong climate and renewable energy goals for the 2020 to 2050 time frame. In order to achieve long-term decarbonisation goals there are in principle five categories of options:

- Avoiding or preventing energy use;
- Improving energy efficiency of appliances and energy conversion technologies;
- Deployment of carbon capture and storage technologies;
- Deployment of biomass-based technology options;
- Deployment of carbon free electricity production technologies (e.g. wind, solar PV and nuclear energy).

The implementation of none of these particular options is without particular costs or controversies but earlier studies indicate that is very likely that a combination of all alternatives is needed in order to achieve climate targets. Given the different cost and availability potentials for these options and the public attitude towards these options, the increased deployment of especially wind and solar based technologies seems to be key in achieving future climate targets in the Netherlands.

Increasing need for system flexibility
The wind and solar based technologies are largely intermittent in nature and can bring forward significant challenges when it comes to the instantaneous balancing of the electricity system. Although the amount of installed wind and solar PV capacity present in the Dutch energy system has increased significantly over the last 10 years (as has the electricity production from this capacity), the need for additional sources of flexibility in the system has been limited. But given the recently agreed targets from the SER '*Energie Akkoord*' and the continuing push for decarbonisation thereafter, there will be an increasing need for system flexibility over the next decades.

The term flexibility can be interpreted in different ways, but in the context of an analysis of the integral energy system it is about making sure that the energy system as a whole is successful in accommodating different types of imbalances between demand

and supply over different time horizons. It is about accommodating a peak supply of intermittent renewable electricity in particular hours of the year or a longer period of days or weeks in which there is hardly any intermittent renewable electricity supply, while at the same time meeting energy demand with its own particular daily and seasonal patterns.

Increasing need for (renewable) energy carrier versatility
In the long-term, the key challenge in achieving a carbon-neutral energy system is to decarbonize those energy end-user sectors that are currently heavily dependent on fossil fuel resources such as oil (transport, industry) and natural gas (built environment). The options to reduce carbon intensity of energy use in those sectors is relatively costly and difficult to realise as the alternative number of carbon free technologies is very limited. One of the options to decarbonize final energy use in the mentioned sectors is to convert the relatively abundant potential of wind and solar energy – produced in the form of electricity – into (renewable) hydrogen and implement hydrogen-based technologies in industry (as feedstock and source for heating demand), transport (as fuel for fuel cell or hybrid –based transport technologies), and the built environment (as source for heating demand).

Current developments in P2G
A review of the current state of electrolysis technologies – which is the key technology for P2G – illustrates that most types of electrolysis technologies have yet to pass a required level of maturity in terms of investment cost and efficiency. The most commercially advanced electrolysis technology, is only used in relatively small-scale applications and is mainly run in base load. This means that from the perspective of using P2G as a means to provide flexibility to the energy system the relevant underlying technologies still need to be further developed, also regarding flexible operation properties. In contrast with the Netherlands, where only a small-scale demonstration project based on methanation is taking place in Roozenburg, neighbouring Germany can boast a number of about 20 different projects applying the P2G concept.

What future role for P2G?
Although the current interest in P2G is mainly associated with the large amounts of electricity from renewable intermittent energy sources during an increasingly large amount of hours of the year, not all of the current initiatives are based on the concept of 'surplus' electricity. This makes it the more interesting to provide an integral system analysis on the role P2G could have in different future energy scenario's.

This study explores the possible role for P2G in the transition of the Dutch energy system between now and 2050 and explicitly assesses both the role for P2G as provider of system flexibility and the role for P2G as a technology to convert electricity into a gaseous energy carrier (hydrogen or Synthetic Natural Gas (SNG)) for the use in traditional fossil fuel based end-user sectors.

1.2 Project background

The system analysis study of power-to-gas has been executed in the context of a new innovation policy of the Dutch government. At the core of this policy are private-public partnerships within nine top sectors, aiming for optimal utilization of public resources

for knowledge and innovation. This policy has been translated into agreements between Dutch industry, knowledge institutes and the government and resulted in so called Top consortia for Knowledge and Innovation (TKI), which are structural partnerships in which different parties collaborate along the entire knowledge value chain.

The consortium in this project operates within the top sector Gas and specifically focuses on 'power-to-gas' (P2G). The consortium partners are: Alliander, DNV GL[2], EBN, Energy Research Centre the Netherlands (ECN), Energy Valley, Enexis, Nuon Vattenfall, N.V. Nederlandse Gasunie, Rotterdam Climate Initiative (RCI), Siemens Nederland, TAQA and Tennet.

An earlier deliverable produced in the context of this P2G system analysis project was published by DNV KEMA in June 2013[3]. The techno-economic assessment that is contained in this deliverable has been key input for the P2G undertaken by ECN and reported on in this background report. More specifically, the DNV KEMA report has produced technology fact sheets for a range of electrolysis, methanation and electricity storage technologies that have been used as a direct input in the model-based analysis and have been partly used in the case study analysis.

A summary of this background report is available in both Dutch and English:

- ECN (2014). J. de Joode. De rol van Power-to-Gas in het toekomstige Nederlandse energiesysteem: Samenvatting, ECN-O-14-010 (available at www.ecn.nl);
- ECN (2014). J. de Joode. *The future role for Power-to-Gas in the Dutch energy system: Summary*, ECN-O—14-030 (available at www.ecn.nl).

1.3 Research questions

This power-to-gas system analysis study aims to identify the future role and viability of the power-to-gas concept in the Dutch energy system (within the context of the European energy market). The complexity of the energy system requires an integrated approach in which the entire electricity and gas value chains are incorporated. The final goal is to draw conclusions on the viability of P2G in the future Dutch energy system.

The main research question in the system analyses study has been defined as follows:

Under which circumstances and in which situations can power-to-gas play a role in the transition towards a cleaner and sustainable energy system in the Netherlands?

Main research question

Sub-questions addressed are:

- What are the factors affecting the case for P2G?
- Under what conditions is it potentially beneficial to invest in P2G technology?
- What role could P2G play in a future Dutch energy system?
  - Does P2G contribute to system decarbonisation and / or the integration of ‘excess ‘ electricity production from intermittent energy sources?

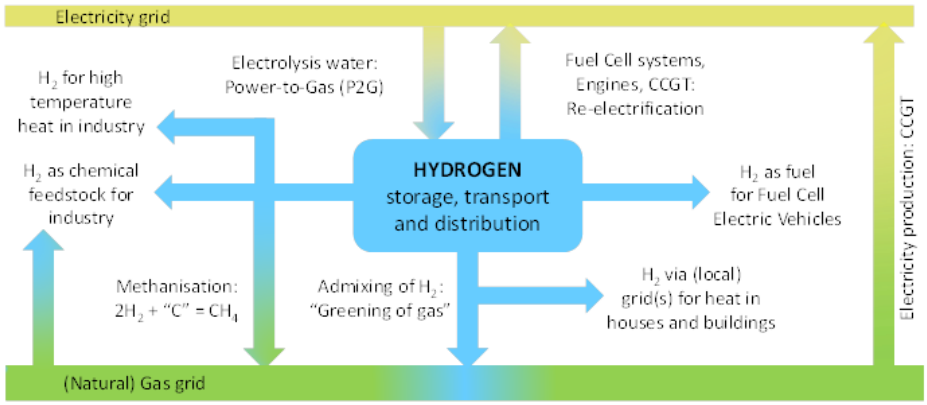
[2] Previously known as DNV KEMA.

[3] DNV KEMA (2013). L. Grond, P. Schulze, J. Holstein. Systems analyses Power to Gas: A technology review, Report GCS 13.R.23579 (available at: http://www.dnv.com/resources/position_papers/systems_analyses_power_to_gas_a_technology_review.asp)

1.4 Scope and definitions

In the context of this study, the concept of P2G is not exclusively used to indicate a pathway for using electricity – from for example intermittent renewable electricity sources – to produce methane (i.e. Synthetic Natural Gas; SNG) via the methanation process. In this study a broad interpretation is used that also considers hydrogen as a gas, and which includes the direct deployment of hydrogen as an energy carrier. The different possible routes for the hydrogen acquired via electrolysis of renewable electricity is depicted in the figure (**Figure 1**) below. Although the P2G concept is often linked to the conversion of particularly *renewable* electricity, this study does not preclude the conversion of electricity from other sources such as nuclear or gas-based electricity.

Figure 1: Illustration of the broad interpretation of the P2G concept in this study



The broad interpretation of the concept of P2G also requires the use of a top-down, integral energy system 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 in its entirety. In an energy system that has to comply with increasingly strong 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 the most cost-efficient CO_2 emissions be reduced? And: what does this imply for the use of energy sources and CO_2-free technologies in the energy mix? An approach aimed at merely 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.

The system boundary in this study is the Netherlands. This implies that solely the Dutch energy system is studied in a high level of detail. However, the option to import fuels from the rest of the world as well as the option to exchange electricity with neighbouring electricity systems are taken into account.

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 targeted of 80% to 95% CO_2 emission reductions in 2050 compared to 1990. The model used in the study calculates which energy technology mix

leads to a significant 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 triggers 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 not necessarily corresponds with the perspective of 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 not desirable.

When using terminology such as to 'carbon reduction' targets or 'CO_2 emission levels' we refer to the damaging emissions of greenhouse gases (GHG). When the text or graphs mentions CO_2 emissions we actually mean CO_{2eq}. In exploring the role for P2G – and other low carbon options – in reducing CO_2 emissions of the Dutch energy system we adhere to the internationally accepted standard used in reporting on CO_2 emissions. This means that emissions are only accounted for if the activity that causes the emission takes place on Dutch territory. An alternative standard would be the accounting of emissions based on a lifecycle approach taking into account emissions due to activities throughout the value chain even though part of these activities occur abroad. The implication of adopting the national based CO_2 accounting standard implies that the results derived in the modelling analyses optimise for a reduction in CO_2 emissions taking place in the Netherlands. For example, for the level of CO_2 emission in the Netherlands, it does not matter whether imported gas resources originate from Norway or from Russia. An energy system optimisation based on lifecycle / value chain CO_2 emission accounting may give rise to different optimal system configurations.

1.5 Reading guide

The remainder of this background report of the P2G system analysis project is structured as follows:

- Chapter 2 describes the adopted methodological approach and strategy used in answering the research questions;
- Chapter 3 presents the results of the top-down model-based analysis of the future role for P2G;
- Chapter 4 reports on the three bottom-up, case study analyses;
- Chapter 5 contains the overall conclusions from this study and provides some policy and research recommendations.

For a summary of this background report we refer to the separately published management summary (in both Dutch and English) available at www.ecn.nl.

2

Methodology

This chapter describes the adopted research methodology and contains two parts. The first part (Section 2.1) discusses the general factors that affect the role for P2G in an energy system. These factors are crucial in determining the type of analyses performed with the model adopted in this study. This model is central in the second part of this chapter (Section 2.2). The approach used in the case study analyses is not part of this chapter but is included in the chapter that also reports on the results from these case study analyses (Chapter 4).

2.1 Factors affecting P2G

An important starting point for any analysis on the potential role for a particular technology or service is the identification of the possible determinants that could be relevant. This section identifies the broad set of determinants in the case of P2G.

This study aims to explore the role for P2G in the future Dutch energy system from a techno-economic perspective: what could, or should be the role for P2G in the mix of energy technologies if future CO_2 emission reduction goals are to be met at the least cost for society? This is different from exploring specific investment opportunities from a private investor's perspective. Obviously, similar determinants could contribute to both a particular role for P2G in the system from a social perspective and a positive business case from a private perspective. On the other hand, various factors – such as local conditions or specific (sectoral) policies could lead to a positive business case for P2G from a private perspective even though a particular role for P2G from a social perspective is not that solid. When analysing the potential role for P2G from a social perspective there are broadly three categories – or rather determinants - that can be distinguished (See **Table 1**).

Table 1: Overview of P2G business case determinants

Category	Determinants
Costs of P2G	Investment costs
	Operational cost (among which the cost of electricity input
Price of / demand for P2G delivered products / services	Flexibility
	CO_2 emission reductions
	Fuels
Costs / availability of competing alternatives[4]	Competing flexibility options (curtailment, storage, demand response, etc.)
	Competing CO_2 emission reduction options (biomass, nuclear energy, CCS)

Firstly, the role for P2G is determined by the costs of this technology option. These include the cost of investment, the operational costs (e.g. O&M) and the costs of procuring electricity. The investment cost of electrolysis and methanation assets could decrease over time due to economies of scale and learning. The cost of electricity procurement are linked to the price of electricity on the market, which in turn may be affected by the share of intermittent energy sources in the electricity mix. An increasingly large share of wind and solar-based electricity production may lead to lower hourly electricity prices for a long period of the year.

Secondly, the role for P2G is shaped by the price of – or demand for – either (a) flexibility, (b) CO_2 emission reductions, and (c) fuels. The value of flexibility in a system determines the reward for P2G when delivering a flexibility service. Generally speaking, the value of flexibility could be related to the magnitude of the flexibility issues brought about by the increasing penetration of intermittent renewables in the system. Strong emission reduction targets determine whether P2G generates an added value as an enabler of reducing CO_2 emissions. This may be indicated by the price of CO_2 emissions rights or a CO_2 tax. Finally, the demand for hydrogen or SNG as a fuel in for example the transport sector can also influences the revenues for P2G.

Thirdly, the role for P2G depends on the costs and availability of alternative technologies or technology routes that are capable to deliver the same services or products mentioned above. P2G competes with other low-carbon alternatives in achieving CO_2 emission reductions over time and competes with other flexibility and storage options in providing flexibility to the system. The costs of these competing options may change over time due to technological learning in the value chain or due to increased scarcity of the resource. The technical potential of the alternative options is relevant, but just as relevant is the public acceptance of those options. Finally, the P2G business case is influenced by the availability and price of hydrogen-based end-use applications, such as fuel cell cars.

Specific policy and policy targets further shape the context for P2G and its competing low-carbon options and flexibility options. Examples of such are technology-specific renewable energy targets (e.g. offshore wind, biofuels), sustainability criteria (for biomass), details of energy efficiency policy, overall market design and regulations of the electricity balancing market, etc.

[4] The fact that P2G could in practice avoid particular electricity network reinforcement costs is implicitly accounted for via this set of determinants. Developing alternative flexibility options on the flexibility market – such as electricity storage – will also involve associated investment in electricity network assets.

The above set of determinants is used in the various model-based simulations in chapter 3. By assessing the sensitivity of results regarding the role for P2G on changes in these determinants the key drivers may be derived for P2G developments in the future energy system from a social perspective.

2.2 Methodological approach and scenarios

In this study a combined model and case study-based approach is used. The modelling approach involves the use of an integral energy system perspective, with the Netherlands as system boundary. 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
This study adopts an integral energy system perspective. This 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.

Goal: 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% CO_2 emission reductions in 2050 compared to 1990. The model used in the study calculates which energy technology mix leads to a significant 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 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 not desirable.

Scenarios and input data assumptions
The future is uncertain and uncertain factors that could affect the future role of P2G in the Dutch energy system are numerous. When applying the optimization model OPERA we therefore use a range of a range of scenarios in order to properly assess the sensitivity of the P2G business case for different drivers and factors. **Table 2** presents

the developed scenarios and explains how may contribute to insights into the drivers for P2G.

It is important to acknowledge that these scenarios score differently on 'plausibility'. Some of these scenarios are particularly constructed to 'technically' test model sensitivity to specific parameter changes that may be important for the case of P2G (see the list of determinants in Section 2.1).

Table 3 provides the parameter values that have been changed from the one scenario to the next. For realistic estimates of the available potential of CO_2 storage, biomass and nuclear energy we adopt assumptions as used in ECN (2012). The maximum CCS capacity of 50 Mton per year represents the estimated technical potential for CO_2 storage in the Netherlands. The maximum biomass potential estimate of 500 PJ is based on an estimated 200 PJ domestic biomass potential and an estimated 300 PJ of additional biomass resources that may be imported from other regions in the world. For nuclear energy it is assumed that the Netherlands will in the future only see a maximum amount of nuclear energy capacity of 5,000 MW_e. For comparison: the current nuclear power plant at Borssele has a capacity of 450 MW_e[5]. The assumption of a 10% admixing limit for hydrogen into the gas system should be interpreted as a possible admixing limit in 2050. The current admixing limit is set at 0.02%, while the target admixing limit for 2023 is 0.5% (Groen Gas Forum, 2014). In the model simulations a 10% admixing limit will be used, while sensitivity analyses are performed for admixing limits of 1% and 50%. The values (percentage-wise) that have been used in the set of scenario's are to some degree arbitrary. As has been noted before, not all scenarios simulated with the OPERA model can be considered realistic as some scenarios are particularly chosen to test the direction of effects and the order of magnitude, rather than to determine the precise figures. As this study is the first to explore the particular range of scenarios in which P2G could be part of a future energy system, it is important that the corner solutions are identified. The large degree of uncertainty that is inherently present in assessing 2050 energy systems is the key reason for adopting a rather large range in some variable assumptions.

[5] Newly built nuclear power plants tend to be much larger than the relatively old Borssele plant. For example, the Finnish nuclear power that is under construction in Olkiluoto, the first European Pressurized Reactor (EPR) has a capacity of 1,600 MW_e

Table 2: Overview of scenarios (including description) and P2G determinants assessed therein

P2G determinant analysed	Factor influenced	Scenario	Description	Meaning for P2G
Costs	Costs P2G	Lower costs for P2G	50% lower costs for electrolysers	Effect of lower costs of P2G
Benefits CO_2	Value CO_2 emissions reductions	Varying level of emissions targets in all scenarios	Emissions targets of 130, 90, 50 Mton/a for all scenarios	Effect of higher scarcity of CO_2 emission reduction and derived effects on the energy systems.
Benefits flexibility	Intermittent supply	Target wind & Solar	Targets (MW) for wind and solar-PV	Isolated effect of increased intermittent supply
		Target wind & solar, including priority access	Targets (MW) for wind and solar-PV + priority access for renewables	Isolated effect of increased intermittent supply, emphasized by obligation to absorb supply at any moment
		Target wind & solar, including priority access and unlimited flexibility at zero cost	Targets (MW) for wind and solar-PV + priority access for renewables and unlimited flexibility at zero cost	Effect of increased intermittent supply, emphasized by obligation to absorb supply at any moment in combination with effect of system without any residual demand for flexibility
Benefits fuel	Fossil fuel prices	Higher fossil fuel prices	100% higher fuel prices	Increased value of hydrogen as a substitute for fossil fuels
		Lower fossil fuel prices	50% lower fuel prices	Decreased value of hydrogen as a substitute for fossil fuels
Alternatives flexibility	Availability flexibility	Full free flexibility	Free and unlimited flexibility (e.g. from foreign countries)	Effect of system without any residual demand for flexibility
Alternatives low carbon	Availability CO_2 emission reduction electricity supply	Restrictions Nuclear	Maximum of 2500 MW (50% lower)	Effect of lower potential of low carbon electricity
	Availability CO_2 emission reduction fuel supply	Restrictions biomass	300 rather than 500 PJ/yr available	Effect of lower potential of low carbon fuels
		Restrictions CCS	30 rather than 50 Mton/yr available	Effect of lower potential of low carbon fuels/ electricity
Downstream costs and demand	Cost of hydrogen application	Low H_2 admixing limit	Maximum of 1% admixture (valid for each hour)	Lower potential for low-cost hydrogen application (higher hurdle), and lower benefits from gas system flexibility
		High H_2 admixing limit	Maximum of 50 % admixture (valid for each hour)	Higher potential for low-cost hydrogen application (lower hurdle) and higher benefits from gas system flexibility
		Lower cost H_2 transport	50% lower investment cost for H_2-based transport applications	Effect of lower cost of potential H_2 demand on P2G
	Demand for hydrogen	H_2 in transport	35 PJ of hydrogen demand from transport sector to be met	Demand for hydrogen given: competitive position of P2G as compared to other hydrogen production

Table 3: Overview of input assumptions for the different scenarios

Parameter	Reference scenario	Target Wind & Solar	Target and priority wind & Solar	Target and priority wind & Solar	Target and priority wind & Solar, full free flexibility	Restrictions Nuclear	H_2 in transport	Lower cost H_2 transport	Restrictions biomass	Restrictions CCS	Lower costs P2G	Low H_2 admixing limit	High H_2 admixing limit	High energy prices	Low energy prices	Full free flexibility	No P2G
Max. CCS capacity (Mton / yr)	50	50	50	50	50	50	50	50	50	30	50	50	50	50	50	50	50
Max. biomass potential (PJ)	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Min. wind capacity (GW_e)	-	36.5	36.5	36.5	36.5	-	-	-	-	-	-	-	-	-	-	-	-
Priority access wind & solar	No	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No
Min. solar capacity (GW_e)	-	45	45	45	45	-	-	-	-	-	-	-	-	-	-	-	-
Max. nuclear capacity (PJ / yr)	5,000	5,000	5,000	5,000	5,000	2,500	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5.000	5,000
H_2 admixing limit for gas system (%)	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	1%	50%	10%	10%	10%	10%

Table 4 provides the assumed fuel prices for 2050 for a range of energy carriers. They are expressed in $€_{2012}$, as are all monetary values in this study.

Table 4: Overview of fuel price assumptions for 2050 used in the model analysis

Energy carrier	Reference value [€/GJ]
Natural gas	7.9
Coal	2.7
Oil	15.2
Uranium	0.7
Waste	-9.0
Biofuels	20.9
Biomass	6.4

2.3 OPERA model description

2.3.1 Introduction

This part of the report gives a concise description of the OPERA-model, which has been applied for the system analysis.

OPERA is an optimisation tool that finds a mix of energy technologies that satisfies energy system restrictions (for example CO_2 emission reduction targets) at least cost for society

OPERA (Option Portfolio for Emissions Reduction Assessment) is an integrated optimisation model, and the successor of the *'Optie Document'*. It is a bottom-up technology model that determines which configuration and operation of the energy system combined with other sources of emissions meets all requirements, whether market-driven or policy imposed, at minimal energy system costs. These requirements generally include one or multiple emission caps. In addition to energy related emissions and technologies, the model is capable to include emissions and technologies that are not energy-related as well.

For the choice of technologies (technology options), it draws upon an elaborate database containing technology factsheets, as well as data on energy and resource prices, demand for energy services, emission factors of energy carriers, emission constraints and resource availability. The technology fact sheets for electrolysis, methanation and electricity storage used in the OPERA model are based on the findings of the techno-economic assessment by DNV KEMA (2013).

When used for the Dutch energy system, OPERA derives various scenario data from the Dutch Reference Outlooks and National Energy Outlooks. These provide a baseline based on extrapolation of existing and proposed policies. Among others, this baseline provides the demand for energy services (e.g. space heating, demand for transport, demand for products) that must be met. In addition, OPERA uses the baseline to compare its results with regarding additional emission reductions, additional costs and changes in energy demand and supply.

OPERA can tackle either fixed or exploratory policy targets, and the calculated effects include physical energy flows, emissions quantities as well as costs. Where in the past, the tool could only present the difference with a given background scenario, the new version does include the background scenario as well, so that also absolute remaining emission levels can be present, including the cost of the remaining technologies in the background scenario.

The baseline scenario is represented by a technology portfolio based on the complete energy balances of the Netherlands as reported in MONIT (www.monitweb.nl). These energy balances distinguish between energetic energy use (with energy in- and output of CHP separately reported), non-energetic use (feedstock in e.g. petro-chemical industry) and other conversions (e.g. cokes ovens or refineries). Energy service levels are also derived from the baseline, whether as energy demand (electricity and/or heat)

or a projected activity level expressed in physical units (e.g. iron and steel, ammonia, ethylene, passenger road transport, freight road transport).

In this study, the OPERA model simulations combine this baseline scenario and energy balance with three different target levels for GHG emissions: 110, 70, and 30 Mton in order to represent three different target years. The 30 Mton target level corresponds with a reduction of the CO_2 emission level by 85% (as compared to the 1990 level of CO_2 emissions). The 110 Mton and 70 Mton levels correspond with reductions of about 50% and 70% (again compared with the 1990 reference). These CO_2 emission reduction levels may be associated with particular target years: an 85% emission reduction target may correspond with a 2050 setting, while the other emission reduction targets reflect intermediate years.

Emissions currently covered are the greenhouse gases CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and SF_6. The model will be complemented with air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), particulate matter (PM10 and PM2,5) and non-methane volatile organic compounds (NMVOC). Thereby, both climate targets as well as air pollutant targets and effects can be analysed.

Being a flexible and versatile tool, OPERA may incorporate any other target pollutant or substance, given that they are accompanied by factsheets that contain the required information on their effects.

2.3.2 Energy system representation

The model covers both the supply and demand side of the Dutch energy system, as well as the energy networks connecting the various parts of the energy system.

The energy supply sectors covered are:

- Electricity: covering both centralised and decentralised technology, and both fossil fuel and renewable-based;
- Gas: covering both natural gas as well as biomass-based gas, with both possibly combined with carbon capture and storage (CCS);
- Heat : covering both centralised and decentralised technology, and both fossil fuel and renewable-based;
- Hydrogen: centralised and decentralised based on fossil fuels (without and with CCS), renewables and electricity;
- Grids: differentiated levels and storage
- Energy conversion: refineries, liquid fuels from fossil and biomass (without and with CCS).

Energy technology representation

The model database contains traditional technologies describing the actual energy system on supply and demand sides, as well as existing and future alternatives. Generally, the alternatives are favoured over traditional technologies as emission constraints get tighter. More specific limiting constraints, such as additional technology or energy limitations (e.g. limits on nuclear expansion or CCS or biomass availability) will limit the role of the directly affected technologies and technologies linked to these,

while favouring the position of other technologies that fulfil the same functions. Constraints imposing minimal values (e.g. target to meet a certain amount of wind or solar energy) favour the affected technology while placing competitors at a disadvantage). There are various ways in which technologies influence each other: technologies may compete with each other, but they may also favour each other. For example, a lot of intermittent renewable energy may favour the position of storage and peak load technologies, and a lot of electricity supply is likely to favour the position of technologies that convert electricity to other energy carriers.

For all end-use demands, at least one alternative technology is available. In most cases a small portfolio of technologies that draw upon different energy sources (e.g. fossil, biomass, solar) is present, that all satisfy the same demand. In this way, the model does not contain biases towards the one or the other energy source.

Table 5 provides a list of the different elements in the modelled energy system chains.

Table 5: Broad overview of technology options included in the energy value chain as modelled by OPERA

Production / supply	Conversion	Infrastructure	mand
• Centralised electricity (and heat) plants based on: - coal - gas - biomass (without and with CCS) - nuclear - renewables: wind on shore and off shore - hydrogen FC • Decentralised electricity plants CHP based on: - Gas - Biomass - Hydrogen - Solar PV	• Fossil fuel conversion: - Refineries (without and with CCS) • Biomass conversion (without and with CCS): - Into gas - Into liquid fuels • Hydrogen production based on: - Electricity - Natural gas (without and with CCS) - Biomass (without and with CCS)	Electricity network Natural gas network Hydrogen network	• Boilers based on fossil fuels (without and with CCS): - Coal - Liquids - Gas • Boilers based on biomass (without and with CCS) - Hydrogen - Industrial processes: - Iron and steel - Ammonia - Ethylene • Electric appliances • Saving technologies: - Heat based - Electricity based - End use technologies like different vehicle types

GHG emission reduction sources

GHG emission targets are an important issue in explorations of future energy systems. Basically, there is a limited range of primary resources for GHG emission reduction: end use energy savings, CHP, nuclear energy, CCS, biomass, other renewables (e.g. wind, solar, geothermal), fuel switch and reduction options for other greenhouse gases. All categories are represented in OPERA. Individual technologies may exploit only a single source (e.g. nuclear energy) or multiple sources (e.g. biomass based CHP with CCS).

Generally, the technologies that directly exploit a primary resource produce energy in a form that can be directly applied (biofuels, biogas, electricity, heat, hydrogen).

However, there seldom is a perfect match between supply and demand. Therefore, secondary transformations are required to deliver energy in form that is directly applicable for the various end-use sectors (e.g. electricity to hydrogen, electricity to heat, biogas to heat, biogas to electricity).

Generally, the small scale end-use sectors such as the built environment and the transport sector have less often direct access to primary resources, while the large scale end-use sectors and the energy supply have more direct access. As a consequence, transformation technologies such as P2G may play an import role in decarbonizing the energy system, as they convert carbon free energy harvested in the energy supply sector into a form which better meets the requirements of some end-use applications.

Table 6: Availability of energy related GHG emission reduction primary resources in sectors (direct application only)

Sector	Energy supply	Industry	Agriculture	Built environment	Transport
Savings	+	+	++	++	++
CHP	++	++	++	+	
Nuclear	+++				
CCS	+++	+++			
Biomass	+++	+++	++	+	
Other renewables	+++	+	++	++	
Fuel switch	++	+			++

+++: large, ++: medium, + small

P2G / hydrogen value chain representation

For P2G, the representation of hydrogen and a possible lay-out of a hydrogen network has received specific attention in OPERA. The existing representation, with only some production technologies (SMR and electrolysers) has been expanded with transport, distribution, conversion and various demand technologies. The figure below illustrates the approach of the model. While OPERA allows a regional differentiation, the P2G model analysis study does not look into local or regional aspects of supply, infrastructure and demand[6].

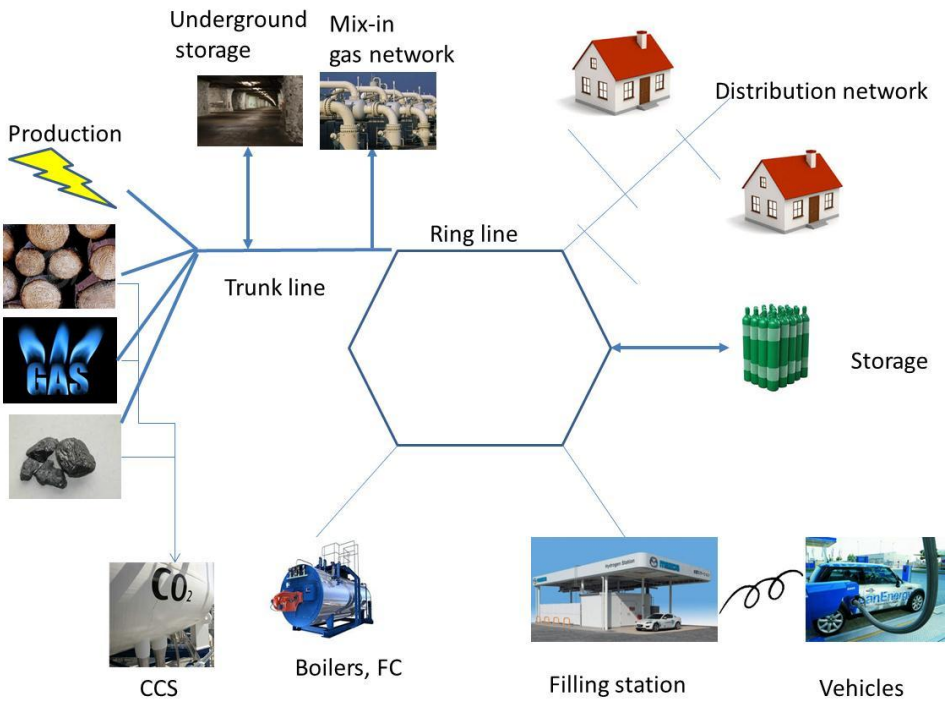
Hydrogen can be supplied by different technologies based on the input energy carrier (electricity, natural gas, biomass, fossil fuels). The network representation is kept deliberately simple as explained above: a trunk line feeds in a ring line around large demand centres (e.g. Rotterdam area, Randstad) which on its turn disperses in medium (industry, filling stations for transport) and low pressure distribution lines (households, service buildings) to end-users.

[6] However, the case studies (reported on in Chapter 4) do provide an approach in which local and regional aspects are represented.

The hydrogen may be consumed as such in fuel cells (both stationary as mobile), boilers etc. or mixed in the natural gas grid. The tool can apply varying maximal shares for mixing-in. Another possibility is the further conversion into methane (methanation process (not illustrated), which couples hydrogen with CO_2 from capture units). This can be used in all traditional and new natural gas applications.

In order to enhance flexibility of the hydrogen flow, several storage options are taken into account: large underground storage (similar to underground gas storage) is envisaged on the trunk line level, while local or regional storage can be achieved at the ring line level.

Figure 2: Schematic illustration of the hydrogen infrastructure represented in OPERA



2.3.3 Representation of infrastructure

For P2G, and given the diversity of levels of demand (households consume low voltage electricity, industry medium or high voltage), it is important to take into account that energy, electricity, gas and hydrogen, is not directly consumed at the suppliers site. To transport energy from the suppliers to the end-users, a network capable of transmitting sufficient amount of energy at any moment is required.

A stylised representation of the different grids is included in the model (See **Figure** 3 below).

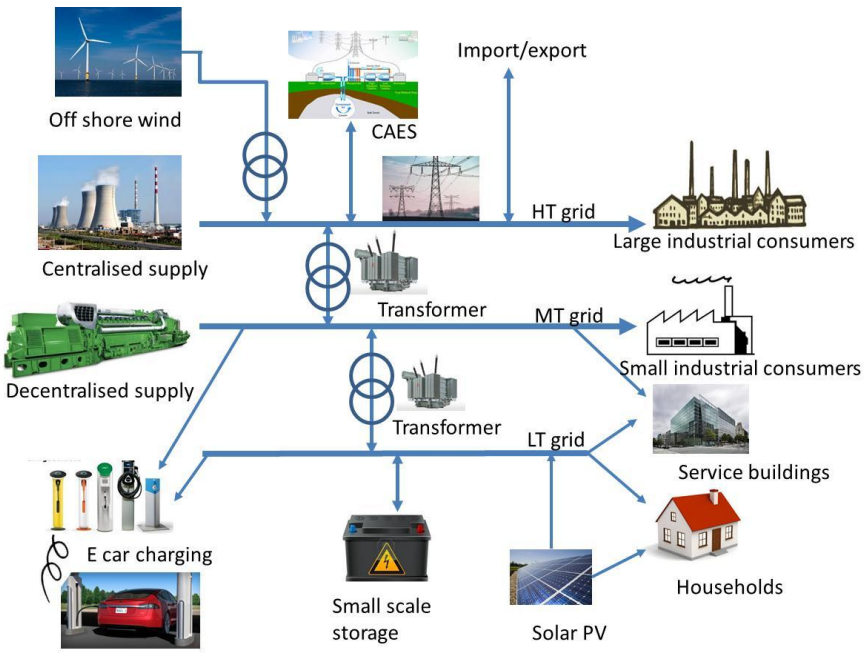
The electric network is differentiated in three voltage levels (high, medium, low) with on each levels the appropriate supply options as well as the demand and consumers (based on statistic data on level of consumption a “fixed” share of different voltage levels by sector is currently assumed, later this will be made flexible).

In order to be able to convey energy at different grid levels, electric transformers are included as well. They can ensure the flow of electricity between the voltage levels, in both directions. As has been explained by the stakeholders in P2G, the grid capacity is not the limiting element, it is the capacity of the transformers. Therefore, in addition to an estimated existing capacity in transformers (based on Liander and Enexis data), several expansion transformers (different MVA/kVA) are included in the database. OPERA may choose to invest in these transformers if the required peak flows between two voltage levels exceeds the existing capacity.

In addition, and especially targeted to P2G issues, a number of specific elements have been included in the electric network description:

- On the high voltage level, there is the possibility to make use of compressed air energy storage (CAES) as well of balancing by import/export;
- Off shore wind electricity may be connected at the high voltage grid, with a dedicated off-shore grid which is connected to the land grid by special transformers. These three elements (turbine-grid- transformer) are connected but not rigidly: the model can choose each capacity independent of the other: this allows for instance that ,in order to avoid high investments in transformers to convey peak production to the land grid, the model can chose to limits this capacity investment and to perform curtailment if this would be more cost-effective. Thus is the capacity of the transformer sufficient for the baseload/bulk output of the wind turbines, but not for the peaks.
- On the low voltage grid , stationary end users may use solar PV to provide (part of) their electricity demand and in the case of excess production, deliver into the grid;
- Also on low voltage, small scale storage is possible, mainly by means of battery technologies (see DNV KEMA, 2013) for an overview of options and technologies;
- The model includes charging stations for pure electric or hybrid cars.

Figure 3: Schematic illustration of the electric supply, infrastructure and demand



For the natural gas grid, the model applies a similar but much simpler representation, as it is expected that any imbalance between demand and domestic production, both from traditional gas extraction as from biomass sources (green gas), will be covered by imports or additional production.

The gas grid has different pressure levels, similar to the electricity voltage levels: a high pressure with most production facilities feeding in as well as the hydrogen mixing-in. The medium pressure grid and a distribution network serve most end users. Between the pressure level, connectors are modelled which reduce pressure from high to low. In contrast with electricity no pressurising from a lower to a higher pressure is envisaged as this go against quality assurance of the gas on the different levels (e.g odorisation and dilution with N_2 to maintain low caloric quality for most end users vis-a-vis high caloric gas consumption by a growing number of industrial end users). Distribution and transmission system operators generally expect the existing capacity of the gas grid to be sufficiently large for meeting current and future demand for gas, as the projected gas demand in the built environment is expected to show a stagnant or declining trend (related to the adoption of energy efficiency measures).Therefore, increases do not require expansion technologies, but do result in increased energy consumption for pressurizing the transported amount of gas.

2.3.4 Representation of time units and relevant demand and supply profiles

OPERA explicitly deals with needs to achieve a match between supply and demand at any moment. In order to do so within computability limitations, the OPERA model applies a time slice approach, in which the 8760 hours of the years are attributed to separate time slices. OPERA adopts an innovative approach in utilizing all relevant patterns in energy demand and supply covering the 8760 hours of the year, while not explicitly modelling each of these hours separately.

The basic approach is to smartly group together those hours of the year that have very similar characteristics with respect to the demand and supply of energy and the time sequence. Energy supply and demand exhibits particular patterns over the hours of the day, over the week, across seasons etc. Based on historical hourly data on all relevant supply and demand patterns (i.e. wind and solar profiles, heat and electricity demand profiles), time slice algorithms smartly combine those hours of the year that are (most) similar, and take account of the sequence of a particular hour relative to the daily peak in demand. In this way, model simulations can capture the different energy system balances throughout the year, while not putting to heavy requirements upon computing power capacity. The approach is flexible as the desired amount of time slices (and associated computing time per scenario run) can be varied in the OPERA interface. In live interactive sessions a lower number of time slices is used than in model simulations performed for reporting purposes. For a more elaborate explanation of the time slice approach we refer to Appendix A.

3
Results modelling analysis

This chapter presents the results from the model-based analysis with the OPERA model. This model was described in the previous chapter (Section 2.2). This chapter is divided into three sections:

- Section 3.1 presents and discusses the model results for a reference scenario simulation. An explanation of the particular model output used in assessing the role for P2G is included therein.
- Section 3.2 contains a number of sensitivity analyses that test the observations from the reference scenario results presented in Section 3.1. The sensitivity analyses of which the results are presented are based on the determinants that may affect the case for P2G that were identified in Section 2.1.
- Section 3.3 summarises the observations from the model-based analyses reported in this chapter.

3.1 Role for P2G in reference scenario

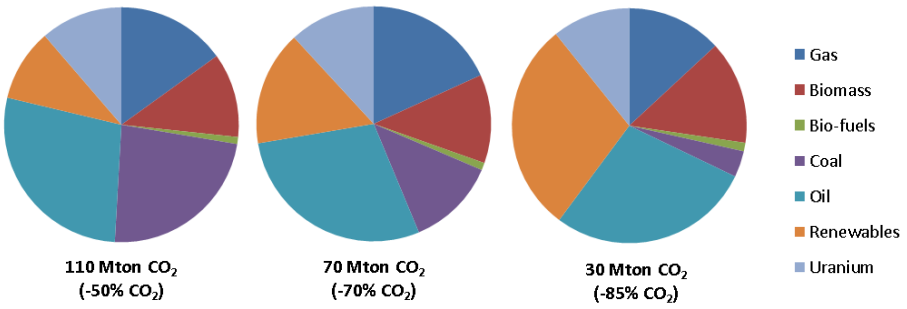
Introduction

This reference scenario represents a hypothetical policy setting in which there are only targets for reducing CO_2 emissions, and no separate targets for renewable energy technologies. In this setting, a cost optimal mix of primary energy sources and technologies for different level of CO_2 emission reduction levels is derived. Therein, each technology and primary energy source achieves its cost-optimal share.

The energy mix of the reference scenario, for different CO_2 targets, can be found in **Figure 4**. Note that the figures represent the net consumption of energy carriers. Since the net trade balance for electricity, heat, hydrogen, waste and biogas shows a net contribution of zero, they are not represented in the figure. It is clear that the role of non-biomass renewables increases with increasingly stringent CO_2 emission reduction targets. Another important observation is that oil continues to deliver a share in the primary energy mix. This is the result of the fact that a large share of the oil is used for the production of plastics. The carbon is stored in the plastic and process emissions

from the productions of plastics can be captured and stored. Therefore the large amount of oil used for plastics has a modest share in the GHG emissions.

Figure 4: Mix of primary energy sources in the **reference scenario**



P2G output sheet results

In analysing the role for P2G in a future energy system the focus will be on a targeted set of indicators that are relevant for the case of P2G. These indicators are collected in a so-called P2G output sheet. **Table 7** presents the P2G output sheet with results from the reference scenario simulation with the OPERA model. The table includes an explanation of the indicators featuring in the P2G output sheet.

Table 7: P2G output sheet results for the reference scenario

Indicator	Unit	Explanation	Reference scenario		
CO_2 emission level	[Mton / yr]		110	70	30
CO_2 reduction	[1990 = 0%]		-50%	-70%	-85%
CO_2 shadow price	[€/ton]	CO_2 shadow prices needed to realize CO_2 reductions[7]	34	112	439
Total energy system cost	[Bln€/yr]	Total annual energy system costs	55	57	65
Wind	[GW_e]	Amount of installed wind-based electricity generation capacity	7	16	35
Wind	[TWh/yr]	Annual electricity production using Wind turbines	25	67	148
Solar PV	[GW_e]	Amount of installed solar-based electricity generation capacity	31	40	40
Solar PV	[TWh/yr]	Annual electricity production Solar PV	30	38	38
Curtailment wind	[TWh/yr]	Amount of wind energy not realized due to switching off turbines	0	0	8
Curtailment wind	[%]	Percentage of wind energy not realized due to switching off turbines	0	0	5
Curtailment solar PV	[TWh/yr]	Amount of solar electricity not realized due to switching off solar panels	0	1	1

[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 scares, 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.

Indicator	Unit	Explanation	Reference scenario		
Curtailment solar PV	[%]	Percentage of solar electricity not realized due to switching off solar panels	1	2	1
Electrolysis	[GW_e]	Amount of installed electrolysis capacity, expressed as electricity input	-	-	1
Electrolysis	[TWh/yr] (input)	Annual amount of electricity fed into electrolysis	-	-	7
Electrolysis	[kton H_2/yr] (output)	Annual amount of hydrogen generated via electrolysis	-	-	155
Electrolysis	[hours]	Full load hours for electrolysis	-	-	5070
Electrolysis investment	[M€/yr]	Annual amount of capital investments for electrolysis	-	-	67
H_2 demand	[kton H_2/yr]	Total annual demand for hydrogen	-	-	155
Gas network (H_2 admixing)	[kton H_2/yr]	Total annual amount of hydrogen injected in the natural gas network	-	-	153
Transport	[kton H_2/yr]	Total annual amount of hydrogen consumed by the transport sector	-	-	0
Other H_2 demand	[kton H_2/yr]	Hydrogen demand for other applications	0	0	2
Methanation	[kton H_2/yr]	Amount of hydrogen used for methane generation	-	-	-
Electricity Storage (large-scale)	[TWh/yr]	Annual amount of electricity stored using large scale storage facilities	0	0	1
Electricity Storage (small-scale)	[TWh/yr]	Annual amount of electricity stored using electrical vehicles	5	9	12
Electricity imports / exports	[TWh/yr]	The annual amount of imported and exported electricity (net exchange always equals zero)	0	1	2

The results in **Table 7** show that electrolyser technology is only considered part of a cost-optimal mix of technologies in the case of a -85% CO_2 emission reduction target, with a simulated amount of electrolyser capacity of 1,400 MW_e. With about 5,000 operating hours a year, the yearly amount of hydrogen produced with this capacity is about 155 kiloton per year. Even though the amount of intermittent generation from wind and solar resources significantly increases in the -50% (39 GW_e) and -70% (56 GW_e) cases compared with the current situation (≈3 GW GW_e), this increase does not lead to the implementation of P2G. This suggests that the need for electricity system flexibility is no driver for the adoption of P2G. It is only in the deep decarbonisation case that P2G is part of the energy mix. This suggests that deep decarbonisation is a stronger driver for P2G than the need for electricity system flexibility due to the increasing penetration of renewable intermittent sources. This will be further investigated in the sensitivity analyses in Section 3.2.

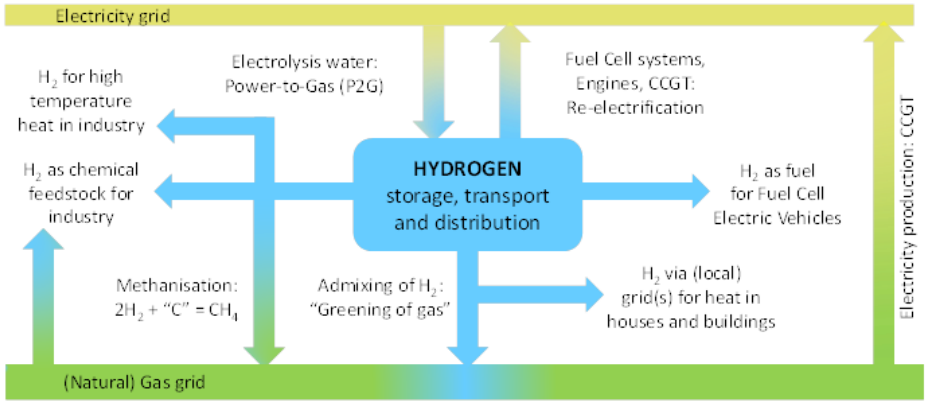
Below we first elaborate on the reference scenario results for:

- The demand for hydrogen (*which applications consume the hydrogen produced via electrolysis?*);
- The composition of the electricity balance (*How does the electricity system deal with increasingly stringent CO_2 emission reduction targets?*).

Applications of electrolysis-based hydrogen

In principle, the hydrogen produced via electrolysis can be consumed by the full range of applications depicted in Figure 5. Based on the imposed system requirements and the economics of the options, the model optimises the 'routes' that are considered to lead to the most cost-efficient energy mix for society.

Figure 5 Illustration of the possible routes for the use of hydrogen from electrolysis as modelled in OPERA



In the reference scenario hydrogen from electrolysis mainly used for admixing in the gas system

In the reference scenario results, the hydrogen produced via electrolysis in the -85% CO_2 emission reduction case is primarily used for admixing in the gas system: the hydrogen from renewable electricity is thus used by end-users connected to the gas system (built environment, industry). The latter implies that hydrogen consumption cannot be traced to a particular end-user sector or segment. As the model optimizes for total system cost, the explanation for this observation lies in the relative economics of the different technology options that simultaneously compete. The main difference between the hydrogen admixing application vis-à-vis hydrogen in mobility or industry is the relatively low cost of distribution: both the mobility or industry application of hydrogen involves investment in new distribution infrastructure and new dedicated hydrogen appliances. However, it should be noted that the possible cost of adapting gas value chain assets and appliances to the use a different gas specification in 2050 (i.e. with a higher share of hydrogen) have not been taken into account in the model analysis. The magnitude of these costs partly depends on the speed at which assets or appliances will need to be replaced or refurbished in the next decades in any case (because the end of economic or technical lifetime is reached). In addition, part of replacement costs may or may not be attributable to other gas quality developments.

Furthermore, it should be realised that the model provides a one-shot optimisation including all energy system aspects (available technologies, infrastructure implications, etc.). This implies that the particular application of hydrogen is not determined *after* determining the optimal amount of electrolysis, but that in determining the optimal amount of electrolysis the potential hydrogen applications are *simultaneously* taken into account. Further analyses of alternative scenarios in section 3.2 will be used to further explore the underlying drivers for the application of hydrogen.
The methanation route (combining the hydrogen with carbon-dioxide to produce synthetic methane) is not considered part of the cost-optimal mix of technologies in any of the reference scenario cases. This may have to do with the additional cost of conversion (i.e. energy loss) of this route and with the fact that there is a high 'penalty' involved for a continuing distribution of carbon dioxide in deep decarbonisation scenarios (with -85% CO_2 emission reduction targets). When distributed to dispersed final end-users the cost of capturing the CO_2 is very high – if possible at all. In such a constrained energy system it may be more cost-efficient to directly put underground

the available CO_2 before methanation rather than combining it with renewable hydrogen for distributed end-use.

The sensitivity analyses in Section 3.2 will further explore the drivers for the use of hydrogen in different applications, and the case for methanation. Below we turn to discuss the options used in accommodating the increasing amount of intermittent generation capacity in the system

Provision of system flexibility

The P2G output sheet results (**Table 7**) illustrate that there are several options that can provide system flexibility. Curtailment of solar and especially wind electricity is a very important possibility to get rid of excess electricity production. According to the figures from this table about 9 TWh of wind and solar electricity is curtailed. This is more than the total amount of electricity used for electrolysis. Other flexibility options present in the P2G output sheet are storage (large and small scale) and the interconnection with other countries (import/export). In particular small scale storage, i.e. electrical vehicles, are a very important flexibility option. For the target level of 30 Mton, 12 TWh of electricity is absorbed by electrical vehicles. Dispatchable power generation, not included in the P2G output sheet, is able to produce electricity in those periods of the year where the electricity production from wind and solar is limited and therefore also represents an important category of flexibility technologies.

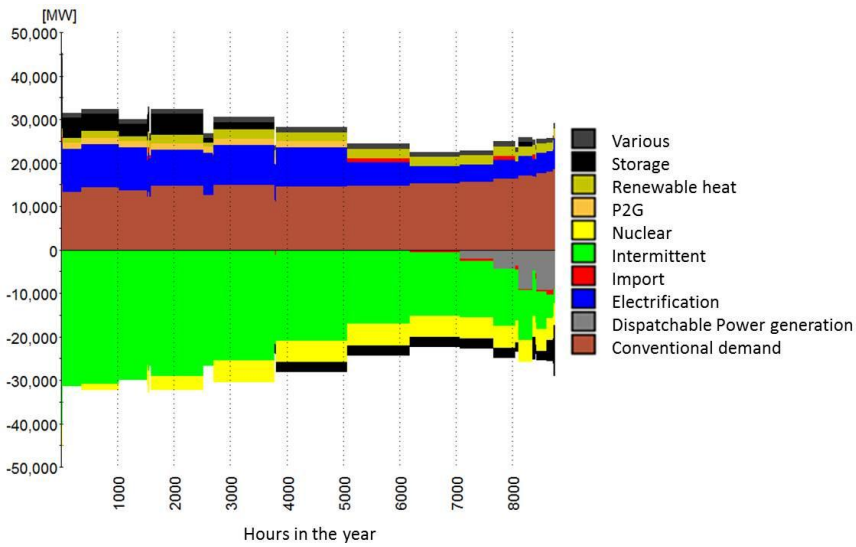
Besides the P2G output sheet, the energy balances for the electricity system are another useful output for analysing the role for P2G. **Figure 6** presents such a figure for the case of a 30 Mton emission level in the reference scenario. The horizontal axis covers all 8760 hours of the year and the vertical axis presents the electricity capacity – in this example in MW required. The data below the horizontal axis represents the supply of energy via different (groups of) technologies, and the data above the horizontal axis represents the total demand for energy for (groups of) technologies. The time slice approach groups together particular hours of the year that are very similar regarding their profile on hourly energy demand (electricity, heat) and hourly intermittent energy supply (from wind and solar PV). The stepwise shape of the figure shows the different 'blocks' of hours (i.e. time slices[8]) that have been grouped together. The number of hours represented by each time slice is not uniform: some time slices contain over 1,000 hours, whereas others only represent one hour. The time slices are ranked according to the hourly production of renewable intermittent electricity (i.e. wind and solar PV), from high production volumes on the left side to low production volumes on the right side. Within each time slice the reader can observe the cost-optimal mix of production (below the horizontal axis) and consumption technologies (above the horizontal axis).

By observing the particular sets of time slices the reader can infer the manner in which the required electricity system flexibility is accommodated. The time slices to the utmost left side indicated how the system optimally deals with hours in which the electricity supply from intermittent renewable energy sources is the highest of the year and exceeds total electricity demand. Likewise, the composition of the rightmost time slice demonstrates how the electricity system cost-efficiently deals with situations in

[8] This figure is based on 32 time slices.

which there is hardly or no supply of renewable electricity supply (i.e. total electricity demand exceeding electricity supply from intermittent renewables).

Figure 6: Electricity balance in the reference scenario with a CO_2 target level of 30 Mton[9]



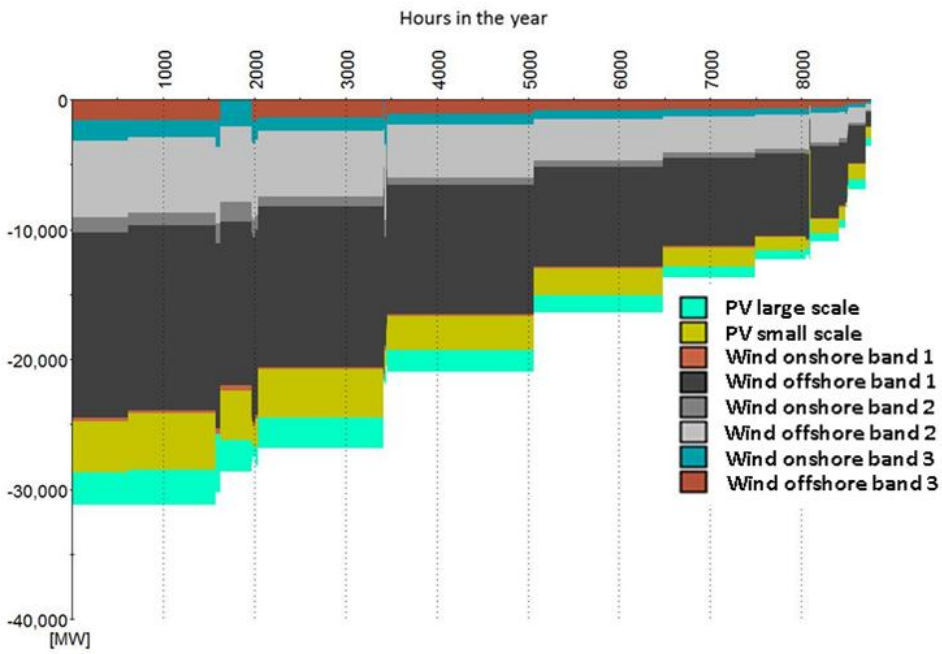
As **Figure 6** is in fact a graph of the electricity balance – the demand and supply of electricity are in balance in each time slice – this graph does not represent the curtailment of wind and solar electricity. The curtailed amount of wind and solar electricity is, however, included in the ranking of the time slices from left to right: the utmost left corner has the largest contribution from wind and solar electricity, the utmost right corner the smallest. Furthermore, the number of categories depicted in the graph has been reduced to the most essential categories from a P2G perspective for the readability of the figure. Underlying the basic categories depicted in **Figure 6** are a manifold of specific technologies. A basic explanation of the categories is provided below:

- **Conventional demand:** conventional electricity demand in for example households and industry, such as lighting, pumping, electrical equipment;
- **Dispatchable power generation:** Electricity generation technologies that are – technically - to various degrees dispatchable. These include coal, gas and biomass technologies, including CCS technology;
- **Electrification:** *new* demand for electricity, for example via technology options such as electric vehicles and power-to-heat options in industry;
- **Import:** the amount of electricity imported (or exported if observed on the demand side in **Figure 6**) Note that a constraint is imposed that ensures that total imports throughout the year are equal to total exports;.
- **Intermittent:** the electricity production from wind and solar sources;
- **Nuclear:** electricity production from nuclear power plants;
- **P2G:** electricity consumed by electrolysis technologies;
- **Renewable heat:** a.o. geothermal
- **Storage:** the electricity (dis)charged in (from) electricity storage options (both small and large scale)**;**
- **Various:** category of a small number of remaining technology options.

[9] For a clarification of the categories of technologies depicted see the text below the figure.

The higher level of detail available in the OPERA model can and has been consulted in interpreting the model results in this study. It is possible to zoom in into different sectors and individual options. An illustration of this higher level of detail underlying the broader categories depicted in **Figure 6** is provided in **Figure 7**. Therein the contribution of individual options under the category 'Intermittent' is given. The categorization used in **Figure 6** is used in the remaining part of the report.

Figure 7: Electricity balance in the reference scenario for the intermittent options[10]



From the results in **Table 7** (the P2G output sheet) and **Figure 6** the following observations can be made regarding the mix of options that together accommodate the fluctuating supply of intermittent electricity throughout the year.

- **Curtailment of intermittent generation**: During some hours of the year there is an excess of electricity generated by wind and solar for which curtailment is considered most cost –efficient option from a social perspective. Curtailments amount to about 9 TWh per year (about 6% of yearly electricity produced from wind and solar) in the -85% case and – as explained earlier on – do not show up in **Figure 6**.
- **Electricity storage**: Storage technologies play a role in bridging electricity supply and demand throughout the year. Storing of excess electricity predominantly takes place in about 4,000 hours a year, with this electricity evenly being released throughout the remainder of the year. The P2G output sheet reports an annual intake of electricity of about 13 TWh per year.
- **P2G**: The 1,400 MW_e of electrolyser capacity has an annual intake of 7 TWh in 5,070 operating hours per year according to the P2G output sheet. From **Figure 6** we learn that the intake profile is relatively flat, but from the observation that P2G is only in operation during the hours with relatively highest intermittent electricity generation

[10] This figure is based on the results with a simulation using 16 time slices.

we derive that P2G also contributes (partly) to the balancing of the electricity system.

- **Demand-side response**: The yearly consumption profile of new demand for electricity – represented by the category electrification (electric vehicles, electric heat pumps, etc.) – suggests that part of this demand is flexible, and therefore contributes to system balancing throughout the year. The demand for electricity in this category is about a factor two higher at times of peak electricity supply from wind and solar (utmost left in figure) than at times of low electricity supply from wind and solar (utmost right in figure). Hence, **demand side response** is part of the mix of flexibility options used in accommodating fluctuating wind and solar-based electricity supply.
- **Back-up generation capacity:** Dispatchable generation based on gas compensates for the lesser availability of solar and wind-based electricity during 1,500 to 2,000 hours in the year.
- **Electricity imports and exports**: Some exchange of electricity flows with neighbouring electricity systems (import / export) takes place in some of the time slices. The P2G output sheet reports a total exchange of about 2 TWh per year.
- **Nuclear energy**: Nuclear energy in current electricity systems is not considered a flexible technology and usually has about 8,000 full-load operating hours a year. However, in **Figure 6** it can be observed that nuclear energy is part of the cost-optimal mix of technologies but is not operating in baseload for 8,000 years. This suggests that also future nuclear energy units may operate relatively more flexible in the face of increasing shares of intermittent sources. Whether or not nuclear energy is being able to operate flexibly is not a matter of technological restrictions but rather a matter of costs. Apparently, a situation with a deep decarbonisation target makes it economically viable, at least from a least cost for society perspective, to operate nuclear resources relatively more flexible.

Although the focus in the discussion above was on the electricity system, these results obvious take into account all necessary restrictions and conditions imposed by other parts of the energy system. After all, the OPERA model represents the Dutch energy system in its entirety. This means that the presented results also account for – for example – the delivery of heat to final users throughout the year. The variation in the demand for heat is mainly observed in the built environment (i.e. the households and services sectors), as other sectors have a much more flat demand for heat over the year. The peak in heat demand in any year is generally in winter. Model output information demonstrates that in the case of a -85% CO_2 emission reduction case, the supply of this peak in demand is mainly done via boilers and geothermal energy for the services sector and high efficiency (HR) boilers for the households. Gas continues to play a role in demand for heating, although part of heating demand switches to electric or hybrid based-technologies. Moreover, the total amount of energy needed for heating demand decreased over time due to the implementation of energy efficiency measures.

Preliminary observations

The results from the reference scenario simulation provide first observations regarding the role for P2G in the energy system. These observations can be summarised as follows:

- Intermittent electricity generation from wind and solar resources play an increasingly large role in the decarbonisation of the Dutch energy system;

- P2G is only part of the cost-optimal mix of energy technologies in case of deep decarbonisation of the energy system, operating about 5,000 hours per year;
- Hydrogen produced via electrolysis in the reference setting is primarily used for admixing in the gas system, implying that P2G contributes to a decarbonisation of total gas consumption (in industry and the built environment). Application of hydrogen in the transport or industry sector does not occur;
- Methanation does not seem to be part of the cost-optimal mix of technologies in this reference scenario setting, which has to do with the fact that P2G is considered an option in the case of deep decarbonisation targets. In such a setting the continuing distribution of a gaseous energy carrier with CO_2 content comes with a particularly high cost;;
- The additional need for flexibility in the electricity system (due to the increasing integration of wind and solar resources) is accommodated by a mix of options, involving:
  - Temporary curtailments of intermittent electricity generation;
  - Exchange of electricity with neighbouring electricity systems;
  - Dispatchable electricity generation (based on gas);
  - Storage technologies (both large-scale at the transmission level and small-scale at the distribution system level);
  - Demand-side response.

Without further analyses, the effects described above (i.e. stronger CO_2 emission targets benefit the P2G case) cannot be isolated from the effects caused by the (associated) increasing shares of intermittent electricity generation (i.e. increase in intermittent renewable capacity benefits the P2G case). The particular drivers for the role of P2G as observed and discussed in this section for a reference scenario simulation are further investigated in the sensitivity analyses in the next section.

To isolate effects, P2G drivers are further investigated

3.2 Analyses on role for P2G and its drivers

This section presents and discusses the results from the range of sensitivity analyses performed. Consecutively discussed are:

- The impact of availability of other low-carbon options on P2G (Section 3.2.1);
- The impact of size of intermittency challenge on the role for P2G (Section 3.2.2);
- The impact of availability of flexibility options on the role for P2G (Section 3.2.3);
- The impact of P2G investment cost on the role for P2G (Section 3.2.4);
- The impact of fuel prices on the role for P2G (Section 3.2.5);
- The impact of potential downstream hydrogen demand on the role for P2G via transport or gas system admixing (Section 3.2.6).

3.2.1 Impact of availability of other low-carbon options on the role for P2G

Rationale for analysis

As the reference scenario shows a particular uptake of P2G in only the case of deep

CO_2 emission reductions, this section first explores whether the availability of low-carbon options (other than renewable electricity) have an impact on the uptake of P2G under increasingly strong CO_2 emission reduction targets. The key question addressed in this section is: how does a reduced availability (or potential) of low-carbon options (other than wind and solar PV) impact the role for P2G?
Consecutively assessed are the impact of a:

- Restricted availability of biomass (300 PJ instead of 500 PJ in reference scenario);
- Restricted availability of CCS (CO_2 storage potential of 30 Mton per year instead of 50 Mton per year in the reference scenario);
- Restricted availability of nuclear energy (2,500 MW_e instead of 5,000 MW_e).

The particular alternative values are to some degree arbitrary. The alternative values in this sensitivity analysis need to be realistic and at the same time differ substantially enough from their value in the reference scenario.

Results

Table 8 presents the P2G output sheet results for the reference scenario and the scenarios involving a restricted biomass, restricted CCS and restricted nuclear energy potential. The table only shows the results for the lowest simulated CO_2 emission level since this is the only one case where P2G enters the optimal energy mix. Under a CO_2 emission level for the Netherlands of 110 or 70 Mton per year, P2G is not considered part of the mix of technologies with the lowest cost for society. This was true for the reference scenario, and all considered alternative scenarios. A first important observation is thus that a restricted biomass, CCS or nuclear energy potential does not directly lead to an earlier adoption of P2G. As will be highlighted below, a restricted potential of other low carbon options does increase the role for P2G in the case of deep CO_2 emission reductions.

Table 8: P2G output sheet results for the impact of the availability of other low-carbon options on P2G

Indicator	Unit	Reference scenario	Restriction biomass	Restriction CCS	Restriction nuclear
CO_2 emission level	[Mton / yr]	30	30	30	30
CO_2 reduction	[1990 = 0%]	-85%	-85%	-85%	-85%
CO_2 shadow price	[€/ton]	439	1202	5067	599
Total energy system cost	[M€/yr]	64,598	72,043	83,085	65,844
Wind	[GW_e]	35	37	37	37
Wind	[TWh/yr]	148	160	166	156
Solar PV	[GW_e]	40	66	66	42
Solar PV	[TWh/yr]	38	58	60	40
Curtailment wind	[TWh/yr]	8	6	1	10
Curtailment wind	[%]	5	4	0	6
Curtailment solar PV	[TWh/yr]	1	2	1	1
Curtailment solar PV	[%]	1	4	1	2
Electrolysis	[GW_e]	1	8	19	2
Electrolysis	[TWh/yr] (input)	7	41	70	8
Electrolysis	[kton H_2/yr] (output)	155	954	1524	166
Electrolysis	[hours]	5070	5258	3748	5070
Electrolysis investment	[M€/yr]	67	447	926	71
H_2 demand	[kton H_2/yr]	155	1317	1524	166
Gas network (H_2 admixing)	[kton H_2/yr]	153	176	138	153
Transport	[kton H_2/yr]	0	1117	1117	9
Other H_2 demand	[kton H_2/yr]	2	25	260	2
Methanation	[kton H_2/yr]	-	-	9	-
Electricity Storage (large-scale)	[TWh/yr]	1	1	1	2
Electricity Storage (small-scale)	[TWh/yr]	12	12	9	12
Electricity imports / exports	[TWh/yr]	2	1	1	2

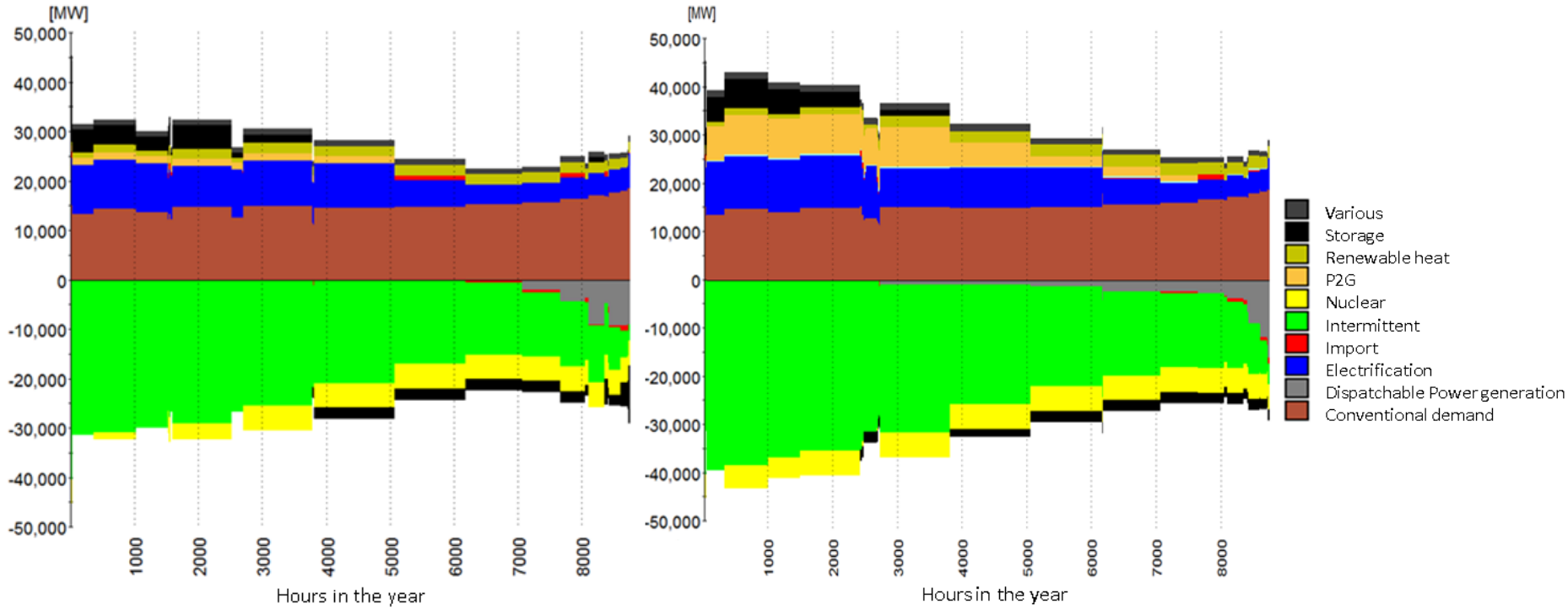
Impact of restricted biomass potential

The simulated restriction of the biomass potentially available for use within the Dutch energy system shows that a smaller role for biomass leads to a larger role for renewable electricity from wind and solar. Installed capacity of wind and solar increases with about 27 GW_e compared with the reference scenario. The additional amount of renewable electricity in needed to compensate for the relative lack of biomass resources as a decarbonisation route. This also implies a larger role for P2G as conversion technology. The amount of installed electrolysis capacity considered optimal for the energy system from a social cost perspective increases from about 1 GW_e to about 8 GW_e. The total amount of electrolysis-based hydrogen increases to about 1,000 kton per year. In this restricted biomass potential scenario the primary application for this hydrogen is no longer the admixing of hydrogen in the gas network, but rather the use in transport

applications. Hence, a reduced availability of biomass for the transport sector seems to be compensated with a larger role for P2G. The larger role for intermittent generation from wind and solar and P2G is observed in **Figure 8**: the increase in the share of electricity supply (below the X-axis) is matched with a similar increase in the share of electricity demand (above the Y-axis). The contribution of dispatchable generation based on gas is reduced due to the increasingly large production of wind and solar electricity.

As expected, the decreased biomass availability makes it altogether more costly to achieve particular CO_2 emission targets. Compared with the reference scenario, the restricted biomass scenario involves significantly higher overall energy system costs. Moreover, the shadow price of CO_2 emission reductions is also significantly higher as relatively more costly CO_2 emission reduction options now need to be deployed in order to compensate for the smaller role for biomass resources.

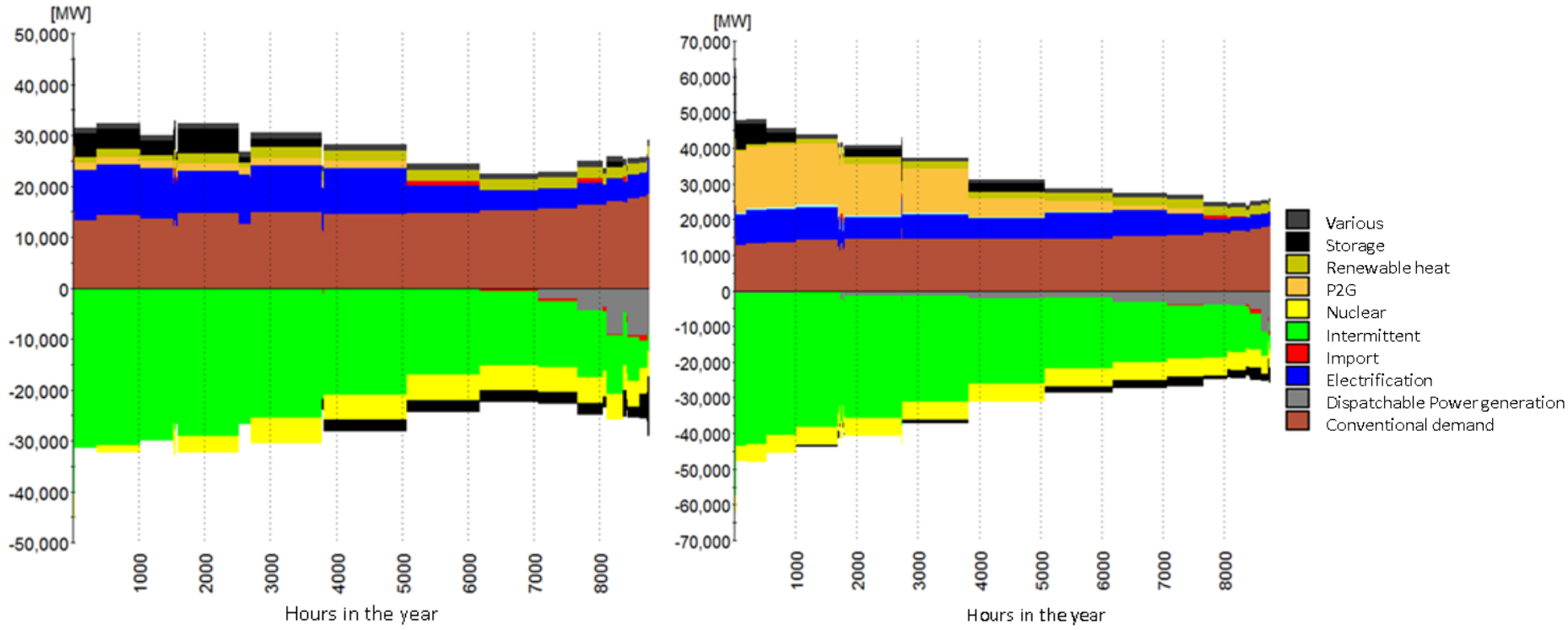
Figure 8: Electricity system balance in the reference scenario'(left) and the restricted biomass scenario (right) in the case of a -85% CO_2 emission reduction target



Impact of restricted CCS potential

Restricting the availability of the CCS route (by assuming a more limited CO_2 storage capacity) puts the energy system comparatively under more stress than the restricted biomass scenario. The relative scarcity of CO_2 storage capacity puts increasingly high pressure on the system to maximally deploy renewable electricity sources based on wind and solar. The total amount of installed intermittent renewable capacity in this scenario is about 103 GW_e, compared with about 75 GW_e in the reference scenario. In this limited CCS scenario it also becomes increasingly important to capture the full potential electricity from wind and solar. The amount of curtailed electricity from these resources falls from an average 4.8% to 0.6%. This indicates that curtailment is becoming a less important solution for intermittency issues. Given the increased value of the renewable electricity for the system, it becomes more economically viable to deploy other, more costlier options. This includes the option of P2G: the amount of electrolysis capacity invested in in this scenario is about 19 GW_e (to be compared with 1 GW_e in the reference scenario). The fact that the number of operating hours reduces to about 3,750 indicates that in a limited CCS scenario, P2G plays an increasingly large part in providing flexibility to the energy system. The hydrogen produced (about 1,500 kiloton per year) is used in different sectors, with a large share going to transport (about 1,100 kiloton per year). A relatively small share of the electrolysis-based hydrogen (about 9 kton of hydrogen per year) is used for methanation. **Figure 9** shows the electricity system balance throughout the year in the reference scenario and the restricted CCS scenario: it clearly shows the different operation profile for electrolyser capacity in both scenario's. P2G (the orange / brownish area) is now operated more flexibly, at the expense of both storage (the black area) and flexible electricity demand (the blue area).

Figure 9: Electricity system balance in the reference scenario (left) and the restricted CCS scenario (right) in the case of a -85% CO_2 emission reduction target



Impact of restricted availability nuclear energy

A limited availability of nuclear energy as a low carbon option (for example because of a lack of public acceptance) seems to have only limited impact on the role for P2G. This suggests that nuclear energy does not play an equally large role in energy system decarbonisation as the previously assessed low-carbon options of biomass and CCS. Results show only a limited compensation of a limited availability of nuclear energy by intermittent electricity sources (+5%). The impact on installed electrolyser capacity and consequent hydrogen production is positive but insignificant. The primary application of the produced hydrogen is the admixing into the gas system. As nuclear energy is a relativity less costly low-carbon option, a reduced availability does increase overall system cost and the shadow price of reducing CO_2 emissions.

Conclusions

The conclusions that may be drawn from the sensitivity analyses reported in this section are the following:

- Both the availability of biomass resources and CO_2 storage capacity have a large impact on the potential role for P2G in the system.
- A reduction in availability of either leads to a larger role for wind and solar-based electricity, and in a larger need for a conversion technology like P2G that enables the use of renewable electricity in traditional fossil fuel dependent sectors (transport, built environment);
- A reduced biomass potential leads to a larger electrolysis-based hydrogen production with a relatively base load profile (about 5,300 operating hours), whereas a reduced CCS potential leads to a larger hydrogen production with a relatively part-load / peak load profile (about 3,700 operating hours);
- The limited availability of nuclear energy seems to have a positive but insignificant impact on the role for P2G, as nuclear energy seems less crucial for overall system decarbonisation.

3.2.2 Impact of size of intermittency challenge on the role for P2G

Rationale

This section analyses whether the increasing need for system flexibility due to increasing capacity of intermittent renewable electricity capacity as such is a sufficient driver for the implementation of P2G. In other words: what is the impact of the size of the intermittency challenge on the role for P2G?

A number of alternative scenarios have been performed to address this question. All alternative scenarios use the particular starting point that there is a fixed target for the integration of both wind and solar PV based electricity generation capacity imposed on the system, *besides the overarching CO_2 emission reduction target.* In the reference scenario wind and solar resources are one of the available means to realise CO_2 emission reductions in the system. Section 3.1 demonstrated that in a reference scenario, the amount of intermittent electricity sources is optimised within the larger energy system. This means that when considering the expansion of installed intermittent generation capacity, not only the direct cost and CO_2 emission reduction impact are considered, but also the possible indirect cost (and associated CO_2 emission effects) of for example additional investment in electricity infrastructure or back-up generation capacity. By imposing particular target levels of wind and solar-based electricity generation capacity on the model in several sensitivity analyses the system is pushed to address a much larger intermittency challenge than was witnessed in the reference scenario results and this presumably affect the role for P2G.

The following alternative scenarios have been simulated:

1. Target for wind (36.5 GW_e) and solar (45 GW_e)-based electricity generation capacity;
2. Target for wind and solar, including priority access (i.e. curtailment of electricity generated from wind or solar resources solar is not allowed);

3. Target for wind and solar, including priority access and 'free flexibility' (i.e. unlimited electricity interconnection capacity with neighbouring markets at zero cost).

Results

Table 9 contains the results for the sensitivity analyses involving separate wind and solar PV targets. The most important observation from the results in this table is that enforcing of very high amounts of wind and solar-based electricity generation at -50% and -70% CO_2 emission reduction levels does not lead to the penetration of P2G into the system.

The separate targets for wind and solar lead to a substantially higher amount of electricity production. This is also observed in **Figure 10** which shows the electricity system balance throughout the year in the reference scenario and the target wind & solar scenario. Comparison learns that the increase of wind and solar-based electricity replaces both coal[11] and nuclear (See **Figure 10**). Overall, the amount of electricity generated increases with 8% and 25% compared with the reference scenario in the -50% and -70% cases: this indicates an increased electrification of the energy system (i.e. new electricity demand) in response to the enforced amount of wind and solar-based electricity generating capacity. In order to maintain electricity system balance the role for electricity storage and temporary curtailments of intermittent generation increases substantially: the total amount of electricity inflow in storage increases from 5 to 9 TWh per year, while curtailments increase from 0 to 26 TWh per year in the case of a -50% CO_2 emission reduction target.

Impact of additional priority access for renewable intermittent sources

The results for the model simulation of a separate target for wind and solar indicated that temporary curtailment of intermittent generation at times when electricity supply exceeds demand is considered a viable flexibility option that is part of the technology mix with the lowest cost for society. In the -50% and -70% CO_2 emission reduction cases of this scenario, the percentage of curtailed electricity was 16% and 11% respectively. Simulation results for the scenario in which these curtailments are ruled out (i.e. priority access for intermittent renewable generation) shows that P2G is not part of the solution for this issue these CO_2 emission reduction levels. The additional amount of intermittent electricity fed into the system is then mainly accommodated by additional electricity demand in the built environment and industry (i.e. electrification), whereas the role for electricity storage in maintaining system balance increases further.

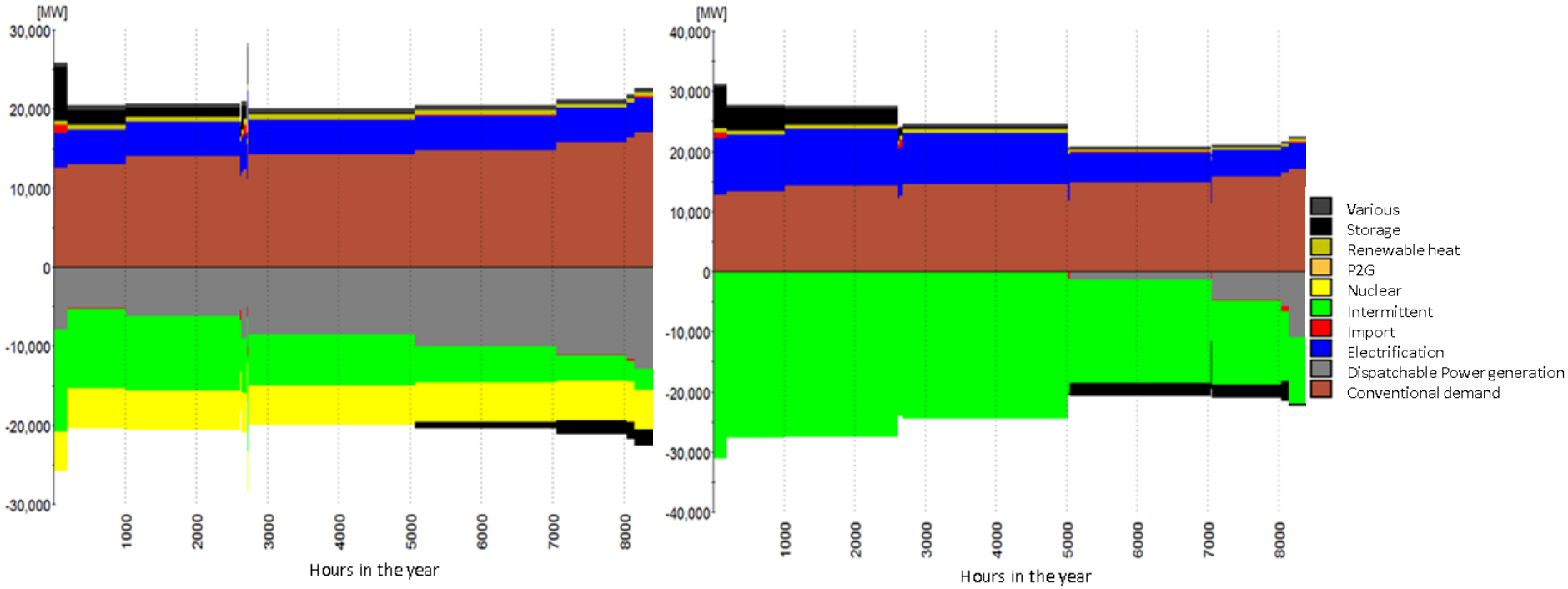
[11] Coal is categorised under the label 'dispatchable generation'.

Table 9: P2G output sheet results for impact of size of intermittency challenge on P2G

Indicator	Unit	Reference scenario			Target wind & solar			Target and priority access wind & solar			Target and priority access wind & solar incl. free flexibility		
CO_2 emission level	[Mton / yr]	110	70	30	110	70	30	110	70	30	110	70	30
CO_2 reduction	[1990 = 0%]	-50%	-70%	-85%	-50%	-70%	-85%	-50%	-70%	-85%	-50%	-70%	-85%
CO_2 shadow price	[€/ton]	34	112	439	4	33	331	4	48	328	4	35	320
Total energy system cost	[Bln€/yr]	55	57	65	59	60	65	60	61	66	60	60	65
Wind	[GW_e]	7	16	35	37	37	37	37	37	37	37	37	37
Wind	[TWh/yr]	25	67	148	139	147	154	164	164	164	164	164	164
Solar PV	[GW_e]	31	40	40	45	45	45	45	45	45	45	45	45
Solar PV	[TWh/yr]	30	38	38	43	43	43	43	44	44	44	44	44
Curtailment wind	[TWh/yr]	0	0	8	25	17	10	-	-	-	-	-	-
Curtailment wind	[%]	0	0	5	15	10	6	-	-	-	-	-	-
Curtailment solar PV	[TWh/yr]	0	1	1	1	1	1	-	-	-	-	-	-
Curtailment solar PV	[%]	1	2	1	1	1	1	-	-	-	-	-	-
Electrolysis	[GW_e]	-	-	1	-	-	2	-	-	2	-	-	2
Electrolysis	[TWh/yr] (input)	-	-	7	-	-	7	-	-	8	-	-	8
Electrolysis	[kton H_2/yr] (output)	-	-	155	-	-	155	-	-	159	-	-	162
Electrolysis	[hours]	-	-	5070	-	-	5061	-	-	5060	-	-	5217
Electrolysis investment	[M€/yr]	-	-	67	-	-	66	-	-	68	-	-	68
H_2 demand	[kton H_2/yr]	-	-	155	-	-	155	-	-	159	-	-	162
Gas network (H_2 admixing)	[kton H_2/yr]	-	-	153	-	-	152	-	-	155	-	-	159
Transport	[kton H_2/yr]	-	-	0	-	-	0	-	-	0	-	-	0
Other H_2 demand	[kton H_2/yr]	0	0	2	0	-	2	0	0	2	-	0	2
Methanation	[kton H_2/yr]	-	-	-	-	-	-	-	-	-	-	-	-
Electricity Storage (large-scale)	[TWh/yr]	0	0	1	1	2	2	1	1	1	0	0	0
Electricity Storage (small-scale)	[TWh/yr]	5	9	12	9	9	9	9	9	10	9	10	11
Electricity imports / exports	[TWh/yr]	0	1	2	1	0	1	2	2	2	592[12]	507	281

[12] Note that the volume of electricity imports in this alternative scenario are – intentionally – unrealistically high, but that the net electricity import of the Netherlands over the year is zero.

Figure 10: Electricity system balance in the reference scenario'(left) and the target wind and solar scenario (right) in the case of a -50% CO_2 emission reduction target[13]



Impact of availability of free unlimited electricity system flexibility

In a simulation where the Dutch energy system has unlimited access to electricity system flexibility – think of a very large electricity interconnection with Norwegian hydro resources that may be operated at zero cost – we still observe a role for P2G in a future energy system in the case of a -85% emissions reduction target. Although the plausibility of this scenario is extremely low, this result demonstrates that the key driver for the adoption of P2G is not the need for flexibility in the electricity system but rather the increasing decarbonisation of the energy system.

[13] These electricity balance graphs are based on a model simulation with 16 time slices.

Conclusions

The analyses presented in this section give rise to the following conclusions:

- The role for P2G does not change when the intermittency challenge due to the integration of intermittent wind and solar-based electricity generation capacity is significantly increased;
- An additional need for electricity system flexibility as a consequence of ambitious separate targets for wind and solar energy is accommodated by a mix of options, but predominantly involving curtailments (if allowed) and electricity storage;
- Irrespective of the size of the intermittency challenge, P2G always has a role to play in an energy system faced with deep CO_2 emission reduction targets. This role is not primarily based on the need for flexibility: even in the theoretical case of free and unlimited exchange of electricity across the border as a means to balance the electricity system, P2G still enters the mix of technologies with the lowest cost for society.

3.2.3 Impact of availability of flexibility options on the role for P2G

Rationale for analysis

Results for the reference scenario presented in Section 3.1 showed that electricity system flexibility under increasingly stringent CO_2 emission reduction targets involved the deployment of a mix of flexibility options with P2G only playing a role in the case of deep CO_2 emission reductions (-85%). In order to test whether the need for electricity system flexibility or deep decarbonisation is the key driver for P2G in this deep emission reduction case a simulation is performed that involves a unlimited availability of flexibility at zero costs.[14] A practical interpretation of this rather theoretical case is the availability of electricity interconnection capacity with Norway of unlimited size with free access to its hydro-based storage systems.

Results

Table 10 presents the P2G output sheet results for the reference scenario and the 'free and unlimited flexibility scenario' for the -85% CO_2 emission reductions case. These results underline that the key driver for the role for P2G are CO_2 emission reductions rather than the need for electricity system flexibility: P2G is still considered part of the cost-optimal mix of energy technologies from a public perspective. The amount of installed electrolyser capacity remains at about 1,400 MW_e. The fact that the number of operating hours and amount of hydrogen produced decreases (both by about -12%) suggests that P2G does partly contribute to the provision of flexibility services to the electricity system in the reference scenario. Due to the unlimited availability of flexibility across the border the amount of electricity curtailments of intermittent sources is reduced by over 2 TWh per year, while the electricity input of electrolysers is reduced by 1 TWh per year.

[14] This particular sensitivity analysis was also performed in combination with separate targets for wind and solar-based resources in Section 3.2.1.

Table 10: P2G output sheet results for the impact of availability and cost of other flexibility options on P2G

Indicator	Unit	Reference scenario	Free flexibility
CO_2 emission level	[Mton / yr]	30	30
CO_2 reduction	[1990 = 0%]	-85%	-85%
CO_2 shadow price	[€/ton]	439	400
Total energy system cost	[Bln€/yr]	65	64
Wind	[GW_e]	35	34
Wind	[TWh/yr]	148	145
Solar PV	[GW_e]	40	40
Solar PV	[TWh/yr]	38	38
Curtailment wind	[TWh/yr]	8	6
Curtailment wind	[%]	5	4
Curtailment solar PV	[TWh/yr]	1	1
Curtailment solar PV	[%]	1	1
Electrolysis	[GW_e]	1	1
Electrolysis	[TWh/yr] (input)	7	6
Electrolysis	[kton H_2/yr] (output)	155	135
Electrolysis	[hours]	5070	4565
Electrolysis investment	[M€/yr]	67	65
H_2 demand	[kton H_2/yr]	155	135
Gas network (H_2 admixing)	[kton H_2/yr]	153	134
Transport	[kton H_2/yr]	0	0
Other H_2 demand	[kton H_2/yr]	2	1
Methanation	[kton H_2/yr]	-	-
Electricity Storage (large-scale)	[TWh/yr]	1	0
Electricity Storage (small-scale)	[TWh/yr]	12	11
Electricity imports / exports	[TWh/yr]	2	8

Conclusions

The conclusions from this sensitivity analysis on the need for flexibility as a driver for the role of P2G are the following:

- The availability of unlimited electricity system flexibility at zero cost does not reduce the system contribution of P2G to zero, demonstrating that the need for flexibility is not the key driver for the role for P2G (but rather that deep decarbonisation is the key driver);
- P2G is partly affected by the unlimited and free flexibility, suggesting that it does contribute to the need for flexibility to some degree.

3.2.4 Impact of P2G investment cost on the role for P2G

Rationale for analysis

By simulating a breakthrough in either the cost and / or efficiency of electrolysis technology that effectively reduces the cost of investment by 50% (compared to the reference scenario assumptions) we explore whether the cost of the technology are to be considered a key driver for the role for P2G in the future energy system. Such a reduction in expected capital cost may or may not be considered realistic, but gives an

insight into the sensitivity of results for alternative assumptions on the costs of P2G technology.

Results

Table 11 presents the results for this sensitivity analysis on the impact of the cost of electrolyser technology. This table only reports on the results for the most stringent CO_2 emission reduction target as P2G does not enter the energy mix at lower reduction targets in either the reference scenario or the alternative lower P2G cost scenario.

The simulated cost reduction has relatively limited impact on the role for P2G. The amount of installed electrolyser capacity remains unchanged. The cost decrease does increase total electrolyser output due to an increasing number of operating hours (+15%). The 50% reduction in electrolyser CAPEX leads to an increase in the role for electrolysis-based hydrogen of about 15%. The primary application for the electrolysis-based hydrogen remains admixing in the gas system.

Table 11: P2G output sheet results for impact of investment cost on P2G

Indicator	Unit	Reference scenario	Lower cost P2G
CO_2 emission level	[Mton / yr]	30	30
CO_2 reduction	[1990 = 0%]	-85%	-85%
CO_2 shadow price	[€/ton]	439	439
Total energy system cost	[Bln€/yr]	65	65
Wind	[GW_e]	35	35
Wind	[TWh/yr]	148	148
Solar PV	[GW_e]	40	40
Solar PV	[TWh/yr]	38	38
Curtailment wind	[TWh/yr]	8	8
Curtailment wind	[%]	5	5
Curtailment solar PV	[TWh/yr]	1	1
Curtailment solar PV	[%]	1	2
Electrolysis	[GW_e]	1	1
Electrolysis	[TWh/yr] (input)	7	7
Electrolysis	[kton H_2/yr] (output)	155	179
Electrolysis	[hours]	5070	5827
Electrolysis investment	[M€/yr]	67	44
H_2 demand	[kton H_2/yr]	155	179
Gas network (H_2 admixing)	[kton H_2/yr]	153	177
Transport	[kton H_2/yr]	0	0
Other H_2 demand	[kton H_2/yr]	2	2
Methanation	[kton H_2/yr]	-	-
Electricity Storage (large-scale)	[TWh/yr]	1	1
Electricity Storage (small-scale)	[TWh/yr]	12	12
Electricity imports / exports	[TWh/yr]	2	1

Conclusion
The conclusion concerning the sensitivity of reference scenario results for assumptions on the cost of electrolysis technology is that the role for P2G – in terms of hydrogen output – is only moderately sensitivity to significant cost reductions and does not seem to impact the application of hydrogen.

3.2.5 Impact of fuel prices on the role for P2G

Rationale for analysis
In this section the hypothesis tested is whether the level of fuel prices (oil, coal, gas) matters for the P2G business case. As the hydrogen produced from renewable electricity via electrolysis may be directly used to substitute fossil fuels in particular sectors there may or may not be a strong link between the level of prices and the role for P2G in the system. The sensitivity for both a strong decrease (-50%) and a strong increase (+100%) compared with reference scenario fossil fuel prices is assessed. **Table 12** presents the fossil fuel price assumptions used.

Table 12: Overview of fossil fuel price assumptions

Energy carrier	Reference	High	Low
Natural gas	7,94	15,88	3,97
Oil	2,67	5,34	1,33
Coal	15,19	30,39	7,60

Results
Table 13 contains the P2G output sheet results on the sensitivity for alternative fossil fuel price levels. A higher level of fossil fuel prices has a positive impact on both the uptake of wind-based electricity generation and electrolysis-based hydrogen production. As conventional technologies are relatively more expensive, there is more economic potential for low-carbon alternatives, in for example the transport sector. Changes in the level of investment in electrolysis capacity across the reference scenario and the two sensitivity simulations are insignificant and overall capacity stays below 2 GW_e. The level of hydrogen produced increases somewhat in *both* scenarios (+12%). This asymmetric result suggests that there are multiple mechanisms playing a role in the relationship between the level of fossil fuel prices and the role for P2G in the energy system. The primary application for the electrolysis-based hydrogen is the admixing in the gas system. In addition, a higher level of fuel prices positively affects the role for hydrogen in the transport sector. The simulation with a 100% higher level of fossil fuel prices shows an uptake in the demand for hydrogen in the transport sector, albeit relatively small.

Table 13: P2G output sheet results for impact of fuel prices on P2G

Indicator	Unit	Reference scenario	Low fossil fuel prices	High fossil fuel prices
CO_2 emission level	[Mton / yr]	30	30	30
CO_2 reduction	[1990 = 0%]	-85%	-85%	-85%
CO_2 shadow price	[€/ton]	439	500	448
Total energy system cost	[Bln€/yr]	65	53	87
Wind	[GW_e]	35	33	37
Wind	[TWh/yr]	148	142	156
Solar PV	[GW_e]	40	40	40
Solar PV	[TWh/yr]	38	38	39
Curtailment wind	[TWh/yr]	8	7	9
Curtailment wind	[%]	5	4	6
Curtailment solar PV	[TWh/yr]	1	1	1
Curtailment solar PV	[%]	1	2	1
Electrolysis	[GW_e]	1	1	2
Electrolysis	[TWh/yr] (input)	7	7	8
Electrolysis	[kton H_2/yr] (output)	155	173	174
Electrolysis	[hours]	5070	5879	5059
Electrolysis investment	[M€/yr]	67	84	75
H_2 demand	[kton H_2/yr]	155	173	174
Gas network (H_2 admixing)	[kton H_2/yr]	153	171	156
Transport	[kton H_2/yr]	0	0	14
Other H_2 demand	[kton H_2/yr]	2	2	2
Methanation	[kton H_2/yr]	-	-	-
Electricity Storage (large-scale)	[TWh/yr]	1	2	2
Electricity Storage (small-scale)	[TWh/yr]	12	12	10
Electricity imports / exports	[TWh/yr]	2	1	1

Conclusions

The following conclusions may be drawn based on the sensitivity analysis in this section.

- Both a 100% increase or a 50% decrease in fuel prices is not a game changer for the role for P2G: it leads to neither a much earlier adoption of P2G, or a much larger uptake of P2G;
- Both higher and lower fossil fuel prices affect the role of P2G in a modest way;
- The asymmetric effect observed in the P2G output sheet results suggests the presence a more complicated set of mechanisms lies behind the relationship between fossil fuel prices and the role for P2G.

3.2.6 Impact of downstream hydrogen demand on the role for P2G

Rationale for analysis

The role for P2G is influenced by the presence of potential demand for hydrogen in different end-user sectors. A large set of input parameters may affect the potential role for P2G downstream. This ranges from the possibilities to inject hydrogen in the gas system in the future to the costs of hydrogen based end-user applications such as hydrogen-based fuel cell vehicles. In order to test sensitivity of results for this type of parameters these two parameters have been varied in separate model simulations.

- *Hydrogen demand via gas system admixing.* Current regulations allow for a maximum hydrogen admixing in the gas system of 0.02 mol%. By 2030, this limit will be set at 0.5 mol%. In the model simulations the limit for hydrogen admixing (in 2050) is set at 10% in the reference scenario and at respectively 1% and 50% in alternative scenarios.[15]
- *Hydrogen demand in the transport sector.* The cost of adopting hydrogen-based vehicles is considered an important factor in the potential uptake of hydrogen in the transport sector. In a separate model simulation the impact of a 50% reduction of investment costs of hydrogen-based applications in transport is therefore assessed. In addition, the possible impact of potential government policies aimed at encouraging the uptake of hydrogen in transport is assessed. Currently, government encourages a range of low-carbon options in the mobility sector. One of those options includes supporting hydrogen based applications. Although the type and effectiveness of support policies can vary in practice, one model simulation assumes a certain target for hydrogen use in the fuel mix in the transport sector. This target is set at 35 PJ per year, amount of energy consumed by about 2.5 million fuel-cell driven electric vehicles in 2050.

Results

Table 14 presents the results of the sensitivity analysis regarding downstream demand assumptions.

Hydrogen admixing in gas system

The results for the higher and lower H_2 admixing limits show that this parameter is important in determining the share of P2G in the optimal energy mix. This may have been expected given that hydrogen admixing in the gas system was the primary hydrogen application in the reference scenario. Increasing the hydrogen admixing limit to the theoretical 50% leads to a more than doubling of installed electrolyser capacity compared to the reference simulation. The amount of hydrogen produced would increase by about 100%, with a decrease in full load hours of about 10%. As the additional opportunities to inject hydrogen in the gas system, it also becomes more economical to capture the peak electricity supply from wind resources. This is shown in a reduced level of curtailments of electricity from wind (-40%). The same is not true for the level of curtailment of solar PV, as the latter technology is generally connected at the distribution level. The decrease in running hours for electrolysers indicate that installed electrolyser capacity is operated relatively more flexible. The primary application for the hydrogen from electrolysis remains the admixing in the gas system,

[15] The admixing limit successfully tested in the Ameland project operated by Gasunie en Stedin was 20%.

with the amount of hydrogen injected increasing from about 155 to 315 kton per year. A lower hydrogen admixing limit has the expected the opposite effect. The optimal amount of electrolysis capacity is halved, running hours reduced by about 12%, and hydrogen production is reduced with about 72%. Due to the restricted admixing limit, the primary application for the hydrogen is in the transport sector. On a system level, the shadow cost of reducing CO_2 emissions increases (decreases) if the hydrogen admixing limit is more (less) restrictive. The same holds for overall energy system cost.[16]

Hydrogen demand in transport sector

First the results regarding the impact of a reduced cost for hydrogen-based transport are discussed, thereafter focus shifts to the results for the impact of a hydrogen target in the transport sector. Results in **Table 14** illustrate that reducing the cost for hydrogen based transport options has a relatively small impact on the role for P2G. The cost reduction does not lead to an increase in the optimal amount of electrolyser capacity installed, but it does affect the allocation of the hydrogen produced across end-user sectors. Whereas the reference scenario primarily saw the admixing of electrolysis-based hydrogen, a reduced cost simulation sees a shift of part of that hydrogen to the transport sector. The total amount of hydrogen produced via electrolysis increases with about 12%, which is related to the increase in electrolyser running hours.

According to model results enforcing the use of hydrogen in transport at all levels of CO_2 emission reduction targets does not lead to the earlier adoption of P2G. The separate target involving the use of 35 PJ of hydrogen in the transport sector induces the demand for hydrogen produced with traditional steam methane reforming based on natural gas. At CO_2 targets less stringent than 85%, SMR based hydrogen production is considered more economical than electrolysis based hydrogen. At the most stringent emission target level simulated, the hydrogen in transport target increases the use of P2G compared with the reference scenario with about 50%. In this situation, the drive to reduce CO_2 emissions leads to a shift towards electrolysis as the technology used to serve the enforced hydrogen demand. Hydrogen produced via electrolysis (about 310 kton per year) now finds its way to both the transport sector (2/3) and - via hydrogen admixing in the gas system - the gas sector (1/3). The application of hydrogen in transport causes for an increase in the amount of running hours of electrolysis capacity (+13%) as the energy demand from this end-user sector tends to be relatively more base load. As P2G and hydrogen-based transport did not appear in the 50% and 70% CO_2 emission reduction target levels – i.e. are not considered part of the optimal mix of energy technologies with the lowest cost for society – this hydrogen in transport policy target effectively increases total system cost. The shadow price of reducing CO_2 emissions at the different target levels decreases: this effect is due to the fact that a relatively expensive CO_2 reduction measure (hydrogen in transport) is implemented earlier on, making available relatively less costly CO_2 emission reduction measures.

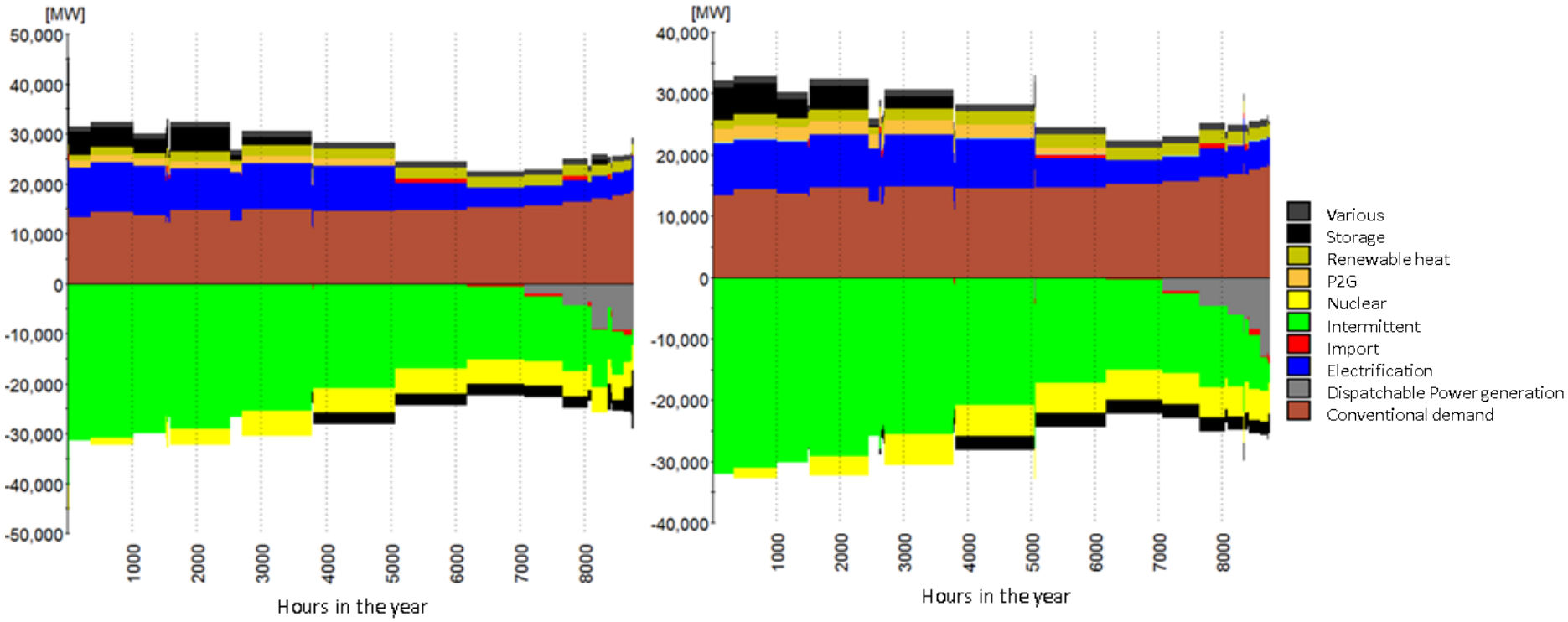
[16] As has been explained in section 3.1 please note that the possible cost related to adaptation of the gas value chain assets and appliances have not been considered in this study.

Table 14: P2G output sheet results for the impact of downstream hydrogen demand on P2G

Indicator	Unit	Reference scenario			1% H_2 admixing limit	50% H_2 admixing limit	Cost H_2 transport lower	H_2 target in transport		
CO_2 emission level	[Mton / yr]	110	70	30	30	30	30	110	70	30
CO_2 reduction	[1990 = 0%]	-50%	-70%	-85%	-85%	-85%	-85%	-50%	-70%	-85%
CO_2 shadow price	[€/ton]	34	112	439	530	372	431	35	95	379
Total energy system cost	[Bln€/yr]	55	57	65	65	65	65	56	58	65
Wind	[GW_e]	7	16	35	34	34	35	7	16	35
Wind	[TWh/yr]	25	67	148	146	148	148	25	69	149
Solar PV	[GW_e]	31	40	40	40	40	40	33	40	40
Solar PV	[TWh/yr]	30	38	38	39	38	38	32	38	38
Curtailment wind	[TWh/yr]	0	0	8	8	5	8	0	0	8
Curtailment wind	[%]	0	0	5	5	3	5	0	0	5
Curtailment solar PV	[TWh/yr]	0	1	1	1	1	1	1	1	1
Curtailment solar PV	[%]	1	2	1	1	4	2	2	2	3
Electrolysis	[GW_e]	-	-	1[17]	1[13]	3	2	-	-	2
Electrolysis	[TWh/yr] (input)	-	-	7	2	14	8	-	-	13
Electrolysis	[kton H_2/yr] (output)	-	-	155	44	315	173	-	-	311
Electrolysis	[hours]	-	-	5070	4438	4635	5287	-	-	5723
Electrolysis investment	[M€/yr]	-	-	67	21	159	77	-	-	147
H_2 demand	[kton H_2/yr]	-	-	155	44	315	173	298	298	401
Gas network (H_2 admixing)	[kton H_2/yr]	-	-	153	15	312	157	0	0	103
Transport	[kton H_2/yr]	-	-	0	28	0	13	292	292	292
Other H_2 demand	[kton H_2/yr]	0	0	2	1	3	2	6	6	7
Methanation	[kton H_2/yr]	-	-	-	-	-	-	-	-	-
Electricity Storage (large-scale)	[TWh/yr]	0	0	1	3	1	1	0	0	0
Electricity Storage (small-scale)	[TWh/yr]	5	9	12	10	9	12	6	9	11
Electricity imports / exports	[TWh/yr]	0	1	2	1	1	2	0	0	1

[17] Due to rounding the optimal amount of installed electrolyser capacity is presented to be about 1 GW_e in both the reference scenario and the 1% admixing limit scenario. However, the more precise figure for both scenarios is 1.4 GW_e for the reference scenario 0.6 GW_e for the 1% admixing limit scenario.

Figure 11: Electricity system balance in the reference scenario (left) and the 35 PJ of hydrogen demand in transport target scenario (right) in the case of a -85% CO_2 emission reduction target



Conclusions
The following conclusions may be drawn regarding the impact of downstream hydrogen demand on P2G:

- The hydrogen admixing limit has a large impact on the role for P2G and the level of intermittent curtailments;
- An active 'hydrogen in transport' policy may benefit P2G in case of deep emission reductions, but does not lead to the earlier adoption of P2G;
- Cost reductions in hydrogen-based transport options alone have only a relatively small impact on the uptake of P2G. This could be an indication that other factors such as the associated cost of hydrogen distribution infrastructure or the cost and availability of other low-carbon transport options are relatively more important for the potential uptake of P2G in the future.

3.3 Summary and discussion

From the model-based analyses the following key observations have been made.

P2G plays a role in case of deep CO_2 emission reduction targets
The reference scenario acknowledged an increasingly large role for renewable intermittent sources in the decarbonisation of the Dutch energy system. P2G however was only found to play a role in the cost-optimal mix of energy technologies in deep decarbonisation cases (-85%), with investment in electrolyser capacity of about 1.4 GWe and about 5,000 operating hours a year. The primary application for hydrogen is the admixing of hydrogen in the gas system, thereby contributing to a decarbonisation of overall gas consumption (in for example the built environment and industry). Methanation is not considered an economically viable option from a social cost perspective. The additional need for flexibility in the electricity system (due to the increasing integration of wind and solar resources) is accommodated by a mix of options, involving:

- Temporary curtailments of intermittent electricity generation;
- Exchange of electricity with neighbouring electricity systems;
- Dispatchable electricity generation (based on gas);
- Storage technologies (both large-scale at the transmission level and small-scale at the distribution system level);
- Demand-side response.

Available biomass and CCS potential has a large impact on the role for P2G
Both the availability of biomass resources and CO_2 storage capacity (i.e. CCS potential) have a large impact on the potential role for P2G in the system: a reduction in availability of either leads to a larger role for wind and solar-based electricity, and in a larger need for a conversion technology like P2G that enables the use of renewable electricity in traditional fossil fuel dependent sectors (transport, built environment). A reduced biomass potential leads to larger investment in electrolysis of up to 8 GW_e, with about 5,300 operating hours a year. A reduced CCS potential leads to investment in electrolysis capacity of up to 19 GW_e, with about 3,700 operating hours a year. The

availability of nuclear energy has a positive but insignificant impact on the role for P2G, as nuclear energy seems less crucial for overall system decarbonisation.

A larger than expected intermittency challenge does not increase the role for P2G or speeds up its implementation over time

The role for P2G does not change when the intermittency challenge due to the integration of intermittent wind and solar-based electricity generation capacity is significantly increased. An additional need for electricity system flexibility as a consequence of ambitious separate targets for wind and solar energy is accommodated by a mix of options, but predominantly involving curtailments (if allowed) and electricity storage. Irrespective of the size of the intermittency challenge, P2G always has a role to play in an energy system faced with deep CO_2 emission reduction targets. This role is not primarily based on the need for flexibility: even in the theoretical case of free and unlimited exchange of electricity across the border as a means to balance the electricity system, P2G still enters the mix of technologies with the lowest cost for society.

P2G contributes to electricity system flexibility but is not dependent on it

The availability of unlimited electricity system flexibility at zero cost does not reduce the system contribution of P2G to zero, demonstrating that the need for flexibility is not the key driver for the role for P2G (but rather that deep decarbonisation is the key driver. The fact that P2G is partly affected by an unlimited flexibility at zero cost suggests that P2G does contribute to the need for flexibility (in deep decarbonisation settings).

Investment cost has moderate impact on the role for P2G

The role for P2G – in terms of hydrogen output from electrolysis– is only moderately sensitive to significant cost reductions and does not seem to affect the application of hydrogen: a 50% reduction in technology CAPEX increases electrolysis-based hydrogen production with 12% while hydrogen admixing remains the primary application;

Impact of fossil fuel prices

Both a 100% increase or a 50% decrease in fuel prices is not a game changer for the role for P2G. Neither case leads to either an earlier adoption of P2G, or a much larger uptake of P2G: electrolysis-based hydrogen production increases about 12% in *both* cases. This asymmetric impact on the role for P2G suggests a more complicated set of mechanisms underlying the relationship between fossil fuel prices and the role for P2G.

Application of electrolysis-based hydrogen

From the reference scenario and alternative scenario simulations can be inferred that the admixing of hydrogen in the gas system is an important potential application, whereby the hydrogen admixing limit has a large impact. The possible impact of gas value chain adaptation cost in the long run was not accounted for but may have an impact. Significant penetration of other hydrogen applications in for example transport and industry only seems to occur in the restricted biomass potential and restricted CCS potential cases. The drivers underlying this observation also need to be better understood with further research.

Decarbonisation (rather than need for flexibility) is key driver for P2G

The overall conclusion that deep decarbonisation of the energy system is a more important driver for P2G than the need for flexibility in the electricity system is

supported by **Figure 12**. Based on results from the OPERA analyses[18], this figure illustrates the relationship between:

1. The amount of wind and solar-based electricity generation capacity (in GW_e) that is considered to be cost-optimal from a social perspective;
2. The level of CO_2 emission reduction target set (in terms of CO_2 shadow prices in € per ton required to achieve the target), and;
3. The role for P2G (in terms of electrolysis-based hydrogen production).

Figure 12: Relationship between the amount of wind and solar-based electricity generation, the level of CO_2 emission reduction target set (in terms of CO_2 shadow prices required to achieve the target), and the role for P2G (in terms of electrolysis-based hydrogen production)

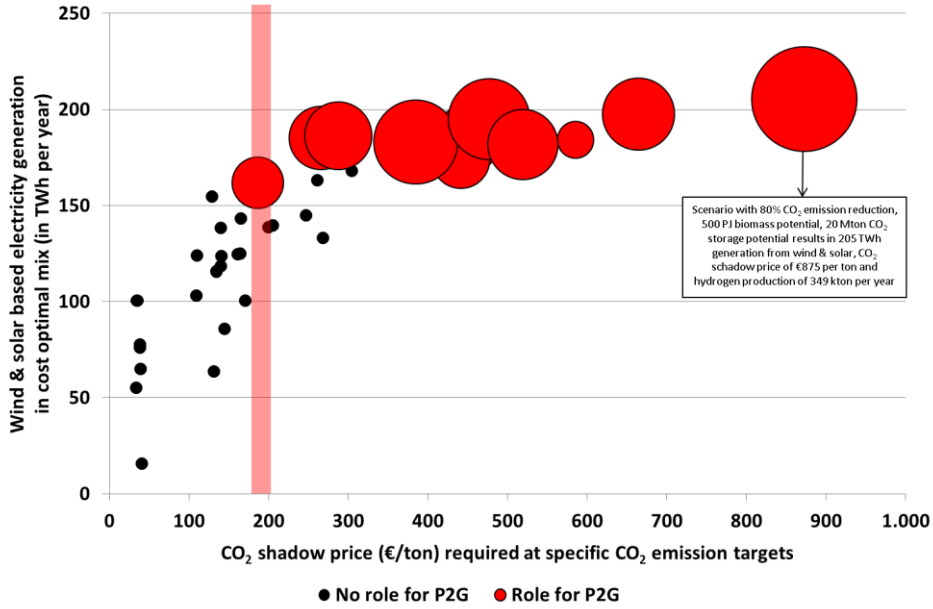


Figure 12 contains results obtained from the model analysis. Depending on the envisaged level of CO_2 emission reduction, which, for the purpose of mutual comparability of scenarios has been translated to the so-called CO_2 shadow price , and depending on the future scenario that is used, there is a specific volume need for of installed electricity capacity based on wind and solar. ,A in which 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: 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 at the lowest cost to society. Secondly, the figure shows that P2G primarily contributes to achieving deep emission reductions

[18] This figure is based on P2G factsheet output for the reference, restricted biomass, restricted CCS, restricted nuclear, high hydrogen admixing limit, low hydrogen admixing limit, high fossil fuel prices and low fossil fuel prices scenarios. This selection of scenario's is based on their higher level of plausibility compared with the other scenarios (i.e. free unlimited flexibility, enforced hydrogen targets in transport, etc.). Apart from the 110, 70 and 30 Mton cases reported on in Chapter 3, this figure is also using results from additional OPERA model runs for the 60, 50, and 40 Mton levels.

with an implied CO_2 shadow price of around €200 per ton. Thirdly, the figure illustrates that P2G only plays a role when there is a relatively large volume of installed wind and solar-based electricity capacity. 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.

4

Results case study analysis

4.1 Introduction

4.1.1 Goal, research questions, scope

The goal of this chapter is to explore the economic viability of implementing P2G in a specific regional context in the medium term.

Key questions addressed are:

- What is the economic perspective for implementing P2G from a private investor's perspective?
- Which P2G applications offer the best business case perspectives?
- Can excess electricity in the region be a driver for a positive P2G business case?

This implies that both intermittency issues – related to the (local or regional) integration of intermittent renewables rationale – a possible demand for 'green' gas (i.e. decarbonised gas based on hydrogen produced via electrolysis) are considered as possible drivers for a P2G business case. A bottom-up, case study based approach, that is complementary to the top-down modelling based approach is used to address the above questions. Three case studies have been performed with each case covering a specific geographic target region with a particular underlying rationale for the local application of P2G. See **Table 15** for an overview.

Table 15: Overview of P2G case studies

Case study	Geographic region	Rationale behind P2G	Covered in section
1.	North of the Netherlands(Groningen)	Avoiding electricity infrastructure investment	Section 4.2
2.	Rotterdam industrial harbour complex	Hydrogen demand for local industry and transport applications	Section 4.3
3.	'Three cities triangle' of Apeldoorn, Zutphen en Deventer	P2G as flexibility provider at distribution system level	Section 4.4

The case study analyses assess both the physical and economic aspects of applying P2G and take into account the local energy system configuration with regards to the available energy infrastructure and the demand and supply of electricity. Whereas the previously described model-based analysis uses 2050 as time horizon, the case study analysis focuses on the time frame of now until 2030.

The case studies share a common structure that consists of the following elements:

- **Scope**: this part describes the particular scope of the case study analysis, referring to a particular geographical scope and to particular sub research questions addressed;
- **(Electricity) system description**: this part describes some (electricity) system characteristics of the region assessed;
- **Flexibility challenge**: based on the information in the previous part, this part evaluates the degree in which the region assessed faces a particular flexibility challenge (i.e. is the region likely to experience large electricity imbalances in 2030?);
- **Potential hydrogen applications**: this part describes the type of hydrogen demand in the region based on its current and expected energy system features;
- **Economic analysis**: this part builds forward on the economics of P2G in Section 4.1.2 from the perspective of the case study;
- **SWOT analysis**: this part characterises the strengths, weaknesses, opportunities and threats related to the implementation of P2G in the case study region;
- **Conclusions and recommendations**: this part presents the case study analysis's key messages which are used in the case study synthesis in Section 4.5.

4.1.2 Common case study assumptions

For the 2030 energy price assumptions we adhere to the assumptions that have been used by ECN in its evaluation of the Dutch Energy Agreement (in Dutch: *Energie Akkoord (EA)*). However, as the EA uses the target year 2023 (ECN/PBL, 2013), some additional assumptions need to be made in order to obtain valid assumptions for the target year of 2030 that is used . in these P2G case study analyses. This section summarizes the adopted assumptions. The resulting assumptions on energy prices and electricity demand up until 2030 are presented in **Table 16**. The price of coal, gas and CO_2 in 2030 have been extrapolated based on the price trend in the period up until 2023.

For coal and gas prices, the development is in line with IEA WEO 2011 Current Policies scenario (IEA, 2011). The base case CO_2 price projection was made by PBL taken into account recent economic EU developments and existing '2013' EU climate policies. Therefore the CO_2 price in 2030 is lower than in the (ECN/PBL, 2012) Energy Projection (20 vs. 35 € per ton CO_2 in 2030). The long term coal and gas price projections are largely based on IEA's WEO 2011, Current Policy Scenario. The more recent IEA WEO 2013, Current Policies Scenario, arrives at almost similar values. So, an increasing long term gas price trend. The IEA WEO 2013 'New Policies Scenario' shows a lower gas price path for Europe (IEA, 2013).

The electricity price assumption is based on simulation runs with ECN's electricity marker model COMPETES, based on the assumed gas, coal and CO_2 prices. In this simulation recent and expected development of the electricity generation capacity in the Netherlands and its neighboring countries (notably Germany) have are taken into account (ECN, 2013, 2013a). Power demand, electricity generation capacity, interconnections and fuel and CO_2 prices all together the wholesale electricity prices

Table 16: Overview of energy price assumptions[19]

		2014	2017	2020	2023	2030
Coal Price (excl. coal tax as of 2016)	[€/GJ]	3.9	3.3	3.4	3.5	3.6
Natural gas price	[€ct/m^3]	26.1	25.8	29.3	30.9	33.6
CO_2 price	[€/ton]	7.1	9.0	10.8	13.5	19.7
Electricity demand the Netherlands	[TWh/yr]	120.0	123.5	126.0	127.2	126.6
Electricity wholesale price	[€ / MWh]		53.9	54.4	55.6	57.0

Cost of hydrogen from electrolysis and allowable cost for hydrogen from end-user perspective

Figure 13 presents the cost of producing hydrogen via electrolysis in 2030. It separately shows the different cost components: capital expenditures, operation and maintenance costs (O&M), the cost of electricity (used as input in the process), and an indicative cost for storing hydrogen. The latter cost component may not always be relevant for the evaluation of a particular P2G application. The figure demonstrates that electrolyser CAPEX dominates the cost of hydrogen at low number of running hours, whereas at increasing number of running hours eventually the electricity cost become the dominating factor. As a result of increasing average cost of electricity at increasing number of running hours (due to price duration curve profile) the cost of hydrogen pass through a minimum, although it is a very weak minimum in the considered cases. Electricity price curves of 2011 to 2013 (source APX) have been combined with the average electricity price assumption presented previously in order to construct a possible price duration curve for 2030. A figure depicting the 2030 price curve is shown in **Figure 14**.

[19] ECN (2013) reports on a number of sensitivity analyses that were performed as part of its evaluation of the Dutch Energy Agreement.

Figure 13: Cost of producing hydrogen via electrolysis in 2030

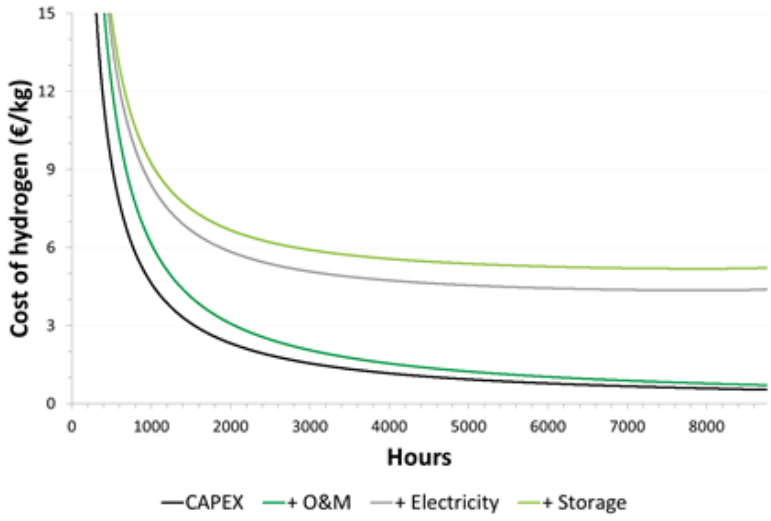
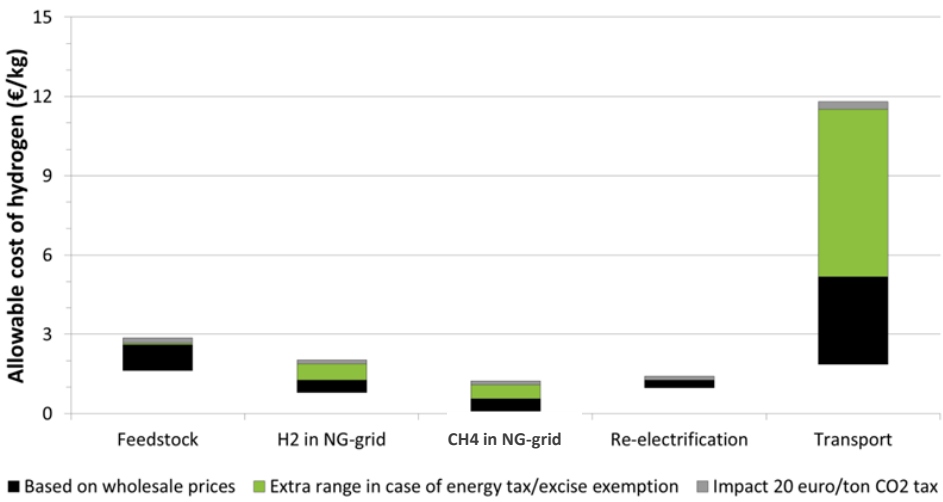


Figure 14: Constructed electricity price duration curve for 2030

Figure 15 presents the allowable cost of hydrogen for a number of applications. The allowable cost of hydrogen are based on input assumptions used in the HyUnder project (HyUnder, 2014).

Figure 15: Allowed cost of hydrogen for range of different applications / sectors

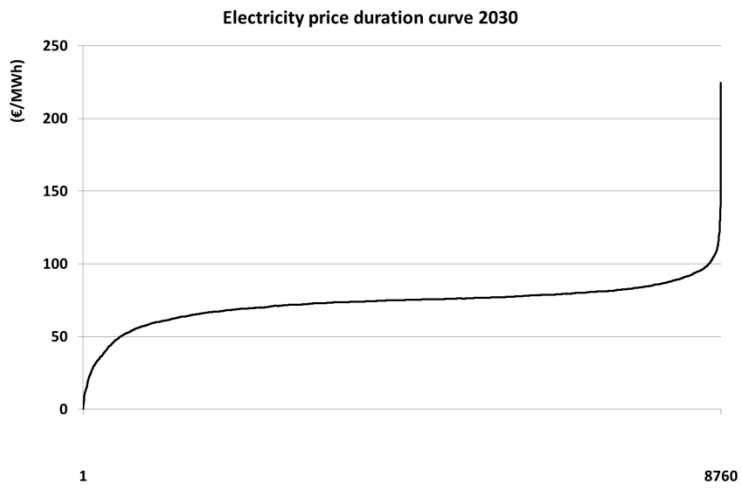


Estimates for the allowable cost of hydrogen have been obtained from HyUnder (2014).

As a result of large-scale implementation of renewable intermittent electricity generation sources, future electricity price duration curves are likely to show much higher volatility of electricity prices, with potentially lower prices at the low-end side of the curve, and much higher prices at the high-end side. This could offer improved perspective for storage in a price arbitrage scheme for electricity, i.e. produce hydrogen at low electricity prices and sell electricity from hydrogen at high prices. Following the

methodology developed by LBST[20] a 2030 price duration curve is estimated and depicted in **Figure 14**.

Figure 16: Constructed electricity price duration curve for 2030



4.2 The role for P2G in the North of the Netherlands

4.2.1 Scope

The large-scale presence of energy infrastructure and energy intensive industries makes the Eemsdelta region – the region covering Delfzijl, Appingedam and Eemshaven an important energy hub in The Netherlands. Moreover, strong electricity and gas transmission links with nearby energy systems makes it an important hub for a wider Northwest European region. Other strong points that make the region suitable for future implementation of P2G concepts is the large regional potential for implementing (offshore) wind energy, and the present knowledge infrastructure. The combination of energy and industry activities in the area provide opportunities for a wide range of P2G related activities. For a full list of strengths, weaknesses, opportunities and threats of adopting the P2G concept in the region we refer to Appendix B.

The exploratory analysis on the viability of different P2G applications options in the Eemshaven region in this case study is explicitly linked to the planned investment by Tennet in a new onshore HVDC transmission line of about 200 km between Eemshaven and Diemen (Tennet, 2013). This planned investment should relieve expected bottlenecks in the transmission network in the North of the Netherlands (see **Figure 17**).

[20] Die Ludwig-Bölkow-Systemtechnik GmbH: www.lbst.de.

Figure 17: Bottlenecks in existing electricity transmission infrastructure due to (expected) electricity supply in the Eemshaven region (Tennet, 2013)

By including this particular investment explicitly in the analysis of the economics of potential P2G applications a rough estimation of the value of a P2G application in avoiding electricity transmission investment can be acquired. This case study is, among other aspects, exploring the value of P2G as a mean to avoid expansion of electricity transmission capacity. The Eemshaven – Diemen electricity transmission line will serve as a test case.

Research questions

Apart from addressing the general case study research questions mentioned in the introduction of this chapter, this case study also addresses the following particular questions:

- What is the benefit of applying P2G in terms of avoiding investment in additional electricity transmission capacity?
- What is the impact of this benefit on the overall P2G business case?

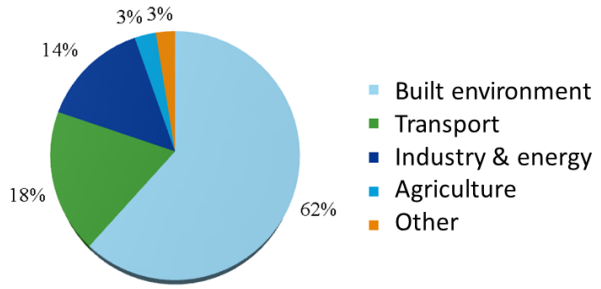
4.2.2 Electricity system developments in the region

Before turning to the economic analyses on the application of P2G-based applications vis-à-vis the reference case investment of a new HVDC line between Eemshaven and Diemen, first a description of the current state of electricity infrastructure and expected developments in demand and supply are characterised below.

Regional electricity demand

The current level of electricity demand in the province of Groningen is estimated at about 2.11 TWh per year[21]. This is about 15% of total final energy demand in the province of Groningen. **Figure 18** presents the sectoral composition of final energy demand.

Figure 18: Sectoral composition of final energy use in the province of Groningen[22]



Conventional electricity generation near Eemsdelta

The Eemsdelta is a concentrated area for conventional electricity generation, with the presence of gas-fired, coal-fired and multi-fired (with biomass) electricity plants. The current installed electricity production capacity in the Eemsdelta region is about 3630 MW. Recently, new electricity plants of Eneco, Nuon and RWE/Essent have either been commissioned or have become operational. The production capacity therefore increased to max. 5230 MW. Combined with the expected increasing number of connections to onshore and offshore wind parks, the region is faced with a significant challenge with respect to accommodating electricity flows and maintaining reliability standards. Only a small share of conventional electricity generation in the region qualifies as 'must run' due to heat demand: about 200 MW_e. The few units concern a waste to energy unit and some combined heat and electricity generation units. From an electricity demand and electricity network management perspective, these units need to be considered non-controllable.

Intermittent electricity generation near Eemsdelta

Currently (Q1 2014), the largest onshore wind park is located in the Eemsdelta, consisting of 90 wind turbines with a total installed generation capacity of 276 MW_e. In addition there is a small offshore wind park a total installed capacity of 15.4 MW_e. In the short term, offshore wind electricity capacity will increase to 600 MW_e, as a result of the realisation of wind park 'Gemini', located near Ameland and Schiermonnikoog. The medium to longer term ambition for on-shore and offshore wind electricity generation is translated into national and regional (i.e. provincial) energy policy. The national target level of onshore wind is set at 6,000 MW_e for 2020 and covers 850 MW_e in the province of Groningen[23]. Onshore wind electricity capacity could be increasing in the further future to about 2.5 GW_e post-2020 (Provincie Groningen, 2012). In a long term perspective, a total of 9 GW of wind energy could be realized in the larger North Sea area. Given the existing onshore electricity transmission infrastructure, it is expected that a significant part of this offshore wind capacity may be connected to the

[21] Source: http://www.klimaatmonitor.databank.nl

[22] Source: http://www.klimaatmonitor.databank.nl

[23] According to IPO: http://www.ipo.nl/publicaties/verdeling-6000-mw-windenergie-over-de-provincies

national electricity transmission system near Eemshaven. Solar PV is considered to be out of scope as this technology is generally not connected to the transmission grid.

High voltage electricity transmission infrastructure
Eemshaven is an important point in the national high voltage transmission system of Tennet. The current electricity AC transmission network in the region consist of 1x 380 kV, 3x 220 kV and 1x 110 kV electricity lines that connect the northern Netherlands with the southern grid (and with Germany). The existing network capacity from Eemshaven to Diemen is about 4,000 MW and in order to avoid future congestion in the network this connection will be reinforced up to 5,610 MW for 2018, by realizing the 380 kV Eemshaven – Diemen transmission line. This new high voltage connection is expected to be operational in 2018. The Eemsdelta is also an important node in the international electricity transmission network, with existing connections to Germany and Norway and planned expansion to Denmark and Norway. There are plans to extend the existing DC interconnection to Norway (NorNed: capacity 740 MW), with a second connection (NorNed2: capacity 700 MW). The planned interconnection with Denmark (named COBRA) involves a capacity of 700 MW.

4.2.3 Flexibility challenge in the North of the Netherlands

Based on the descriptions of regional electricity demand, electricity generation capacity, and current electricity transmission infrastructure capacity, it is apparent that regional electricity generation exceeds regional electricity demand by far, and the large transmission network interconnections to neighbouring markets and to the rest of the Netherlands allow this region to be a significant electricity exporting hub. The anticipated increase in renewable intermittent generation in the form of additional onshore and offshore wind parks will only add to this function.

In theory, the nominal capacity of the total of expected interconnection capacity with neighbouring markets (Germany, Norway, Denmark) is more than sufficient in accommodating future intermittent electricity flows from the increasingly large amount of wind-based capacity.

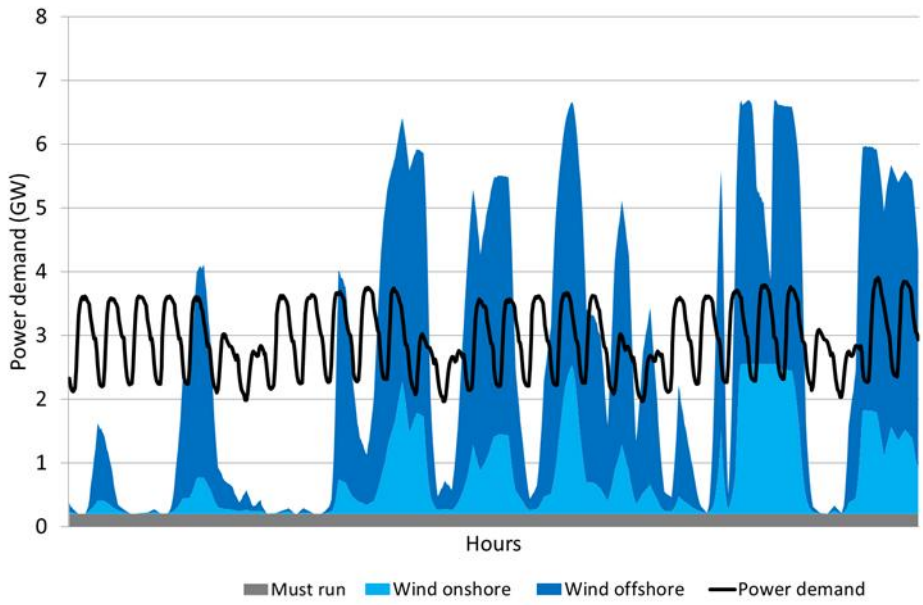
Table 17 gives an overview of the resulting regional electricity imbalances under different assumptions with respect to the availability of (future) interconnection capacity. In the case of none of the nominal interconnection capacity being available, there would be an electricity surplus during about 3,600 hours of the year, totalling about 7.7 TWh. If on the other hand the full nominal interconnection capacity would be available, then the surplus electricity would be reduced to only 0.1 TWh per year (257 hours). Both cases however did not yet include the planned expansion of the new Eemshaven – Diemen transmission line of 1,610 MW. If this additional capacity would be included, then there would no longer be any electricity surplus in the region.

Table 17: Overview of intermittency challenge under different assumptions regarding availability of national and international electricity transmission capacity in 2030

Electricity demand		Intermittent generation		Interconnection capacity		Surplus	
Groningen (GW_{peak})	NL via 4000 HV AC (GW_{peak})	GW_e	TWh / yr	GW_e	Availability	TWh / yr	Hours
0.4	4.0	7	22	3.8	0%	7.7	3604
0.4	4.0	7	22	3.8	25%	4.6	2943
0.4	4.0	7	22	3.8	50%	2.2	2154
0.4	4.0	7	22	3.8	75%	0.7	1057
0.4	4.0	7	22	3.8	100%	0.1	257
0.4	5.6	7	22	3.8	100%	0.0	0

For illustrative purposes, **Figure 19** shows the hourly imbalances in electricity demand and regional intermittent electricity generation in 2030 in the case of 0% of nominal interconnection capacity availability and the planned new Eemshaven – Diemen line not being built. Total demand depicted in this figure corresponds with a yearly demand of an estimated 2.8 TWh per year in the province of Groningen and a demand of about 24.7 TWh per year elsewhere in the Netherlands that is being served by generation capacity in the Eemshaven region *via* the existing 4,000 MW transmission line between Eemshaven and Diemen.

Figure 19: Illustrative pattern of intermittent generation in the Eemshaven region and the combined electricity demand in Groningen and demand elsewhere in Netherlands served by the existing 4 GW connection to Diemen in 2030 in the month June



The conclusion that may be drawn from the calculations above is that the size of the contribution by the new transmission line expansion to solving of a regional electricity imbalance in the Eemshaven / Groningen region crucially depends on the availability of the interconnection capacity with Germany, Norway and Denmark. In practice, the imbalance in electricity supply and demand in the north of the Netherlands may be

either relieved or worsened depending on electricity system imbalances in the countries directly connected to the region.

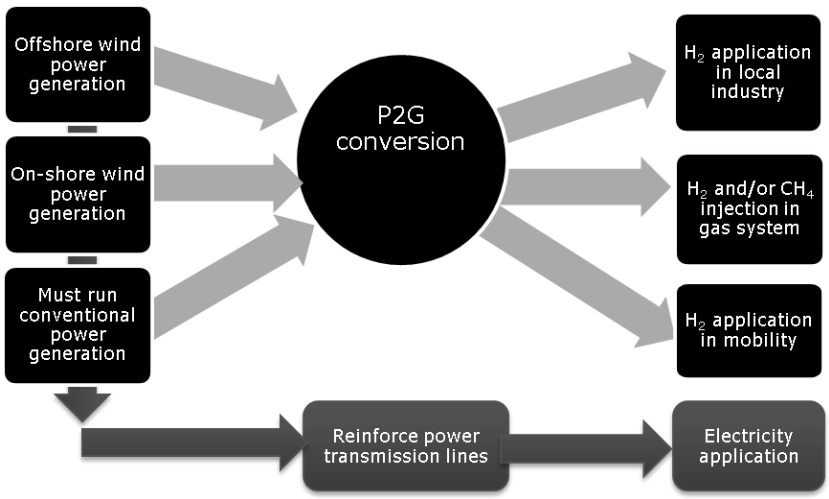
As this case study set out to explore whether a specific P2G–based application could have been a viable alternative option in order to prevent possible electricity imbalances (i.e. surplus electricity) in the region, it is important to assess the contribution of this additional investment in accommodating intermittent generation. Combining (1) hourly wind patterns for an average year in the Netherlands with (2) the assumption that the full 100% of the additional 1,610 MW capacity could be dedicated for the integration of additional intermittent generation capacity, it can be deduced that the total wind-based capacity that could be accommodated is about 1.75 GW_e.[24] This corresponds with an electricity production about of 6.4 TWh per year. This is taken as a starting point in the analysis of the economic viability of P2G applications below.

4.2.4 Use hydrogen from P2G

As an alternative to the investment in the 1,610 MW transmission line expansion between Eemshaven and Diemen – capable of accommodating about 1.75 GW_e offshore wind capacity – the electricity generated may be converted into hydrogen via P2G. There are several pathways for hydrogen use from P2G in the Eemshaven region:

4. Admixing of hydrogen in the gas grid;
5. Methanation of hydrogen (and admixing in the gas grid);
6. Hydrogen-based electricity generation;
7. Hydrogen use in the transport sector;
8. Hydrogen use in industry (as feedstock).

Figure 20: Overview of P2G applications evaluated in case study #1



A combined elaboration on options 1 and 2 follows below.

Admixing of hydrogen or methane in the gas grid

In theory, the admixing of hydrogen from renewable electricity is a relatively cost-efficient application in comparison with hydrogen applications in for example the

[24] The difference between the nominal capacities of 1,610 MW for the transmission project and the 1.75 GW_e offshore wind park relates to the availability factor, which is estimated at 92%.

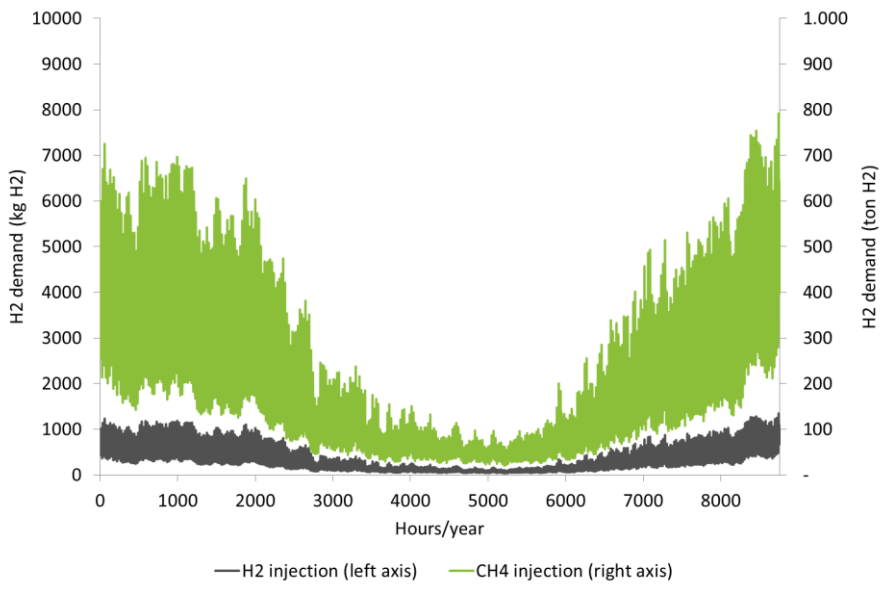
transport sector or industry. This was also confirmed in the model analysis: the primary application under least cost for society considerations is the admixing of hydrogen in the gas system and secondary applications concern the use of hydrogen in transport, industry and the built environment.

The wider Groningen / Eemshaven region has a strong gas infrastructure capacity related to important gas production, storage and gas transport activities and gas demand. This offers opportunities for the admixing of hydrogen in the gas grid. According to TSO Gasunie Transport Services H-gas transport capacity is about 3 million m^3 per hour, which equals about 26 GWh/hour and 208 TWh/year. Although the potential for hydrogen admixing in gas infrastructure is significant, limitations are imposed due to constrains in the end-users equipment: not all end-user equipment is currently sufficiently capable of dealing with different gas / hydrogen mixtures. The current entry specification for hydrogen admixing is set at 0.02 mol%, while the mid-term (2030) specification is set at 0.5 mol%. The latter limit allows for a potential hydrogen feed in of 45 MWh per hour and 0.36 TWh per year. More downstream on a regional transport level, GTS estimates a potential of 90-120 MWh/hour for the admixing of hydrogen produced in the Eemsdelta region. In the long term it is expected that H-gas transport capacity will be significantly expanded due to the expected decrease in G-gas transport related to depletion of the Groningen gas reserves.

The potential for the admixing of hydrogen in the gas grid varies largely throughout the year as the demand for gas (and the consequential gas flow) has a very distinct pattern. In summer the gas demand and the gas flow at a specific admixing point is generally low due to the absence of demand for heating. This implies that the potential amount of hydrogen that could be injected at the specified 0.5% limit is also low . In contrast, the potential for hydrogen admixing in winter is relatively larger.

The maximum amount of hydrogen that could be injected in the specific admixing point in the North of the Netherlands is calculated using the capacity and hydrogen admixing restrictions mentioned previously. **Figure 21** shows the hydrogen and methane admixing potential on an hourly basis. The hourly pattern in gas demand from households has been used a proxy for the gas flow pattern at the admixing point, since the hourly gas flow pattern as may be observed in practice is not publically available. In practice, the actual gas flow at the admixing point may be relatively more base load than assumed here. Firstly, because part of the gas flow may be destined for transit to neighbouring markets, and secondly because part of the gas flow may be destined for other gas consuming sectors with a less variable pattern. If this is indeed the case, than the figure may underestimate the potential for hydrogen admixing somewhat. In this example, the maximum yearly potential for hydrogen admixing is about 3.3 kton, with an average hourly admixing rate of 377 kg per hour.

Figure 21: Maximum hourly admixing potential for H_2 (0.5%) and CH_4 throughout the year in the Eemshaven region



Whether the admixing of hydrogen with natural gas is a viable economic also depends on whether the hydrogen production pattern (related to the hourly production pattern of renewable electricity) matches with the gas flow pattern (related to the hourly gas demand pattern of gas consumers). We now continue to explore under which conditions these patterns may match. An offshore wind park of 1.75 GW_e will be used as a reference point in this case. To which degree does an offshore wind electricity production pattern match with the pattern in gas demand? Under which admixing limits could the electricity from this park be accommodated at the specific admixing point in the high pressure gas network in the North of the Netherlands?

A 1.75 GW_e offshore wind park may be assumed to deliver a total amount of hydrogen of 127 kton per year. **Figure 22** shows the hourly hydrogen production pattern using a typical pattern for offshore wind electricity production in the Netherlands.

Figure 22: Hourly hydrogen production profile for the month June based on 1.75 GW_e offshore wind-

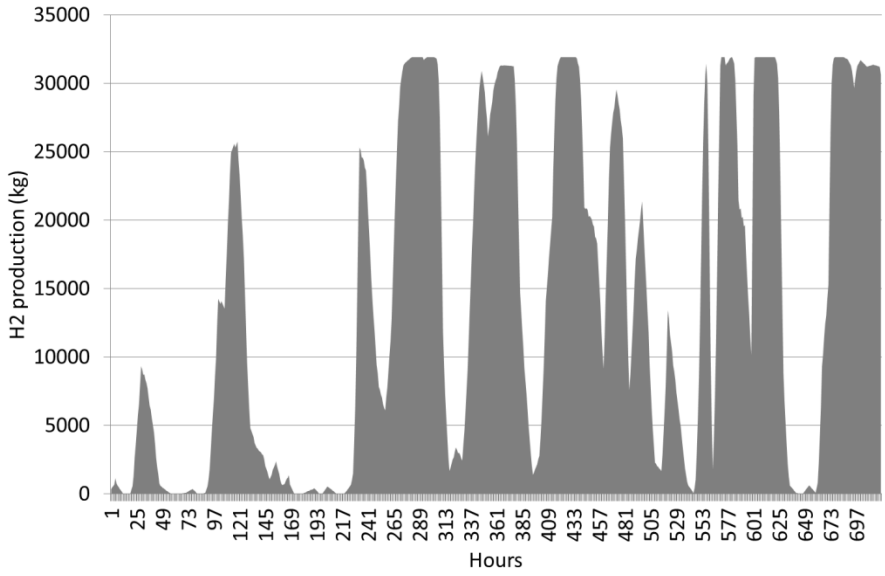


Figure 22 presents the simulated hourly amount of hydrogen that could be injected based on the specified 0.5% hydrogen admixing limit for the gas transmission network. It is apparent that the specified limit severely restricts the possible intake of hydrogen: only 2.2% of the total amount of hydrogen that could be produced can be accommodated in the gas network via admixing. Simulations for different hydrogen admixing limits illustrates that given the relatively low amount of gas demand in the summer months it does not seem possible to fully accommodate the potential renewable hydrogen supply. At a hydrogen admixing limit of 20%, about 56% of total hydrogen supply can be injected throughout the year. Even a hypothetical 100% admixing limit 'only' allows for the admixing of 91% of the renewable hydrogen supply from the 1.75 GW_e wind park.

Table 18 summarizes the results on the hydrogen admixing potential under different admixing specifications.

Table 18: Potential for admixing of hydrogen in North of the Netherlands

Hydrogen admixing limit	H_2 admixing			H_2 not accommodated
	Average (kg per hour)	Maximum (kg per hour)	Kton (per year)	Kton (per year)
0.2%	454	539	1.3	125.5
0.5%	1,056	1,349	2.8	123.9
5%	7,937	13,485	23.3	103.4
10%	13,184	26,970	42.5	84.2
20%	14,463	31,910	70.7	56.0
100%	75,342	269,700	115.4	11.3

The mismatch between hydrogen demand and supply patterns in the case of hydrogen admixing under relatively low hydrogen admixing specifications may trigger the idea of combining the use of hydrogen for gas grid admixing with another hydrogen application

in for example transport or industry. However, as the hydrogen-based applications in the transport and industry sector may have a more base-load character it makes more sense from an hydrogen demand pattern perspective to turn this around and see whether the renewable hydrogen can be used to serve a specific base load demand in industry or transport and use 'surplus' hydrogen for admixing.[25]

One obvious route to address the mismatch problem is to consider the admixing of renewable of methane instead of hydrogen. This avoids the rather restrictive hydrogen admixing limit as methane specifications readily meet the gas system's natural gas specifications. However, there is a consequence to this methane based admixing as the conversion from hydrogen to methane implies a loss of energy of about 15% (DNV KEMA, 2013). Using the electricity that may be produced from a 1.75 GW_e offshore wind park as a reference point, the hydrogen admixing route involves the input of 2.8 kton of hydrogen in the case of a 0.5% limit, compared with about 108 kton (≈85% x 127 kton) of hydrogen input in the methane admixing route.

Section 4.2.5 will turn to some economic considerations of specific P2G applications in the North of the Netherlands.

Hydrogen use in industry or transport

Alternatively, the hydrogen produced in the North of the Netherlands could be used in for example industry or transport.

Hydrogen demand in industry

Major industrial consumers of hydrogen are the refinery sector, ammonia industry, methanol, and metal industries. The total demand for hydrogen in the province of Groningen has been estimated at about 1.250 million m^3 H_2 per year (which equals 112,4 kton or about 3.7 TWh hydrogen per year)[26]. Akzo Nobel produces hydrogen, using chlorine sodium hydroxide electrolysis. Chlorid is the main product for this process, hydrogen is appointed as valuable by-product. The hydrogen by-product is partly used as a chemical component for downstream processes and partly used as a heating fuel. In former process, hydrogen is used to produce monochloro-ethanoic acid. The remaining part of the produced hydrogen is purified, compressed and distributed to Teijin Twaron in Delfzijl and used as fuel by Delesto. Replacement of admixing hydrogen by using hydrogen from excess RES influences the profitability of the chlorine sodium hydroxide electrolysis process, which is not a preferable option for Akzo Nobel.

Recently, plans are being made for the realisation of a syngas (CO and hydrogen) grid in Delfzijl. Heveskes Energy has planned to construct a biomass gasification plant in Delfzijl. The produced syngas is intended to be supplied to local consumers. This so-called ' Green Grid' should be considered part of the larger utilities infrastructure within the Eemsdelta region. The *Green Grid* initiative aims to contribute to a sustainable, and stronger industrial cluster. At the moment it is yet unclear what the long term potential for this Green Grid really is, and what the impact could be on the existing natural gas fuelled end-use appliances in the region.

[25] Whether this also makes economic sense is explored in Section 4.2.5.

[26] Source: Roads2hycom project:

http://www.roads2hy.com/r2h_Downloads/Roads2HyCom%20R2H2006PU%20-%20European%20H2%20Infrastructure%20Atlas%20(Part%20II)%20-%20Industrial%20Surplus%20H2.pdf.

Hydrogen demand in transport

There are several options to decarbonize the final energy demand in the transport sector, and renewable-based hydrogen could be one. In comparison with the existing fossil fuel based alternatives, the bottleneck for a larger penetration of hydrogen in this sector is the lack of a distribution infrastructure.

For illustrative purposes the potential hydrogen demand in two particular segments of the transport sector in 2030 has been estimated based on some indicative figures and an assumed market penetration rate for hydrogen-based vehicles. Based on the current fleet of cars (and vans) (364,765) and auto buses (141) in the Province of Groningen[27], an annual average mileage per car (13,000 km) and auto bus (75,000 km) in the Netherlands as a whole, and a market penetration rate of 2% (HyUnder, 2014) a total estimated demand for hydrogen in Groningen in 2030 can be calculated. Under these assumptions, the yearly demand of hydrogen is estimated at about 0.95 kton. , which equals about 0,029 TWh per year. Using a more optimistic assumption of a 10% market penetration rate for hydrogen fuelled vehicles results in a total hydrogen consumption in transport of about 4.8 kton per year (0,144 TWh).

How does the potential hydrogen demand in industry and transport in the province of Groningen compare with the potential hydrogen produced with the electricity output of a 1.75 GW offshore wind park (i.e. the installed capacity of offshore wind-based electricity generation that could theoretically be accommodated by the new transmission line expansion of 1,610 MW_e between Eemshaven and Diemen)? This question is addressed below.

Table 19 compares this P2G based hydrogen supply with the potential regional hydrogen demand in industry and transport in the Province of Groningen. From the figures in this table we may conclude that from the total amount of hydrogen produced by the offshore wind park about 90% could be used to cover the potential demand for hydrogen in industry and transport by 2030. The 'remaining' hydrogen be injected to the gas grid. As noted earlier on, a 0.5% hydrogen admixing specification could only accommodate 2.8 kton per year. This leaves about 11 kton of hydrogen from the 1.75 GW wind park unused. In order to accommodate this additional amount in the gas network via admixing, the hydrogen specification limit would need to be raised to about 3%. The calculations in **Table 18** already demonstrated that even a theoretical 100% admixing rate (de facto making gas infrastructure dedicated for hydrogen) could not absorb the full 127 kton per year as a result of the relatively low gas flows during the low demand summer season.

Table 19: Potential hydrogen supply and demand in Groningen in 2030

	[kton/yr]
Hydrogen supply (P2G)	127
Hydrogen demand	113.43
$_2$ admixing gas grid (0.5%)	2.8
- Industry	112.38
- Transport	0.95
'Surplus' hydrogen	10.87

[27] Source: CBS Statline

Summary
This section explored the potential demand for (renewable) hydrogen in the province of Groningen in 2030 by looking at the demand from the gas sector (via admixing of either hydrogen or methane in the gas grid) and the industry and transport sector and has put this potential demand in the perspective of the total supply of (renewable) hydrogen from a 1.75 GW_e offshore wind park. Based on total volumes and demand and supply patterns the following two observations have been made.

The renewable hydrogen supply based on the electricity produced with a 1.75 GW offshore wind park is theoretically more than sufficient in covering the total demand for hydrogen in industry in 2030. However, the expected demand for hydrogen in transport is relatively limited and whether the demand for electrolysis-based hydrogen in industry can materialise seems highly questionable due to the implications for the chemical process involved.

When it comes to using the hydrogen produced from intermittent renewable sources, the admixing of either hydrogen or synthetic methane seems the more significant option with the largest potential. However, the total amount of hydrogen cannot be accommodated by the gas grid via admixing of hydrogen at the current limit of 0.02% of the expected 0.5% admixing limit. The full amount of locally produced hydrogen via electrolysis could only be accommodated if methanation would be applied. For illustration, a hypothetical 10% hydrogen admixing limit only allows for about 1/3 of the locally produced hydrogen.

Secondly, there is a mismatch in the pattern for supply and demand for hydrogen in the region. Comparing the intermittent nature of renewable hydrogen supply with the 'demand' for hydrogen from the gas sector raises a problem because current hydrogen admixing specifications are too low to accommodate the hydrogen in each hour of the year. In addition, the seasonal pattern in gas flows may impede admixing of the hydrogen produced in any hour of the year.

The next section will explore the economics of P2G applications, with a particular focus on the monetary value of avoiding investment in the 1,610 MW_e electricity transmission expansion between Eemshaven and Diemen.

4.2.5 Economic analysis

Dimensioning of electrolyser capacity and average hydrogen production cost
Figure 23 presents the cost of producing a kilogram of hydrogen at varying levels of (full load) operating hours, while **Figure 24** presents the duration curve of electricity supply from a 1.75 GW_e offshore wind park. The latter figure indicates that in order to capture all electricity produced for conversion into hydrogen, total electrolysis capacity would need to be dimensioned at 1,610 MW_e. At this dimensioning of electrolysis capacity, the amount of operating hours would be about 8,000, of which only about 1,200 would involve operation at full capacity. Given the shape of the duration curve it is apparent that a decrease in installed electrolyser capacity would increase the number of hours at which equipment is running at maximum capacity, but would also increase the amount of electricity that is not accommodated. Reducing installed electrolyser capacity with

50% (800 MW_e) would increase the number of hours at maximum capacity to about 3,800 and capture 62% of the electricity produced by the wind park in a year. **Figure 24** illustrates this principle. The average integral cost of producing hydrogen in the two capacity cases is respectively €7.6 and €4.7per kg of hydrogen.

Figure 23: Production cost of hydrogen

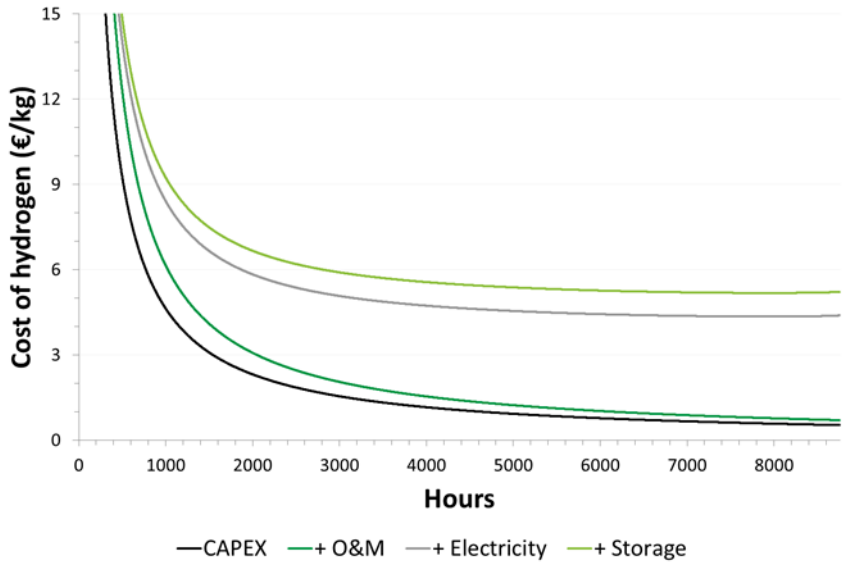
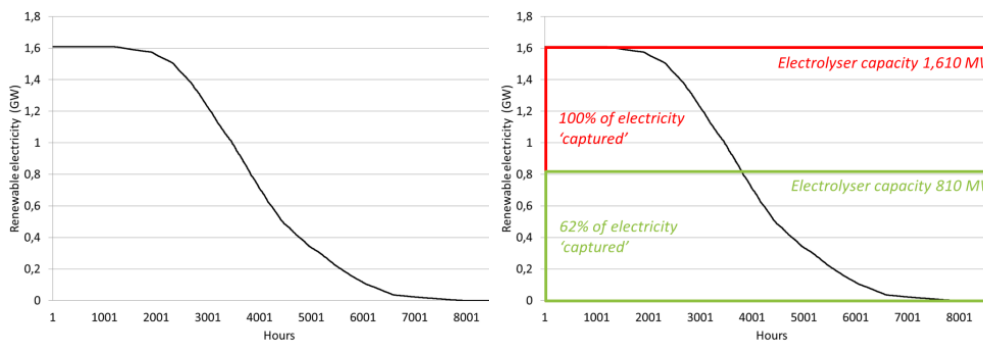


Figure 24: Supply duration curve of a 1.75 GW_e offshore wind park (left) with illustration of the part of electricity supply captured at 1,610 and 800 MW_e electrolysis capacity



Benefits of avoiding 1,610 MW investment in electricity transmission capacity

Instead of building additional transmission capacity in order to accommodate an increasingly large amount of wind-based electricity generation capacity, the produced electricity may be converted to hydrogen and used in for example the gas (via hydrogen or methane admixing), industry or transport sector. Assuming that the specific 1,610 MW investment in additional electricity transmission capacity between Eemshaven and Diemen is fully needed to accommodating the electricity flow from a 1.75 GW_e offshore wind park and that not building it would lead to congestion in the existing transmission to such a degree that the produced electricity can be fed into the grid, the investment costs could provide an indication of the benefit that may be claimed by alternative ways to accommodate the produced electricity. An estimation of the potential benefit is provided below.

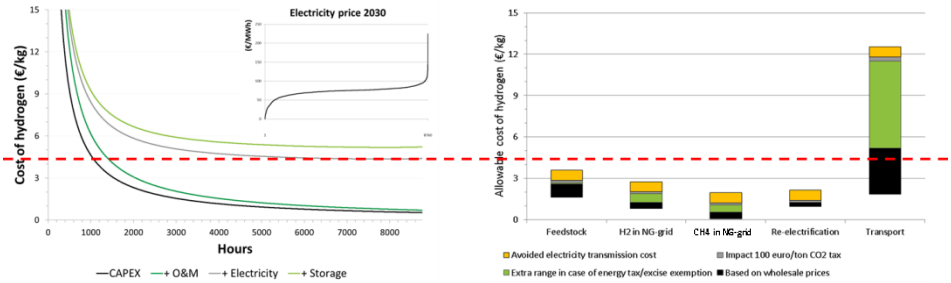
A total investment for the 200 kilometer long transmission line of about €1 billion for 1610 MW corresponds with an investment cost of about €2.8 per KW_e per kilometer. Assuming an economic lifetime of 30 years and an 8% required return on investment, this results in an estimated capital cost of €55.2 per kW_e per year. Relating this capital cost to the total amount of renewable hydrogen (about 127 kton per year) that could be produced from the 6.4 TWh of electricity from the wind park while - assuming an operational cost of 4% of CAPEX – results in an avoided cost (i.e. benefit) of about €0.73 per kilogram of hydrogen.

The calculation above does not take into account the investment and operational cost associated with the admixing of hydrogen in the gas system. In that sense, the result could be interpreted as an upper bound for the avoided cost of investing in electricity transmission capacity.

Economic viability of P2G applications

Figure 25 is an adapted version of the figures presented in Section 4.1 and ads the P2G 'benefit' to the range of allowed cost for hydrogen produced via electrolysis. Although the benefit of avoided investment cost benefits P2G, this element alone does not change the overall economic picture of the different applications.

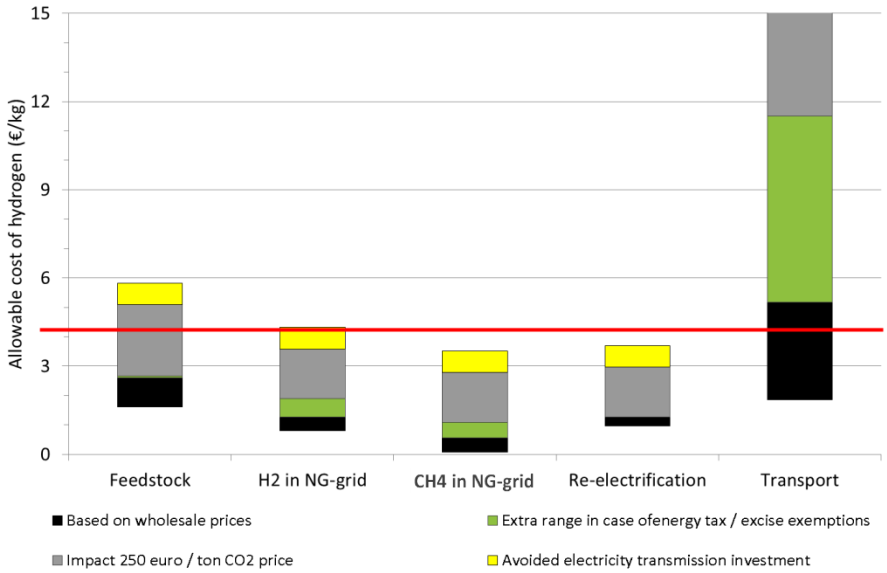
Figure 25: Economics of P2G alternatives in case #1



Impact of higher CO_2 prices

The model based analysis earlier in this report indicated that P2G based applications are generally entering the energy mix at CO_2 emission reduction targets associated with CO_2 prices in the range of €200 – 500 per ton. A sensitivity analysis for the economics of P2G applications in this case study illustrates that a CO_2 price of €250 per ton indeed makes various applications economically viable, including the admixing of hydrogen in the gas network.

Figure 26: Economics of P2G alternatives in the case of a CO_2 price of €250 per ton CO_2



4.2.6 Conclusion

The Eemshaven region and the larger province of Groningen are a true energy exporting hub for the Netherlands, and this is expected to continue to be the case in the near and further future when additional connections to large scale onshore and offshore wind parks are expected.

Whether the large increase in intermittent generation capacity will lead to severe regional imbalances in the electricity system – i.e. increasingly large surpluses of electricity during an increasing number of hours in a given year – crucially depends on the availability of interconnection capacity with neighbouring electricity markets.

Given the dependence of possible electricity surpluses on the uncertain availability of nominal national and international transmission capacity, further research on the economic viability of particular P2G applications seems warranted. However, the analysis on the economics of P2G alternatives has shown that the benefit of possibly avoiding the 1,610 MW expansion of the Eemshaven – Diemen line does not seem to be able to make any of the possible P2G alternatives economically viable. Even though the avoided cost is by no means insignificant – €0.73 per kilogram of hydrogen in this particular case - it does not fundamentally alter the economic picture for P2G alternatives.

All in all, based on the exploratory analysis in this case study the conclusion is that it seems difficult to build up an economically viable business case for P2G in the medium term (to 2030). However, given the exploratory nature of the case study and the relatively high level of abstraction in the analysis, it can't be ruled out that within this time horizon a sound economic business case may be possible. Driving factors therefor could be the successful combination of local potential hydrogen demand (in for

example the transport sector) and a strong push for greening of gas consumption. However, estimations for potential demand in transport show that the total hydrogen demand in the region is relatively small, while the same holds for the potential hydrogen demand in industry.

Based on the perspectives for potential hydrogen demand in the region, the conclusions could be that hydrogen admixing or synthetic methane injection are the best renewable-based hydrogen applications. However, even if the price for gas would be high enough for substantial hydrogen admixing to be economically viable, then the current admixing limits would be a significant bottleneck. Simulations for different hydrogen admixing limits illustrate that given the relatively low amount of gas demand in the summer months it does not seem possible to fully accommodate the potential renewable hydrogen supply in the region. The methanation route could be a technically viable alternative, but is not considered to be viable economically.

Notwithstanding the above messages, the Eemshaven region remains of interest for the further development of P2G in terms of for example demonstration projects in the future as the SWOT analyses points to a number of strong points for the region.

4.3 The role for P2G in the Rotterdam area

4.3.1 Scope

The Rotterdam harbour is home to many active companies with high standards for suppliers and service providers. The network relations between companies, knowledge institutes and governments, and the competition between various businesses within the harbour encourage innovation. The port authority seeks to expand its strategic value by focussing on improving efficiency and innovation (Port of Rotterdam, 2011).

The harbour has a very strong position for large-scale energy production e.g. due to its location, ability to accommodate ships with deep draughts and availability of cooling water. On the other hand, there is also a threat that the harbour becomes locked-in with fossil fuels. The strong position of the harbour in fossil fuel based energy production – and the associated sunk investment costs – pose a barrier for moving to more sustainable production methods. The decreasing availability of fossil fuels and the increasing prices on the world market for (energy) feedstock potentially weakens the position of the harbour, but also the North-West European (energy) industry in general. Furthermore, the fossil fuel based harbour activities deteriorate the image of the living climate in the Rijnmond area.

These arguments provide drivers for change. Due to its strong financial position, the harbour has the capability to avoid deterioration of its position by making new investments. The transition to sustainable (energy) production offers opportunities for the long term due to the available infrastructure and because almost all global players are active in the Rotterdam harbour area. Improving the connection between the chemistry clusters in North West Europe could enhance their global competitive

position and attract relevant parties for new technologies such as production and utilisation of hydrogen from electrolysers.

To this end, the Rotterdam Climate Initiative has set targets for more sustainable practices in the harbour area. Among the various areas such as energy efficiency, the use of biomass and sustainable mobility, it has set a target for 350 MW wind energy by 2020 (RCI, 2014). At national level, the energy agreement stipulates a target for offshore wind energy of 4,450 MW in 2023 (SER, 2013). The draft Rijksstructuurvisie wind op zee (Ministry of Economic Affairs, 2013) shows that for some of the areas appointed for offshore wind parks, the Maasvlakte could be a site to connect to the transmission grid. However, the large uptake of intermittent energy sources provides another challenge: how to deal with excess electricity when supply exceeds demand?

The Rotterdam harbour constantly prepares and adapts to future opportunities in order to maintain a competitive business environment. P2G is a technological option that enables the use of green electricity for which there is no immediate demand by converting it to gas. The technologies and energy system changes needed for converting power to gas on a large scale are still developing. The presence of a hydrogen infrastructure and the associated industrial activities provide the opportunity to experiment with P2G technology in the Rotterdam area, provided that a viable business case is foreseen. On the other hand, those same hydrogen facilities pose a threat to P2G technologies as they are currently more competitive with respect to production costs.

Research questions

The long lead time of investments in the Rotterdam area, require the port authority to make strategic choices on future developments far in advance. With regard to the energy system, the harbour has to facilitate short-term business opportunities while it also has to prepare for energy system changes further ahead. This case study estimates the impact of increasing the share of intermittent sources on the electricity system in the Rotterdam area up to 2030. It answers the following questions:

- What is the demand for flexibility in electricity consumption in 2030, both in terms of electricity produced and time duration?
- Is there a role for P2G up to 2030?
- In which markets could hydrogen from P2G be used?
- What volumes are involved?

Although this case puts a focus on P2G, it will also cover other competing options for providing flexibility in electricity consumption.

Case study methodology

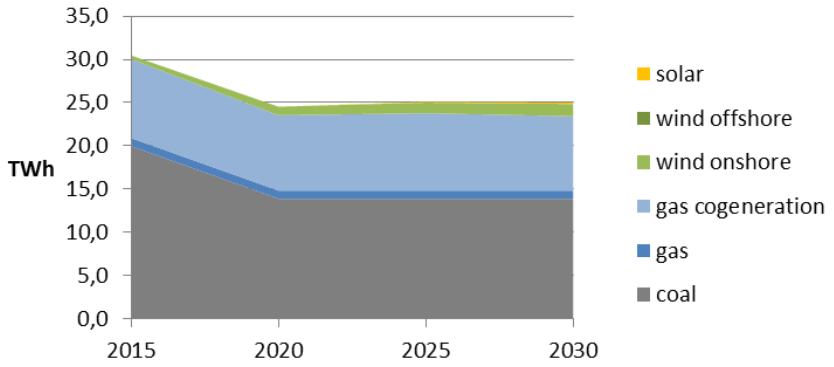
By comparing local electricity production with local demand and the possibilities for transporting electricity to outside the Rotterdam area, the flexibility challenge is determined in terms of time duration and volume of electricity. The economies of using hydrogen in various sectors are assessed also accounting for operating hours of P2G hydrogen production facilities. From that assessment sectors for which P2G hydrogen is economically viable are selected for further investigation. For this selection of sectors hydrogen demand is determined as well as under what conditions P2G facilities should be operated to provide the required flexibility for electricity production while still yielding revenues.

4.3.2 Flexibility challenge in Rotterdam harbour area

Fuel mix for electricity production in Rotterdam area towards 2030

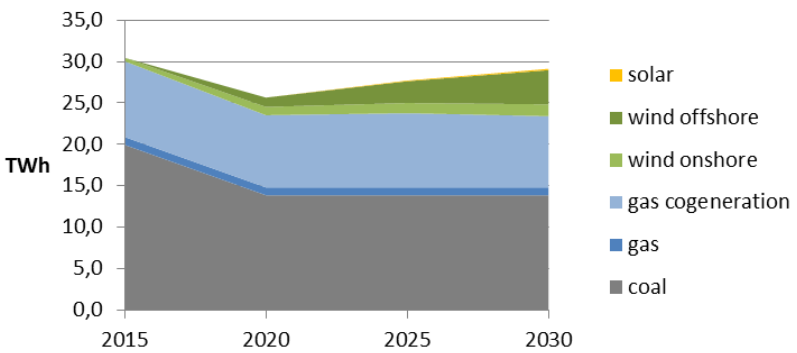
The current electricity production capacity in the Rotterdam area is 5.4 TW (ECN, 2013). **Figure 27** shows that these facilities produce about 30 TWh per year, of which 2/3 by coal-fired plants and 1/3 by gas-fired plants. Apart from the intermittent sources wind and solar, the amount of renewable electricity (e.g. biomass co-firing) is not indicated in **Figure 27**. At 0.4 TWh, the contribution from wind energy is marginal. In a case without connection of offshore wind, the production capacity lowers to 4.8 TW in 2030, producing 25 TWh per year. This decrease is mainly caused by decommissioning coal fired power stations. Production of renewable electricity from wind and solar energy increases fourfold to 1.6 TWh, i.e. 7% of the total production.

Figure 27: Electricity production in Rotterdam area without offshore wind



In the current plans for the location of offshore wind parks within the 12 miles zone of the Netherlands' coast, 1100 MW is foreseen near the Maasvlakte and Zealand. Although there is no final decision on these locations, the draft Rijksstructuurvisie Windenergie op Zee (ministry of Economic Affairs, 2013) makes clear that the Maasvlakte could be a location for connecting future offshore wind parks. For this case we assume 1,100 MW is connected to the transmission grid at the Maasvlakte which significantly changes electricity production in the harbour area(see **Figure 28**). In that case about 20% of all electricity produced in the harbour area is of an intermittent nature. The question is whether this amount of intermittent production may lead to congestion of the transmission grid or demand for flexibility in electricity consumption.

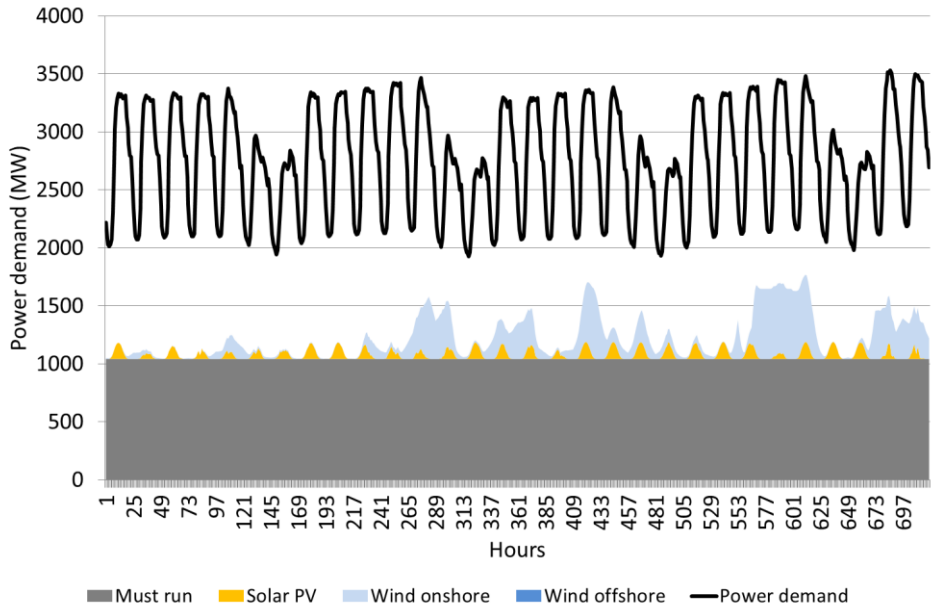
Figure 28: Electricity production in Rotterdam area with 1100 MW offshore wind



Periods of surplus supply after 2030 with connection of offshore wind farm

Figure 29 and **Figure 30** show the electricity balance for June 2030 in the Rotterdam Harbour area, respectively without and with a connection to an 1,100 MW offshore wind farm.

Figure 29: Electricity balance in Rotterdam area for June 2030, without connection of offshore wind parks



Of the total electricity production, 1,000 MW is so-called must-run capacity (grey area in **Figure 29** and **Figure 30**). This is electricity production that is linked to industrial processes and demand for heat. Like the intermittent renewable sources, these facilities are not capable of following electricity demand. The electricity production from intermittent sources solar and wind are added on top of the must run capacity.

The black line in **Figure 29** and **Figure 30** indicates the total demand profile (local consumption plus electricity transported to outside the area). It shows that electricity demand is not distributed evenly over time. Electricity generation in the Rotterdam area exceeds local demand by far. The electricity produced in the Rotterdam area is either consumed locally or transported to the rest of the Netherlands and the UK. For this case study the local demand profile is determined from the weighted average of the demand from the various sectors present in the Rotterdam area. The amount of electricity that is transported to outside the Rotterdam area is determined by subtracting the local demand profile from total production. It follows the demand profile of the Netherlands.

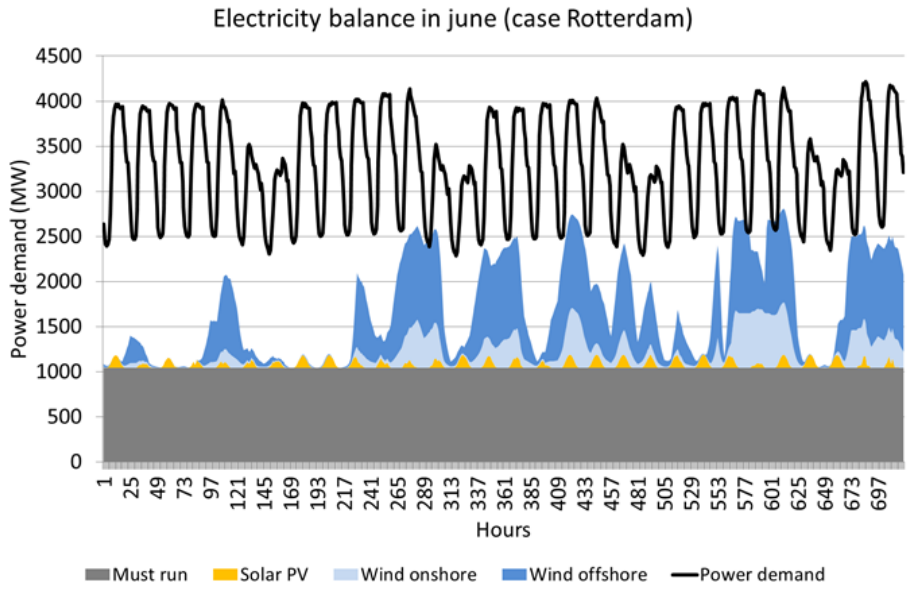
Local electricity consumption is 6.1 TWh per year in 2010, based on the 486,310 houses, 63,185 offices and 6,440 industrial facilities[28]. For offices and industry, various sectors can be distinguished each with their own average annual electricity consumption (CBS, 2014; MONIT, 2014). Based on the electricity consumption change factor estimated for

28 The Rotterdam area includes the following cities: Barendrecht, Capelle aan den IJssel, Krimpen aan den IJssel, Maassluis, Rotterdam, Schiedam, Spijkenisse and Vlaardingen.

the Energy Agreement (PBL/ECN, 2013), the local electricity consumption in 2030 is estimated at 6.4 TWh/yr. According to our model, 18.6 TWh/yr is transported to outside the Rotterdam area in case there is no connection of offshore wind parks. In case there is a connection of an 1100 MW offshore wind farm, this figure rises to 22.7 TWh/yr.

Figure 29 shows that demand is always larger than non-controllable production. In case the connection to offshore wind parks is absent, it turns out that this situation persists throughout the year. There is no production of surplus electricity.

Figure 30: Electricity balance in Rotterdam area for June 2030, with connection of offshore wind parks



In case the transmission system in the harbour is used to connect 1,100 MW offshore wind capacity, **Figure 30** shows that there are occasions where (non-controllable) production exceeds demand. Over the year, these occasions occur 44 times resulting in a minor surplus of 0.013 TWh. The total duration of these 44 situations is 147 hrs.

When wind fronts causing these 44 congestions pass over, they are likely to cause congestions in the UK and Germany as well. Right before and after these congestions the possibility to transport electricity to the UK is limited. During the same periods, excess production in Germany may load the Dutch transmission network, leaving less capacity for the Rotterdam area to transport excess electricity to the rest of the Netherlands. The median duration of offshore wind fronts is 3 hrs. Over the full year, this effect may therefore cause another 132 hours of demand for flexibility around the 44 congestion situations in the Rotterdam area. Whether these 132 hours really materialize and the volume of electricity involved is uncertain as it e.g. depends on the evolution of the wind front and the development of the infrastructure in the UK and Germany.

Sufficient transmission capacity available by 2030

In this case study, the electricity demand profile of transport to outside the Rotterdam area shows a peak capacity of 3.7 TW in case the offshore wind parks connect to the transmission system at the Maasvlakte (and 3.0 TW without offshore wind). The current transmission capacity to outside the Rotterdam area is 3.3 TW.

Figure 31: Transmission network in Rotterdam area by 2030

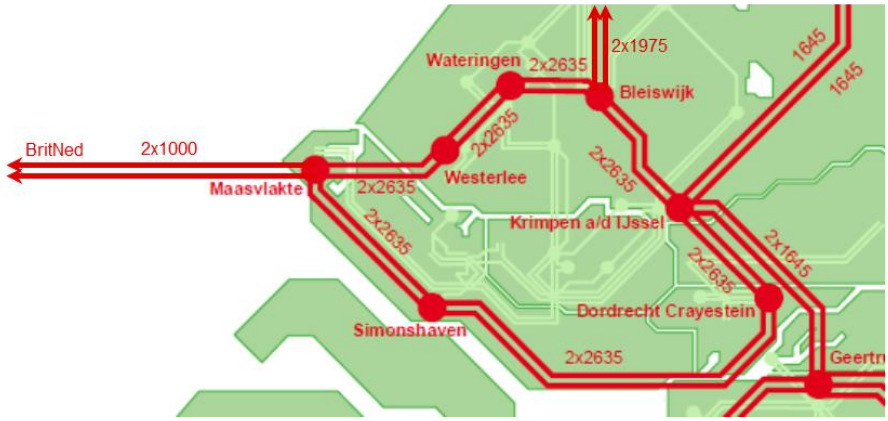


Figure 31 show the current transmission network capacities and the capacity expansions Tennet is constructing to resolve shortage of inland transmission capacity for large production in harbour (Tennet, 2013). A capacity expansion between (Bleiswijk-Vijfhuizen) is due for 2017 and will put the projected transmission capacity to outside the Rotterdam area at 5.3 TW to the rest of the Netherlands. In addition a 1 TW connection to the UK has been available since 2012. The transmission capacity is therefore sufficient to adsorb the peak capacity of 3.7 TW in case an offshore wind farm is connected at the Maasvlakte.

Limited demand for flexibility up to 2030

The impact of the foreseen levels of intermittent electricity generation in the Rotterdam harbour area is limited to an annual demand for flexible electricity consumption of 13 GWh over 147-279 hours per year. This excess electricity may be consumed by tapping into the potential for flexible electricity demand in the harbour area, or via shifting between energy carriers via P2G.

4.3.3 Use of hydrogen from P2G

Converting excess electricity into hydrogen gas (P2G) could be used as a provider for flexibility in the electricity system. In the harbour, there are five basic pathways for the use of P2G hydrogen:

- As feedstock for industrial processes (e.g. ammonia and methanol);
- Feeding hydrogen into the gas grid;
- Methanation of hydrogen (and feeding into the gas grid);
- Re-electrification (produce electricity from hydrogen);
- Transport fuel.

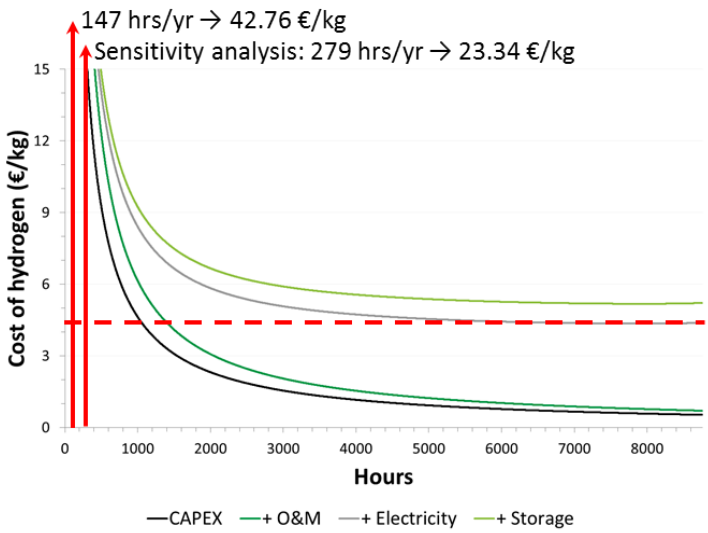
Below, the economic viability of these options is further elaborated. For a selection of options for which viability is foreseen, the potential and operating conditions are determined.

Economic viability of P2G hydrogen

Comparing the costs of hydrogen from P2G with the allowable costs of hydrogen, used in the above-mentioned options, provides a first indication of the economic viability of

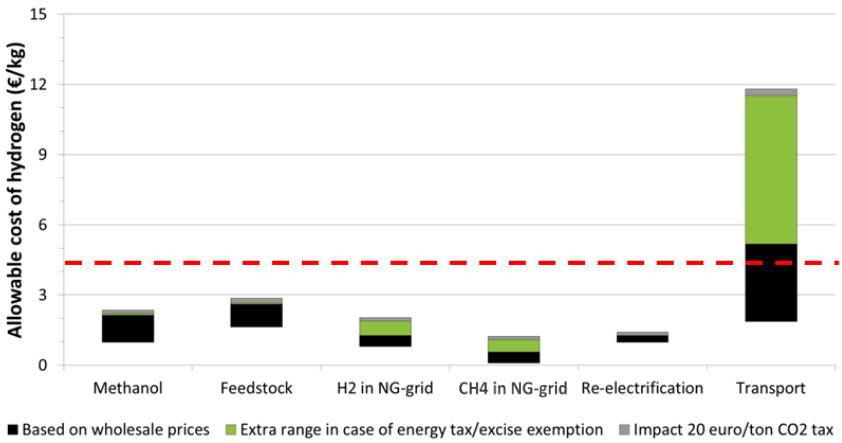
using P2G hydrogen. **Figure 32** shows the cumulated cost components of producing hydrogen from P2G versus the full load hours. The price-duration curve for electricity is based on estimates for 2030 and has an average value of 73 €/MWh. In case of 90% load (8000 hrs), and without the need for storage, the costs of hydrogen are 4.35 €/kg. If an installation would only be used in case of excess electricity production, the full load hours reduce to 147-279 and the hydrogen costs increase to 23.34-42.76 €/kg.

Figure 32: Cumulated cost components of hydrogen from P2G vs. full load hours



For a selection of sectors, **Figure 33** shows the costs at which the use of hydrogen still yields revenues. Based on the prices for current feedstock use, the bars show the cost range of hydrogen if it would replace that feedstock price-neutral. If the costs of hydrogen are below or within the bars, its use still yields revenues. If the costs of hydrogen are above the bars, its use yields a loss. The black sections indicate the basic cost levels without any policy support. The costs of hydrogen can be higher if there are tax exemptions (green sections) and/or carbon pricing. The grey sections indicate the effect of a carbon price of 20 €/ton, expected for 2030. The red dashed line indicates the production cost level of 4.35 €/kg at 90% full load hours determined in Figure 32.

Figure 33: Allowable hydrogen costs for various uses (red line indicates 90% load factor cost level)

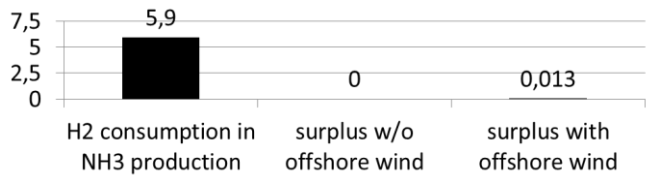


Apart from transport, the costs of producing hydrogen from electrolysis are higher than the allowable costs. If – in case of stringent climate policy in 2050 – carbon prices rise to 100 €/ton (not shown), P2G use as industry feedstock becomes a viable option as well. Apart from that, P2G hydrogen has to compete with much cheaper hydrogen from steam methane reforming (SMR) which is abundantly available in the harbour area. Below we will further elaborate on the potential of using P2G hydrogen in methanol production, ammonia production and as transport fuel.

H_2 from P2G as feedstock for ammonia production

Ammonia is currently produced in Geleen and transported to various users. The total production capacity of that facility is 1,000 kton NH_3 per year. Assuming this production capacity is constructed in the Rotterdam harbour, the annual consumption of hydrogen would be 176 kton. Producing this amount of hydrogen from electricity requires 5.9 TWh/yr. The potential for flexibility in producing NH_3 from electricity is much larger than the amount of excess electricity foreseen in this case (see Figure 34).

Figure 34: Potential of flexibility provided by ammonia production vs. flexibility demand in harbour area without and with connection to offshore wind parks



H_2 consumption in methanol production

Methanol is a commodity that has a global annual market volume of 60 Mton. The recent European market price ranges between 370-408 €/ton (Methanex, 2014). The incumbent production method is to reform natural gas and steam into syngas which is synthesized further to methanol. Currently, there is no methanol production in the Rotterdam area.

The so-called Olah-process, enables conversion of pure hydrogen and CO_2 into methanol (and water) at an industrial scale. A 4,000 ton/yr plant requires an investment of 6 M€ (full depreciation over ten years) and 60 k€ of annual costs for O&M and other costs (Stikkelman et al, 2014). Such a plant consumes 750 ton of H_2 per year. Globally 11.3 Mton hydrogen could be consumed by this process if all methanol was produced in this way. However, **Figure 26** shows the allowable costs for hydrogen for the Olah-process are twice to four times as low as the hydrogen production costs making this use of hydrogen from P2G not economically viable.

H_2 as transport fuel in the Rotterdam area

Figure 33 indicates that by 2030 using P2G as transport fuel is economically viable, even when there is no government support. In Table 20 estimates the potential for hydrogen consumption in transport in 2030.

Table 20: P2G hydrogen consumption in transport in Rotterdam by 2030

	2030	Kg/vehicle	Kton/yr
Number of cars and vans (2013)	415534		
Penetration rate FCEV in NL	2%		
Number of FCEV cars and vans	8310	130[29]	1,1
Number of busses (2013)	421	2300[30]	1,0
Total H_2 consumption			2,1

By 2030, the total share of hydrogen vehicles in the Dutch vehicle fleet is 2% (ECN, 2011). In 2013, the total number of cars and vans in the Rotterdam area was 415534 (CBS, 2014). At 2% penetration by 2030 and assuming no change in vehicle numbers, there are 8310 hydrogen cars and vans by 2030. These consume 1.1 kton hydrogen per year. Assuming that all public transport busses run on hydrogen, public transport requires another 1 kton/yr. The total potential for hydrogen consumption in the Rotterdam area in 2030 is 2.1 kton per year. To produce this amount of hydrogen from electrolysis requires 0.1 TWh of electricity.

Figure 35: Potential of flexibility provided by hydrogen fuelled vehicles vs. flexibility demand in harbour area without and with connection to offshore wind parks

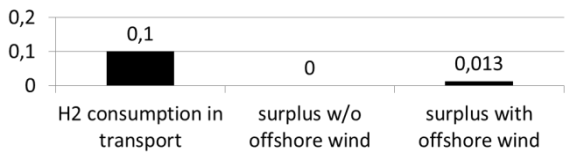


Figure 35 shows that the potential for hydrogen consumption as transport fuel exceeds the flexibility challenge posed by connecting 1100 MW offshore wind by 8 times. This means that the production of hydrogen for transport cannot just rely on surplus wind power, but also needs to be drawn from other sources. Electrolysis may be used to fill this gap. Figure 32 and Figure 33 show that from an economic point of view, it is not viable to run installations only for 147-279 hrs/yr. The business case needs electrolysers to run for more than 3000 hours per year. These installations are capable of providing demand response. On the other hand, the hydrogen that is currently produced through SMR is cheaper and therefore a strong competitor if the green attribute of P2G hydrogen is not valued over the cost difference with hydrogen from SMR.

4.3.4 Other option for providing flexibility in the Rotterdam harbour area

Apart from using P2G technology to provide flexibility in electricity consumption, there are many more other options present to absorb peaks in wind energy production. Examples are:

- Using electricity to 'co-fire' steam boilers
- Intensifying use of shore power for inland ships and ferries.

29 13000 km/yr, 80 kW

30 73000 km/yr, 250 kW

- Flexibly switchable installations in industry.
- Realising a smart grid for electricity.

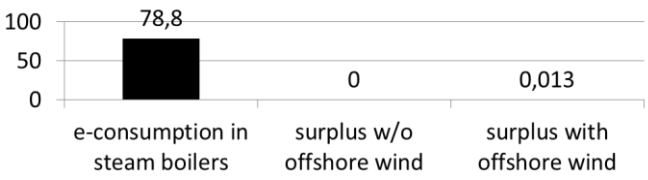
The main barrier for the uptake of these options lies at a system integration level; it requires linking of parties with (control over) heat and electricity demand and supply, control over balancing of these two energy carriers and control over regulations.

Below one of these options – using electricity to 'co-fire' steam boilers - is discussed in more detail. This option is chosen for its economic viability at low full load hours and its large potential.

Electric steam boilers provide economic flexible electricity demand
Adding electric heaters to gas-fired steam boilers enables these boilers to produce heat while varying between electricity and natural gas as energy source. The investment costs are 100 €/kW, making the business case for this flexibility option viable at the current gross market prices for electricity (Stikkelman et al, 2014) while operating at low full load hours.

Determining the potential for electric steam boilers in the harbour is challenging due to the sheer numbers of steam boilers and the sectorial fragmentation of their use. The residual heat production of 10 GW in the harbour area can be used as a conservative first order estimate. Electrifying this heat consumption consumes 78.8 TWh/yr of electricity. **Figure 36** shows that this potential by far exceeds the flexibility demand caused by connecting 1100 MW offshore wind.

Figure 36: Potential of flexibility provided by electric steam boilers vs. flexibility demand in harbour area without and with connection to offshore wind parks



However, in order to make effective use of the flexibility in energy source for steam boilers, risks have to be put with a party that has influence over the risks associated with gas and electricity contracts. Such a party could be a service company providing steam or heat that is capable of balancing between electricity and gas consumption.

4.3.5 Conclusion

The flexibility challenge in Rotterdam harbour is limited and only occurs after 2025. In case 1100 MW offshore wind capacity is connected at the Maasvlakte, electricity production may exceed demand by 0.013 TWh for 147-239 hrs per year.

In the harbour area, there is sufficient potential for providing economically viable flexibility in electricity consumption, e.g. by using electric steam boilers (Stikkelman et al, 2014). These flexibility options could absorb more than 78.8 TWh excess electricity production per year. Accounting for the current expansion plans, the capacity of the

transmission network is sufficient to prevent congestion in case 1100 MW offshore wind is connected to the transmission grid at the Maasvlakte.

The profitability of investments in industrial processes using P2G hydrogen is dependent on a high break-even price for the product and low investment costs for the production method. The investment costs for electrolysers are such high that they deteriorate the economic viability of producing hydrogen from electrolysis for industrial applications up to 2030 at least. Using hydrogen from electrolysis as feedstock in industrial processes is only economically viable under very strict CO_2 reduction targets leading to CO_2 prices of over 100 €/ton. These conditions are not expected before 2050. The potential for absorbing peaks in electricity supply by using hydrogen as feedstock for industry is much larger than the production of excess electricity foreseen in this case study (for 2030). The potential for hydrogen use in industry would easily resolve the flexibility challenge in the Rotterdam area.

For the transport sector, hydrogen production costs are below the costs at which the use of hydrogen as a fuel yields a loss, provided that hydrogen production runs for more than 3000 hours per year. The 147-239 hours in which electricity production exceeds demand are not enough to result in a viable business case in themselves. The amount of hydrogen consumed as transport fuel by 2030 is about eight times larger than the flexibility challenge. This leads to the conclusion that in the Rotterdam area, hydrogen from electrolysis can play a role in fuelling the transport sector, provided that the green attribute is valued over the cost difference with hydrogen from SMR. Electrolysers should be operated at high running time (>3,000 hrs/yr) and can be used as a demand response option when electricity production exceeds electricity demand.

4.4 The role for P2G in the regional energy system of the '*stedendriehoek*'

4.4.1 Scope

This case study explores the implementation of P2G in a specific regional setting linked to an electricity and gas distribution network system. The specific focus here is on the the '*stedendriehoek*' region. Within this region, the communities of Apeldoorn, Brummen, Deventer, Epe, Lochem, Voorst en Zutphen cooperate on a number of policy areas such as mobility, sustainable living, and innovation. This region covers part of the provinces of Gelderland and Overijssel. Within the region a large number of sustainable energy projects and initiatives are taking place. Liander plays an important part in the majority of these projects and initiatives[31], with the major share of the regional energy distribution system being operated by subsidiary Alliander. The distribution system in eastern part of the region (around Deventer) is operated by Enexis.

[31] http://www.liander.nl/liander/innovatie_duurzaamheid/gelderland/stedendriehoek/stedendriehoek.htm.

Figure 37: The geographical area covered by the 'driestedendriehoek' Region (www.regiostedendriehoek.nl)

Energy neutrality in 2040 is technically possible, but is economically not viable
The ambition of the Stedendriehoek Region is to become energy neutral by 2040. Recently, Ecorys (2014) quantified the costs and benefits of the ambition of becoming energy neutral in *2030* through comparison with a reference scenario in which this ambition is not achieved (but in which sustainable energy makes up an increasingly large part of the energy mix). Ecorys concludes that from a financial-economic perspective it is not attractive to strive for energy neutrality by 2030. The financial benefits associated with the necessary investments are insufficient from a private investor's perspective. Moreover, the external effects for society as a whole are not high enough to justify a public subsidisation of these investment to the degree needed to make private investments profitable. The total benefits for society are lower than the total costs for society.

Role for renewable electricity and P2G
In their assessment of the costs and benefits of energy neutrality Ecorys specify three different scenarios. One scenario is based on full energy independence of the region, while the other two scenarios assume a 'net neutrality' over the year. In all scenario's renewable electricity production – and to a lesser degree bio-gas production – play a key role. An important assumption in the study is that in all scenarios the use of conventional (natural) gas is reduced to zero in 2030. Furthermore, it should be noted that the P2G definition and coverage in the analysis is relatively limited. First of all, P2G is almost exclusively used to refer to power-to-methane. The assumption is that power-to-methane is needed to decarbonize in particular the transport sector (heavy duty vehicles) and (part of) heat demand. Power-to-hydrogen only plays a role in a re-electrification route in the scenario assuming full energy dependence. In this scenario power-to-hydrogen is used to temporarily store hydrogen in order to produce electricity in a different time period. In its summary the Ecorys study concludes that the application of power-to-gas – according to the above definition – in transport or heating is not viable from a financial perspective under the current circumstances.

Research questions
The currently available studies on the technical possibilities and economic viability of an increasing use of sustainable energy sources in the Stedendriehoek Region provide important input for the specific questions that are not yet addressed and are considered to be key in this P2G system analysis study.

- Will the increasing integration of particularly intermittent sources lead to flexibility issues within the region?
- Could the need for system flexibility provide a case for the local implementation of P2G?
- And if so, under which conditions and could it be economically viable in the medium run (e.g. 2030)?

4.4.2 Description of the energy system in the region

The Stedendriehoek region can be characterised as a very energy import-dependent region. Total final energy use in 2012 was about 35,000 TJ – which is about 1.1% of final energy use in the Netherlands in 2012 – of which about 560 TJ was produced within the region (1.6%). Energy import dependency on other regions in the Netherlands is thus about 98%.

Figure 38 presents the composition of final energy demand, distinguishing between gas and electricity use with households and businesses. Total electricity demand in 2012 was about 2.2 TWh per year, of which about 7% was generated within the region. **Figure 39** shows the different types of energy production in the region.

Figure 38: Composition of total final energy use in the Driestedendriehoek region in 2012[32]

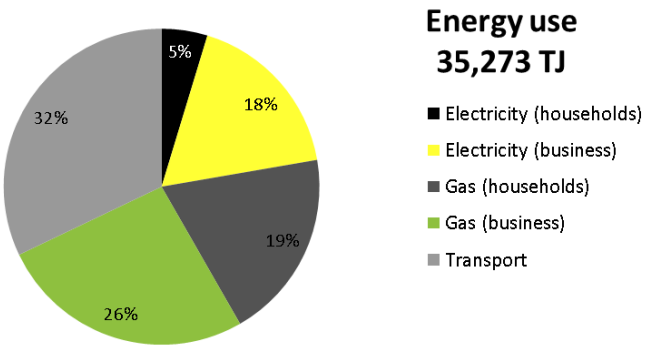
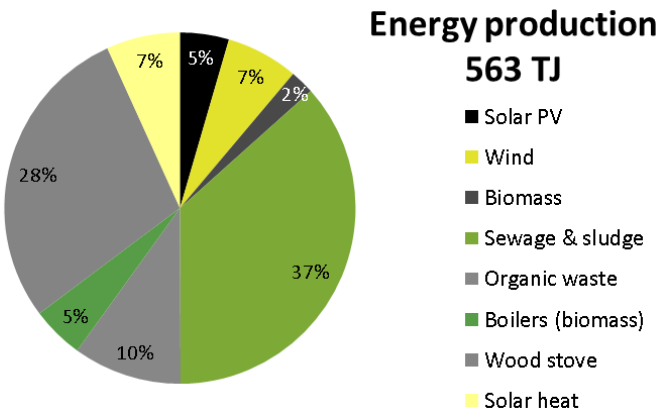


Figure 39: Composition of total energy production in Driestedendriehoek region in 2012[33]

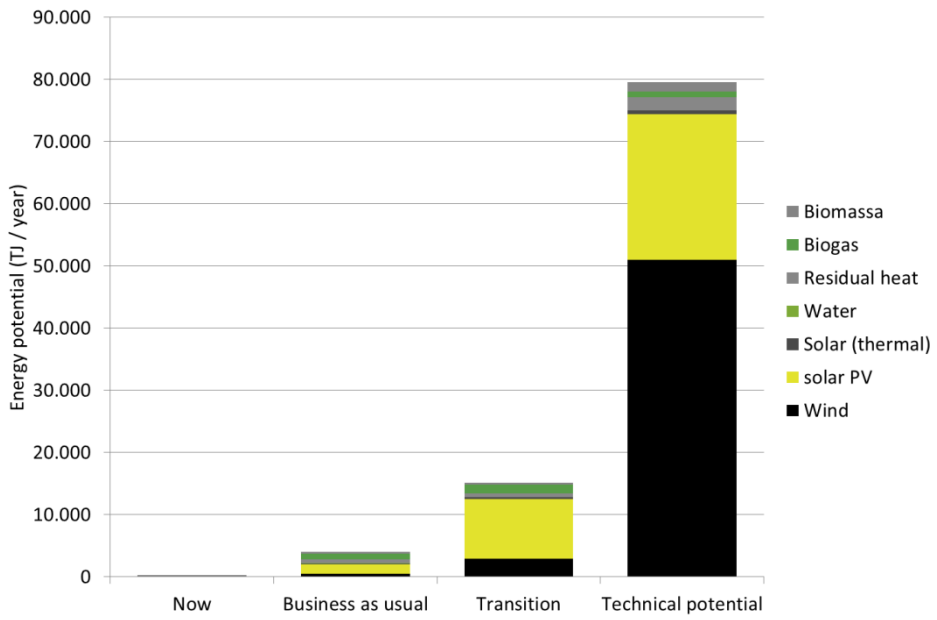


[32] Data available at: http://www.regiostedendriehoek.nl/

[33] Data available at: http://www.regiostedendriehoek.nl/

Earlier studies have explored the technical potential available in achieving this target (Alliander, 2012). The maximum technical potential for the regional production of sustainable energy is estimated at about 80 PJ in 2040, which is over 200% of current total energy demand. However, assuming a continuation of current policies, this Alliander study finds that only about 11% will be realised in 2040 – this is referred to as a business as usual scenario. In a third scenario, referred to as transition scenario, additional policies aimed at strengthening existing policies could lead to a 41% regional coverage of energy demand with sustainable energy sources.

Figure 40: Overview of sustainable energy production and potential in the Stedendriehoek region in different scenarios (Alliander, 2012)



4.4.3 Flexibility challenge in the region

In this section the aim is to estimate the potential surplus of electricity generated within the region based on future projections for electricity demand and the integration of intermittent wind and solar-based generation capacity. Is there an intermittency challenge? And if so: what is its magnitude? For this purpose we use the three scenarios constructed in Ecorys (2014) and an own scenario. These scenarios are briefly described below. Thereafter we turn to an estimation of the intermittency challenge.

Scenarios for penetration of intermittent generation

In assessing the costs and benefits of energy neutrality for the region, Ecorys (2014) specify three energy transition scenarios in which each has a specified energy balance for energy demand in the heating, mobility and transport sector. All scenarios involve a primary energy source mix that achieves energy neutrality for the region. The focus here is on the assumptions used regarding the penetration of onshore wind and solar and electricity demand.

- Scenario 1 (*'Maximaal zon'*) is based on a 'maximum' penetration of solar PV (20 PJ ≈ 7.9 GW_e) in combination with a realisation of the technical potential of all other

renewable energy sources *except wind energy*. Energy neutrality is achieved on a net annual basis: trade with other regions is allowed.

- Scenario 2 (*'Mix zon en wind'*) differs from scenario 1 as onshore wind and solar PV are equally deployed in terms of TJ output. This comes down to an integration of about 1.1 GW_e onshore wind and 4.0 GW_e solar PV capacity. Also in this scenario the energy neutrality goal is achieved on a net annual basis.
- Scenario 3 (*'Zelfvoorzienend met zon en wind'*) shows a strong deployment of both onshore wind and solar PV. In contrast with scenario 1 and 2, this scenario assumes full self-sufficiency (i.e. no trade). This is made possible with the introduction of energy storage in the mix of technologies. Energy storage here implies the storage of hydrogen.

Heating demand across the scenarios is covered by a mix of heat pumps, solar boilers, power to gas (methane) and residual heat, whereas electric vehicles, biogas and P2G (methane) cover total energy demand in the transport sector. Remarkably: the report assumes the deployment of P2G for energy demand for heating and transport purposes while referring only to power to methane. No arguments for this particular choice is given and it remains unclear where the CO_2 that is needed in the methanation process comes from. The report also assumes that there will be no natural gas demand in the region anymore, which of course is related to the fact that energy neutrality is the policy goal at stake and no gas resources are available within the region. The estimated electricity demand in 2030 is about 5.6 TWh per year in scenarios 1 and 2, and 7.1 TWh per year in scenario 3. The higher electricity demand in the latter scenario is linked to the deployment of energy storage via P2G. The 5.6 TWh per year electricity demand in the former two scenarios is about 250% higher than electricity demand in 2012. This can be explained by the presumed use of heat pumps, electric vehicles and P2G: options that are all considered necessary in order to achieve energy neutrality.

Apart from the three scenarios from Ecorys (2014) we will also test an additional scenario based on own estimates. This scenario is not based on achieving energy neutrality in 2030 but is rather based on more plausible electricity demand and onshore wind and solar PV developments in the region. Based on electricity growth estimates used in the Energie Akkoord, a more realistic level of electricity demand in 2030 is set at 2.4 TWh per year (i.e. 10% higher than the 2012 level). More realistic assumptions for the penetration of onshore wind and solar PV in the region have been set at 1 GW_e onshore wind and 1 GW_e solar PV in 2030.

Table 21 presents an overview of the electricity demand and intermittent generation capacity assumptions across the scenarios

Table 21: Overview of electricity demand and intermittent generation capacity assumptions in the scenarios used

	Unit	Own realistic scenario	Ecorys Scenario #1	Ecorys Scenario #2	Ecorys Scenario #3
Installed intermittent RES capacity	[GW]	2,0	7,9	5,1	6,5
Wind	[GW]	1,0	0,0	1,1	1,4
Solar PV	[GW]	1,0	7,9	4,0	5,0
Electricity demand	[TWh/yr]	2,4	5,6	5,6	7,1

Magnitude of the flexibility challenge

Table 22 presents the calculated electricity surpluses for the range of scenarios.

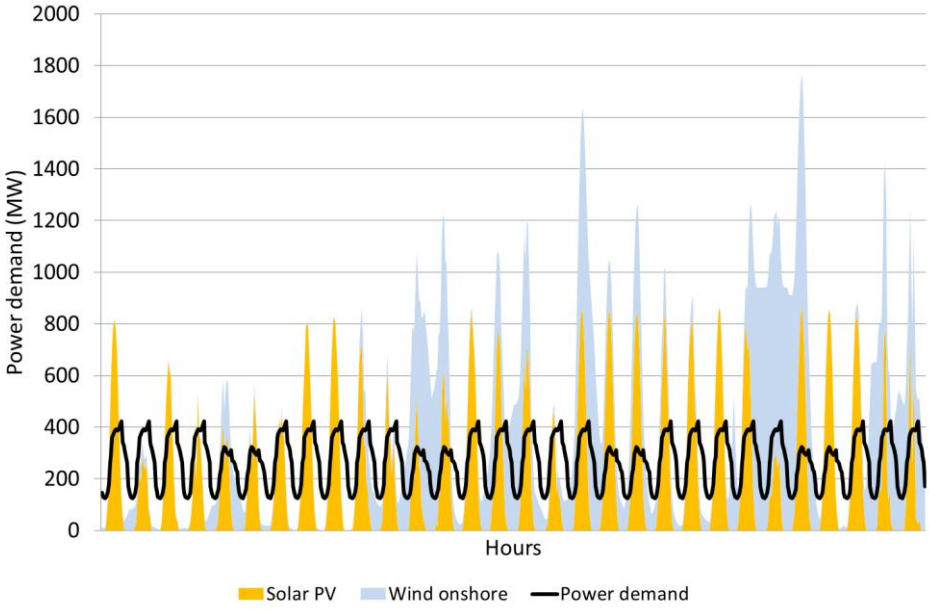
Table 22: Overview of hypothetical electricity surplus in the Stedendriehoek region in 2030 under different scenarios

	Unit	'Own scenario'	Ecorys Scenario #1	Ecorys Scenario #2	Ecorys Scenario #3
Installed intermittent RES capacity	[GW]	2,0	7,9	5,1	6,5
- Wind	[GW]	1,0	0,0	1,1	1,4
- Solar PV	[GW]	1,0	7,9	4,0	5,0
Electricity production	[TWh/yr]	3,2	8,0	6,6	8,2
- Wind	[TWh/yr]	2,2	0,1	2,5	3,2
- Solar PV	[TWh/yr]	1,0	7,9	4,0	5,0
Electricity demand	[TWh/yr]	2,4	5,6	5,6	7,1
Surplus electricity	[TWh/yr]	1,6	5,3	3,0	4,4
	[%]	67%	94%	53%	88%
	[hours]	4173	2650	3758	4266
H_2 supply (max. from surplus)	[kton / yr]	31,9	104,8	58,8	87,8

The estimated yearly demand in the region of about 2.40 TWh in 2030 may be combined with the estimated penetration of intermittent generation capacity based on wind and solar resources. Given representative hourly production profiles for wind and solar PV in the region an average yearly amount of about 3.2 TWh of electricity may be expected from this intermittent generation capacity. This implies that if all generation can be accommodated in the electricity network in the region, there could be a theoretical surplus over the year of about 0.8 TWh that may be exported. However, as the hourly demand and generation profiles do not match during every hour of the year, the total cumulative surplus for any given year will differ. **Figure 41** provides an illustration of the typical mismatch in electricity demand and supply in the month June in 2030. The total cumulative surplus of electricity is actually about 1.6 TWh per year, taking place during about 4,173 hours.[34]

[34] We assume that in 2030 there is no must-run thermal capacity in the region that may contribute to a potentially larger electricity surplus during some hours of the year.

Figure 41: Illustrative pattern of intermittent generation and electricity demand in the Stedendriehoek in 2030 in the month June



Allocation of capacity over distribution and transmission networks

In the exploratory analysis above no account was given of the actual electricity network level to which the estimated wind and solar-based generation capacity would be connected. In practice, part of capacity is likely to be connected to the transmission network operated by Tennet, while part will be integrated in the distribution networks operated by Alliander and Enexis. For onshore wind parks a standard assumption is that most of the added capacity would be connected to the TSO network, given the future size of wind turbines (>5 MW each) and number of wind turbines in a park. Wind turbines built between 2020 and 2030 will be of size above >5 MW. With more than 7 wind turbines , the size is >35 MW so the responsibility of the TSO. Solar PV will be mainly rooftop based and connected to DSO network at the end user level.[35]

Table 23: Allocation of estimated onshore wind capacity in 2030 in the Stedendriehoek region

Onshore wind capacity S3H 2030	With park size < 35 MW (DSO)	Park size > 35 MW (TSO)
1000 MW	200 MW	800 MW

How would this allocation between distribution and transmission network connections impact the magnitude of the potential flexibility challenge in 2030? The reduction in wind-based capacity integrated in the distribution system reduces total intermittent generation capacity connected to the distribution network in the region to 1.2 GW_e. This would reduce the flexibility challenge to a cumulative yearly surplus of electricity of about 0.3 TWh, during about 1,837 hours of the year.

[35] Any cable to connect a wind farm to the closest DSO or TSO network is assumed to be paid by the project developer, so it is not at the cost of the DSO or TSO. However, the cost of these upgrades will need to be taken into account when the business case for P2G is evaluated in Section 4.4.4.

From a policy perspective and the goal of energy neutrality in 2040 the fact that wind turbines are connected to the transmission level rather than the distribution level may be irrelevant, but from a business case perspective this is a relevant distinction to be made.

4.4.4 Use hydrogen from P2G

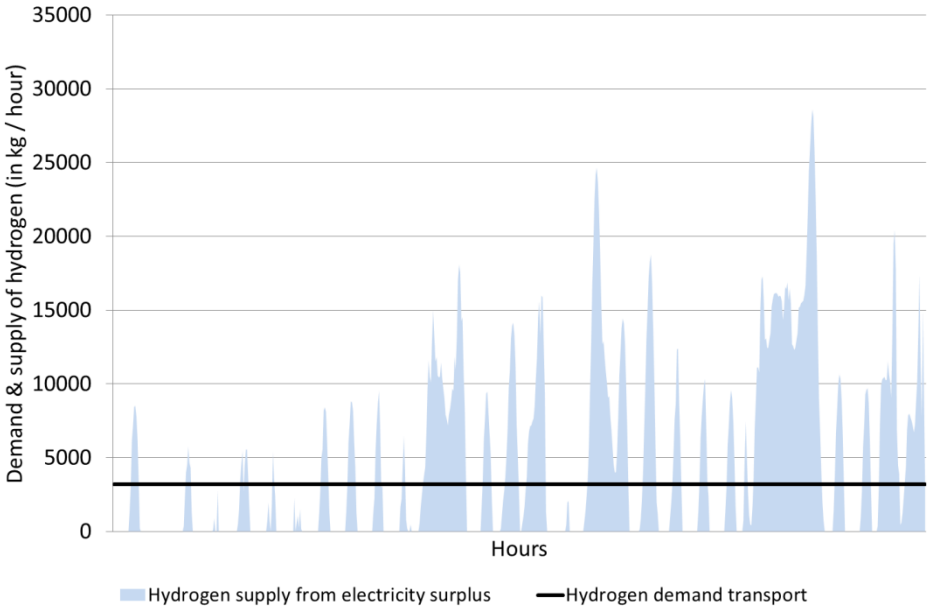
The potential surplus of electricity could be converted into a gaseous energy carrier (hydrogen, synthetic methane) for consumption in other sectors in the region. Two options explored here are the use of surplus electricity for the production of transport fuels and for the admixing of hydrogen or synthetic methane in the gas network for use in the built environment. The option for industrial use of hydrogen is not considered an option for this region due to the lack of particular industries with such (potential) demand.

P2G in transport

Assuming a 2% market penetration rate for hydrogen-based vehicles in the transport sector in 2030 (HyUnder 2014) for the existing fleet of cars, vans and auto buses in the region the estimated amount of hydrogen consumption would be about 0.56 kiloton per year.[36] A more optimistic estimate for the penetration of hydrogen-based vehicles of 10% would increase total hydrogen consumption to 2.82 kiloton per year. In Section 4.4.3 we learned that the theatrical electricity surplus in the region could deliver be as much as 1.6 TWh, which could be converted into about 32 kiloton of hydrogen: this would be more than enough to fully supply energy demand by cars, vans and auto buses in the region (28,16 kiloton of hydrogen demand per year). Even though total supply of hydrogen converted from the surplus electricity of 2.0 GW_e of intermittent electricity generation could theoretically be sufficient to cover 100% of energy demand in transport within the region, **Figure 42** demonstrates that storage solutions will be needed to deal with the mismatch in demand and supply of hydrogen. This picture assumes a baseload demand for transport. In reality, available buffering using hydrogen distribution infrastructure and / or the inherent storage present in vehicles may be used to diminish the need for supply flexibility.

[36] Based on an average mileage of cars and vans of 13,000km and of 58,000 km for auto buses (based on data from Stedendriehoek for 2012).

Figure 42: Illustration of mismatch between supply and demand of hydrogen in the transport sector in the case of 100% penetration of hydrogen-based applications in the transport sector in the Stedendriehoek region in June 2030



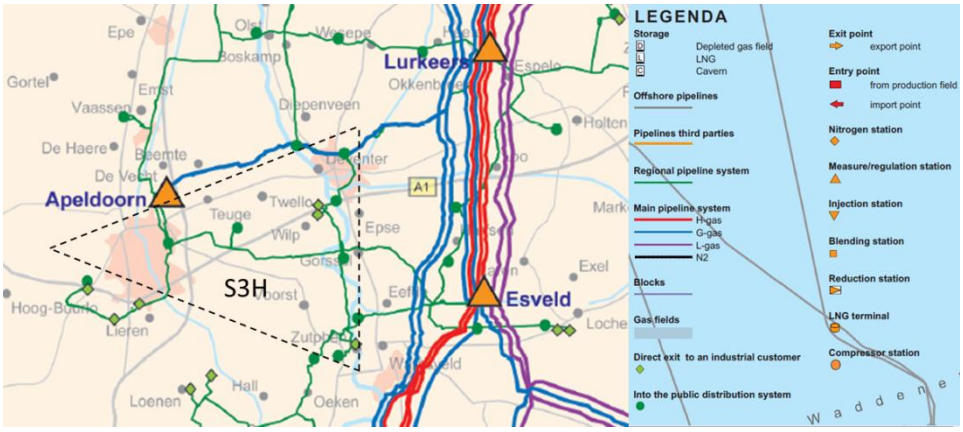
Admixing of hydrogen or injection of methane in the gas grid

Using the renewable electricity surplus in the region to decarbonise part of the gas supply may theoretically involve several routes:

9. It may involve the admixing of hydrogen or the feed in of synthetic methane;
10. It may be done at the distribution or transmission level.

For the admixing there is currently a regulated limit of 0.02%, that will be raised to 0.5% by 2023. This restricts the potential for hydrogen admixing at all levels. The feed in of synthetic methane does not have such a limit, but the scope for injection depends on the gas flow throughout the year. The presence of local storage could alleviate this problem however. **Figure 43** shows the key gas infrastructure in and near the Driestedendriehoek region. This figure demonstrates that only G-gas infrastructure is present within the Stedendriehoek. If the admixing of hydrogen is only allowed for H-gas infrastructure, then the hydrogen converted from any electricity surplus would need to be transported to nearby Gasunie measuring and regulating stations in Lurkeers or Esveld. If hydrogen admixing in G-gas systems is allowed, then the present measuring and regulating station near Apeldoorn may theoretically suffice. Finally, small-scale P2G applications could theoretically involve the admixing of hydrogen locally in the regional gas grid of either Alliander or Enexis.

Figure 43: Overview of main gas infrastructure near the Stedendriehoek (Source: Gasunie)



In 2012 the total demand for gas in the region amounted to about 500 million m^3. Although total gas demand in 2030 is expected to be at a lower level, we use this figure to explore the potential for H_2 admixing and CH_4 injection profile in the region.[37] **Figure 44** shows the maximum potential for H_2 admixing (0.5% limit) and CH_4 injection in the region. Standard profiles for gas consumption in the built environment and services sector have been used to construct the curves in the figure. It demonstrates the relatively lower potential for either admixing or injection during the low demand months in summer.

Figure 44: Maximum hourly admixing potential for H_2 (0.5%) and CH_4 throughout the year in the Stedendriehoek region

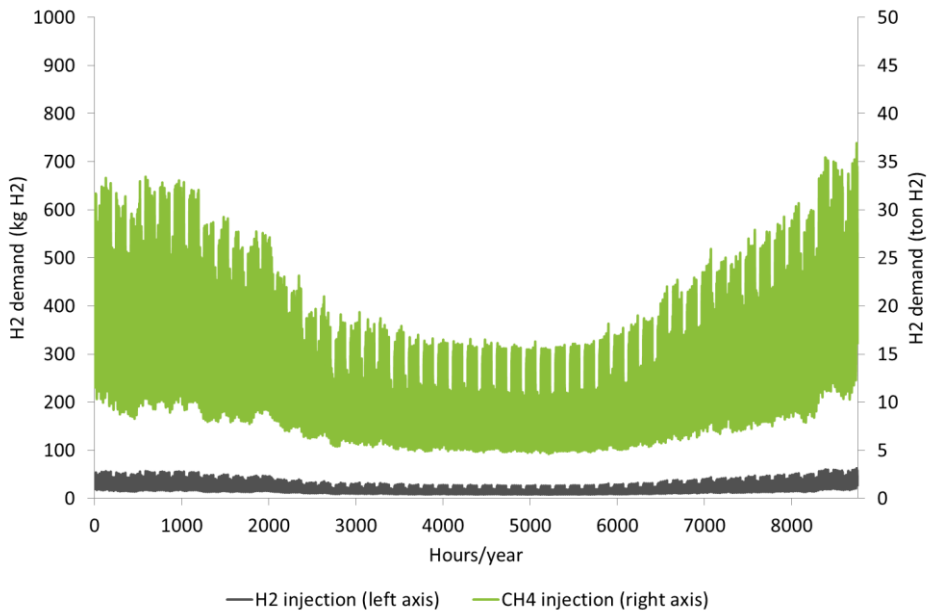


Table 24 contains the potential for both H_2 admixing and CH_4 injection in the gas system in the Stedendriehoek region on an annual basis. The results in this table sketch the trade-off faced when considered the two different routes: the admixing of hydrogen

[37] In its scenarios representing energy neutrality in 2050 Ecorys (2014) assume that there the demand for natural gas is zero.

has no additional losses (15%) compared with the admixing route, while the admixing limit of 0.5% that may apply in 2030 only allows for admixing of about 0.3% of the electrolysis-based hydrogen compared with full compatibility of synthetic methane with natural gas specs and a possible injection of 80% of the initial electrolysis-based hydrogen. Even if the technical and regulatory restriction on hydrogen admixing could be loosened to a theoretical 50% - which may be considered extremely high for 2030 – then still only 30% of the initial electrolysis-based hydrogen could be accommodated in the local gas system.

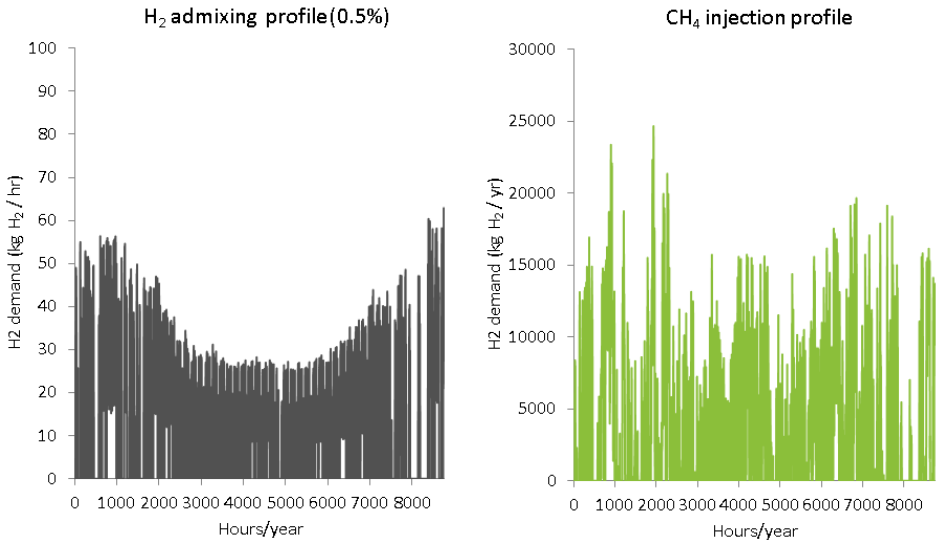
An additional issue for the implementation of the methanation route within the region is the availability of CO_2 required in the methanation process. This may be derived from either biomass resources or from CO_2 capturing assets installed with large-scale electricity generation plants. The amount of biomass within the region is limited to about 1470 TJ (technical potential) and there are currently no large-scale coal or gas based electricity generation units located in the region. Application of the methanation route would thus involve the import of for example biomass or CO_2 captured elsewhere, which would go against the policy goal of energy neutrality for the region.

Table 24: Overview of H_2 admixing and CH_4 injection potential in the Stedendriehoek based on the electricity surplus in the realistic scenario of the integration of 1 GW_e onshore wind and 1 GW_e solar PV

		H_2 admixing			CH_4 injection
		0.5%	20%	50%	
Electricity surplus region	[TWh / yr]	1.6			
	[Kton / yr]	31.9			
H_2 for admixing / injection	[Kton / yr]	31.9			27.1
Loss due to $H_2 \rightarrow CH_4$ conversion (15%)	[Kton / yr]	-	-	-	4.8
H_2 admixed / CH_4 injected	[Kton / yr]	0.1	4.1	9.6	25.5
H_2 not accommodated	[Kton / yr]	31.8	27.8	22.3	3.1

Figure 45 illustrates the yearly profile for both hydrogen admixing (at a 0.5% admixing restriction) and synthetic methane injection given the annual demand for gas in the region of about 500 million m^3 and taking into account relevant hourly gas demand profiles. Note that the large difference in potential feed in is reflected by the different units used on the Y-axis in the two graphs. The intermittent nature of particularly the synthetic methane feed-in profile demonstrates that synthetic methane supply exceeds total gas demand during some hours of the year (witness the 3.1 kton of hydrogen mentioned in **Table 24** as 'not accommodated'), while the synthetic methane supply is zero in other hours. In order for the region to be able to achieve its goal of energy neutrality in for example the energy demand for heating purposes, it would be essential to either substitute to non-gas based heating technology (i.e. electrification), or implement some form of hydrogen or methane-based storage.

Figure 45: Maximum H_2 admixing (0.5%) and CH4 injection in the gas system in the Stedendriehoek based on an 2.2 TWh per year electricity surplus in the region



4.4.5 Economic analysis

Figure 46 presents the production cost curves for the production of hydrogen and the production of synthetic methane as a function of the number of operating hours in a year. The range in the number of hours during which there is an electricity surplus in the Stedendriehoek region across the scenarios assessed in Section 4.2.3 is included. A viable business case for P2G with or without methanation requires a price of respectively €6.50 and € 4.50 per kg of hydrogen. In other words for P2G to be 'in the money', the allowed price should be higher than these two values.

Figure 46: Production cost of hydrogen (left) and synthetic methane (right) in 2030

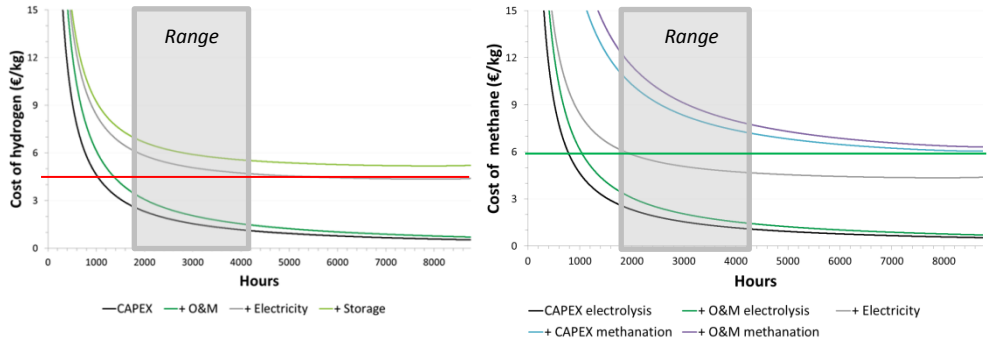
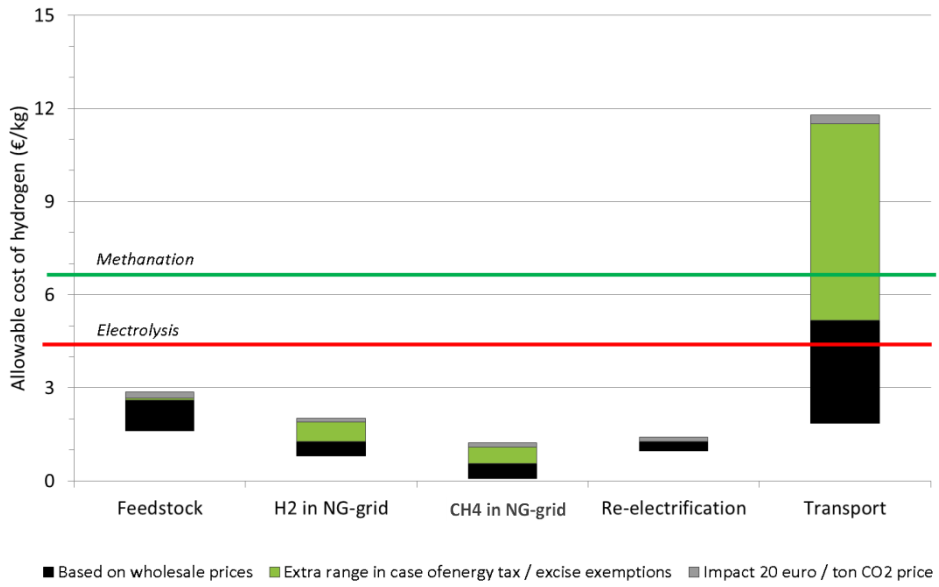


Figure 47 shows how the minimum cost of electrolysis-based hydrogen and synthetic methane compare with the allowed cost for hydrogen or synthetic methane for different applications (i.e. what are the market prices against which hydrogen and synthetic methane need to compete?). The CO_2 price for 2030 is assumed at a level of €20 per ton. From the applications considered only the use of hydrogen or methane in the transport sector may be viable if some degree of tax or excise exemptions are imposed on these energy carriers. Other applications are not in the money by far. In the

next paragraphs we investigate whether avoided network costs (that may be attributed to the implementation of P2G) or higher CO_2 prices can make a difference in the economic viability of applications.

Figure 47: Economics of P2G alternatives: the allowable cost of hydrogen for different applications



P2G as alternative to network reinforcement?

For determining the potential size of the flexibility challenge and the required investment in additional network capacity that may be associated with it is relevant to assess the geographical dispersion of solar PV and wind turbines and the existing electricity infrastructure lay-out and capacity. This will impact both the size of the flexibility challenge at the different nodes in the electricity network and will affect the level of additional network investments that may be required. Apart from the distinction between distribution and transmission assets, also the fact that two different distribution network operators are involved in this region matters for the optimal integration of new generation assets within the region.

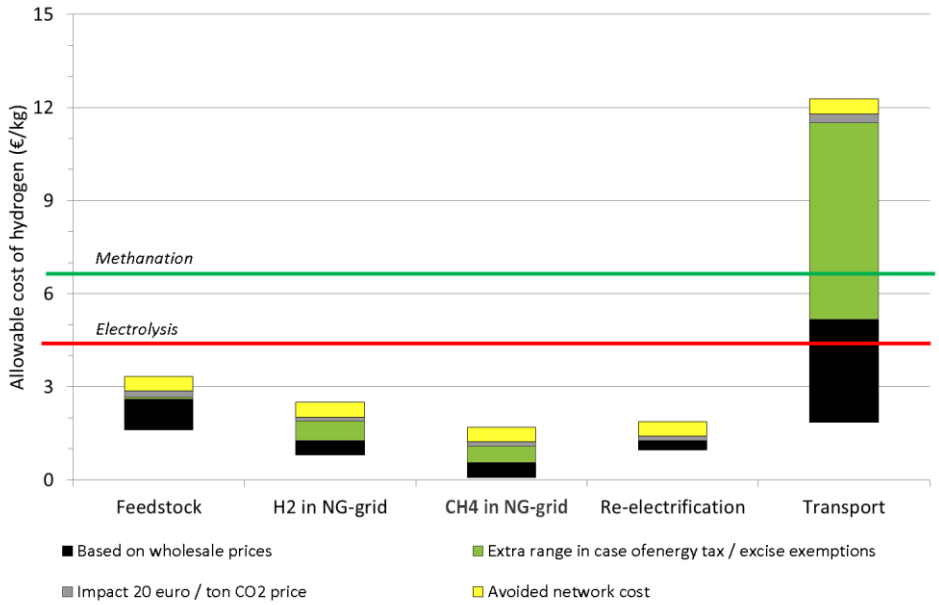
Although it is beyond the scope of this case study to go into these more detailed aspects, it is important for the economic assessment of the role P2G could play to get a feeling for the order of magnitude of the potential benefit of avoiding necessary network upgrades. For this purpose we will use estimates from Ecorys (2014) for network costs related to the integration of wind and solar PV. The cost benefit analysis of energy neutrality in the region in 2030 performed by Ecorys evaluates the additional network cost in the three different scenarios investigated. Based on their calculations we find that the annual network cost varies between €21 - 49 million.[38]

Based on these investment cost estimates for network expansion we may derive an indication of the potential avoided cost of applying P2G. Relating the investment costs

[38] Scenario 1 (*'Maximaal zon'*): €49.2 million for the integration of 7,9 GWe solar PV and 30 MWe of onshore wind, Scenario 2 (*'Mix zon en wind'*): €21.4 million for the integration of 4.0 GWe solar PV and 1,1 GWe onshore wind; Scenario 3 (*'Zelfvoorzienend met wind en zon'*): €28.6 million for the integration of 5.0 GWe solar PV and 1,4 GWe onshore wind.

to the potential electricity surplus in the region in these three Ecorys scenarios (see **Table 22**) in terms of potential hydrogen supply, and using a number of standard assumptions[39], we find a possible avoided network cost estimate of about €0.33 – 0.47 per kilogram of hydrogen.[40] This cost element – which is a benefit for the P2G option – is included in **Figure 48**. We conclude that the avoided network cost component contributes to an improved economic viability, but does not change the overall picture: application of either hydrogen or synthetic methane in the transport sector remains the only possible application that could be economically viable.

Figure 48: Economics of P2G alternatives including the avoided network cost in case #3 of the Stedendriehoek region



Impact of higher CO_2 prices

The assumed CO_2 price of €20 per ton in 2030 may be considered realistic, but what could be the impact of a (much) higher CO_2 price in 2030, or later, say 2050? A higher CO_2 price in combination with the avoided network cost improves the business case for a P2G applications. **Figure 49** presents the results on the competitiveness of electrolysis based hydrogen and synthetic methane for CO_2 prices of €100 and €250 per ton. These CO_2 prices may be considered extreme, but from the model-based analysis in Chapter 3 we learned that the level of CO_2 shadow prices at which P2G options become part of the cost-optimal mix of energy technologies only starts at about €200 per ton (See **Figure 12**). According to the results in **Figure 49** a CO_2 price level of €250 per ton would make the use of electrolysis-based hydrogen in industry an economically viable option.

[39] Return on investment of 8%, economic lifetime of assets of 40 years, operational expenditures of 1% of capital expenditures.

[40] This range may be compared with the avoided transmission investment cost of €0.73 per kilogram of hydrogen in case #1 (Section 4.2.5).

Figure 49: Economics of P2G alternatives the Stedendriehoek region in the case of a CO_2 price of €100 (left) and €250 per ton

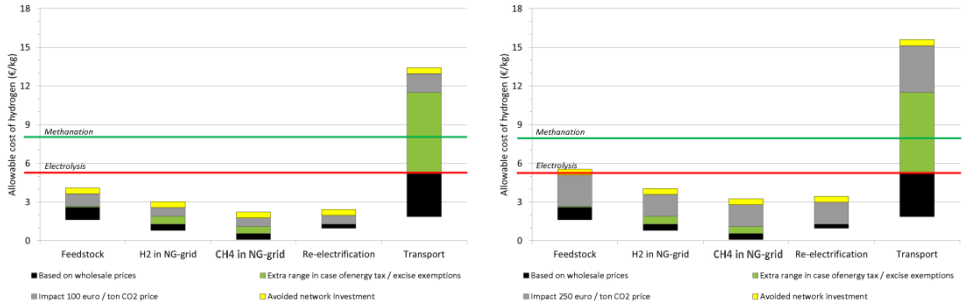


Table 25 contains the approximate CO_2 price levels required to make either hydrogen or synthetic methane competitive for the different applications. For hydrogen to be competitive across the range of applications a price level of about €200-500 is required, whereas the range is about €400-800 for synthetic methane. These figures do not take into account any benefit for P2G due to avoided network cost. If these would be included these price ranges may be about 5 to 10% lower.

Table 25: CO_2 price needed for economic viability of applications

Application	CO_2 price required for economic viability of	
	Electrolysis	Methanation
Feedstock in industry	≈ €200	≈ €410
H2 admixing in natural gas system	≈ €350	≈ €700
Methanation	≈ €490	≈ €800
Re-electrification	≈ €470	≈ €780
Transport	0	0

4.4.6 Conclusion

Achieving the ambitious target of the Stedendriehoek region to become energy neutral by 2040 requires a much larger use of the available onshore wind and solar PV potential in order to decarbonise the transport sector (through electrification or P2G) and heating demand (again through electrification and P2G). Given that existing electricity demand is comparatively low, the flexibility challenge in already 2030 could be considerable. However, this depends on the ability to implement a significant amount onshore wind and solar PV investments until then. If the required high levels of wind and solar-based electricity generation are realised by 2030, the electricity surplus in the region could amount to about 2-5 TWh in about 2,600-4,200 hours a year.

However, conform the conclusions of Ecorys (2014) the goal of energy neutrality comes ate a high cost. Economics indicate that the upgrading of existing electricity infrastructure needed for the integration of intermittent generation is relatively cheaper than applying P2G. The one alternative that could be economically viable, depending on prevailing tax and excise exemptions for hydrogen-based vehicles and /

or renewable transport technologies, the use of hydrogen in transport. In the longer term, P2G applications may become economically viable if strong climate policy pushes for CO_2 shadow prices in the range of €200-500 (in case of hydrogen use) or in the range of €400-800 (in case of synthetic methane use).

The Stedendriehoek may offer specific opportunities for P2G because of the declared energy neutrality goal. This possible leads to an increased availability of additional funding, or at least a certain willingness to provide relatively more funding for this technology development. A possible threat in the ambition of the region is the fact that achieving energy neutrality seems to be dependent on the success in realising onshore wind and solar projects on a large scale.

4.5 Synthesis and reflection on case studies

Based on the case study analyses in this chapter, the following key messages may be formulated.

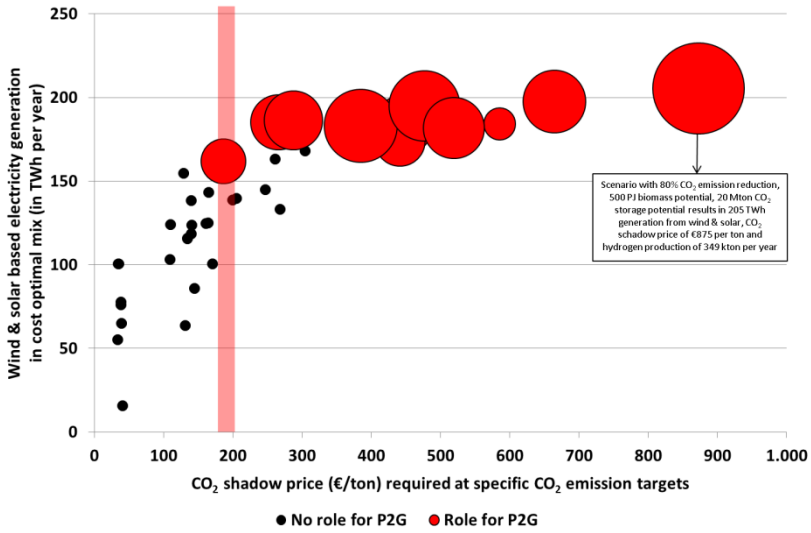
It is difficult for local circumstances to make the difference in P2G economics
The case study analyses use specific local information with regard to networks and infrastructure, local energy demand and supply, while using fixed assumptions regarding the overall system (electricity prices, supply patterns, CO_2 price, etc.). We may conclude that for a viable business case system factors are dominant over local factors. Firstly, alternative local / regional solutions for a flexibility challenge – if there is any significant challenge there in the first place – seem to be more economic than P2G. This concerns for example electricity network upgrades (in case #1 and case #3) and the flexible use of electric steam boilers (in case #2). Case 1 and case 3 demonstrated that attributing avoided network cost to P2G does not sufficiently improve the economics of adopting P2G for different applications, even though the benefit may be in the range of €0.30 -€0.80 per kg of hydrogen. Secondly, it is the CO_2 price that makes the real difference: an economically viable P2G business case requires a CO_2 price in the range of €200-500 per ton.

Case studies and model analyses complement each other and confirm each other's findings
The model-based system analysis explored the wider energy system context (technology developments, overall low-carbon and flexibility potentials, fuel prices, etc.), while the case studies explored specific local circumstances (related to infrastructure, electricity demand and supply, etc.). The results acquired through these different approaches confirm each other:

1. Required CO_2 prices for a viable business case are in the same range (€200-500 per ton for hydrogen, €400-800 per ton for synthetic methane);
2. Required operating time for a viable business case are in the same range (>4,500 hours).

Figure 50 illustrates the first observation. It contains the model-based results that were already presented in **Figure 12** but now includes the required cost ranges found to be necessary for viable P2G business cases in the case studies.

Figure 50: 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



P2G business cases before 2030?

Given the conclusions that system factors seem to dominate local factors, and given the conclusion that relatively high CO_2 prices are required for a viable P2G business case, it is not remarkable that the case studies show it to be difficult to make a business case in 2030.

Even though a sufficiently high CO_2 price seems the dominant component for a viable business case, it can't be ruled out that within this time horizon a P2G business case may be possible. However, this would require a combination of significant, multiple local factors. Examples of such could be:

- Avoided cost of network investment at either the transmission or distribution level;
- A high (monetary) value attributed to the low carbon (green) character of hydrogen[41];
- A high (monetary) value attributed to the contribution of P2G in achieving energy neutrality / independence[42];
- Local demand – and associated monetary value – for other products generated in the electrolysis process (i.e. oxygen and / or heat).

A combination of system factors that may further enhance the business case perspective are:

- The CO_2 price: the higher the prevailing CO_2 price in 2030, the higher the likelihood of a viable business case;
- Flexibility / cost of electrolyser / methanation technology: the more flexible the underlying P2G technology, the more likely that any P2G application may capture additional benefits from delivering flexibility to the electricity system, thereby improving the business case.

[41] As mentioned in the case of a P2G application in the transport sector in the Rotterdam area.

[42] As mentioned in the case of the Stedendriehoek striving for energy neutrality by 2040.

P2G application perspectives

Under changing different system conditions the model-based analysis showed the uptake of P2G by different applications (i.e. hydrogen admixing, transport, industry and built environment) of which hydrogen admixing was considered the primary application. The case study analyses have demonstrated that using a bottom-up approach the application of P2G in the transport sector has the highest potential. Application in the transport sector is dependent on cost and availability of competing low carbon transport technologies. The latter were not considered in the case study analyses. The application of hydrogen admixing is crucially dependent on the restrictions for hydrogen admixing in the gas system. For the 2030 time horizon, the prevailing hydrogen admixing limit is expected to be rather restrictive as the limit set for 2023 is 0.5%. The model-based analysis explored the impact of 1%, 10% and 50% admixing limits.

5

Conclusions and recommendations

5.1 Conclusions

Based on this study the following conclusions are drawn.

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[43], which facilitates the use of renewable electricity[44] 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.[45] The importance of P2G as a conversion technology holds while alternative scenarios or assumptions vary[46]. 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

[43] 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').

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

[45] 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.

[46] 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.

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.

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. 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 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[47], 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.[48] 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.

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

[48] 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.

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 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[49]. 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[50] and it is therefore still impossible 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 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).

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).

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

[50] 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.

5.2 Recommendations

Based on this study the following recommendations are formulated.

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 lowest cost to society, it is necessary that the government arranges the right regulatory framework.[51] For example:

[51] 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.

- 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 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 analyzing 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 neighboring 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 neighboring 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.

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Abbreviations

AC	Alternating current
CAES	Compressed air energy storage
CCS	Carbon capture & storage
CHP	Combined heat and power
DC	Direct current
DSO	Distribution system operator
EV	Electric vehicle
FC	Fuel cell
GW	Gigawatt
HV	High voltage
Kg	Kilogram
Kton	Kiloton
kW	Kilowatt
Mton	Megaton
MW	Megawatt
MWh	Megawatt-hours
OPERA	Option Portfolio for Emissions Reduction Assessment
$P2CH_4$	Power-to-methane
P2G	Power-to-gas
$P2H_2$	Power-to-hydrogen
PM	Particulate matter
PV	Photo-voltaic
RCI	Rotterdam Climate Initiative
SER	Sociaal Economische Raad
SMR	Steam methane reforming
SNG	Synthetic natural gas
TSO	Transmission system operator
TW	Terawatt
TWh	Terawatt-hours
UK	United Kingdom
Yr	Year

Appendix A. Timeslice approach adopted in OPERA

Explanation of adopted Timeslice approach

Demand and (variable) supply profiles are input into the model with hourly resolution. This means that there are 8760 values per profile input into the model. Such a high temporal resolution would lead to excessive runtime and memory use of the model. It was therefore decided to decrease number of time periods used in the optimization loop by grouping the hours of the year into sets, called *timeslices*. The methodology and algorithms to allocate the hours of the year into timeslices have been devised to meet the following requirements:

- The set of timeslices should enable the identification of significant time periods where supply and demand vary (e.g. seasonal variations, daily variations);
- The set of timeslices should enable the identification of periods with shortage/excess of supply vs. demand;
- The user should have full flexibility in choosing the number of time slices in order to achieve the desired compromise between runtime and temporal resolution;
- The user should have full flexibility in choosing what the underlying criterion for the timeslices allocation is:
  1. Fixed time periods (seasonal and/or daily);
  2. Variations in the demand patterns for electricity, heat or total;
  3. Variations in the supply patterns for electricity, heat or total;
  4. Variations in the excess/shortage of supply vs. demand patterns for electricity, heat or total, and the possibility of using storage.

  For each of these 4 criteria a set of special *allocation indicators* has been built in the model. After running several tests it was established that the 4th criterion yields the most valuable output for the P2G project. Therefore the following paragraphs will focus exclusively on the description of the set of allocation indicators for this particular criterion.

Intermittent energy supply profiles

Hourly variable supply profiles concern electricity from wind energy and electricity and heat from solar energy. They are further specified per year (*y*), region (*r*), and option (*o*): $s(y,h,r,o_w)$ for wind profiles and $s(y,h,r,o_s)$ for solar profiles.

An aggregated wind (solar) supply profile per year is created by summing and normalizing all separate wind (solar) profiles:

$$s_w(y,h) = \frac{1}{N_w}\sum_{r,o_w} s(y,h,r,o_w)$$

$$s_s(y,h) = \frac{1}{N_s}\sum_{r,o_s} s(y,h,r,o_s)$$

where N_w and N_s are the normalization factors.

An overall aggregated supply profile is then created using the following equation:

$$s(y,h) = \frac{1}{N}\sqrt{s_w^2 + s_s^2}$$

where N is a normalization factor.

It is important to remark that the aggregated supply profile does not represent a physical quantity. It is used to construct the desired indicator. If new, or additional supply profiles are input in the model, the aggregated profile will change and this will influence the final indicator.

Energy demand profiles

Hourly demand profiles for electricity and heat are provided per year and sector. Following an analogous procedure as for the supply, aggregated profiles for electricity and heat demand, d_e and d_h respectively, are created by summing over the sectors and normalizing. An overall aggregated demand profile, d, is then created by taking the square root of the sum of squares and normalizing.

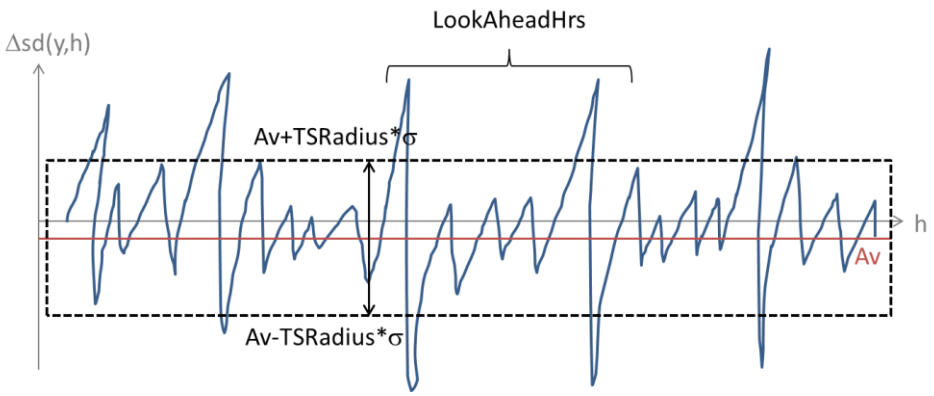
Allocation indicators

Based on the aggregated demand and supply profiles described above, the following allocation indicators have been created:

$$\Delta sd_e(y,h) = s(y,h) - d_e(y,h)$$
$$\Delta sd_h(y,h) = s(y,h) - d_h(y,h)$$
$$\Delta sd(y,h) = s(y,h) - d(y,h)$$

The first two indicators represent a probability of having an excess (positive values) or shortage (negative values) of supply vs. demand of electricity and heat, respectively. The last indicator represents the probability of of having an excess or shortage of overall supply vs. demand.

Allocation algorithm



The figure above shows a sketch of the Δsd indicator, and the parameters that are used by the algorithm to perform the timeslices allocation. The meaning of the different parameters and the procedure steps are briefly summarized in the following bullets:

- Av = Average of Δsd.
- σ = Standard deviation of Δsd.
- *TSRadius* controls the height of the black dashed rectangle; initial value = 1. The values outside the rectangle correspond to extreme situations. Maxima, or

valleys, are likely excesses of intermittent supply. Minima, or peaks, are likely shortages of intermittent supply vs. demand.

- *LookAheadHrs* controls how many hours to look from a maximum (peak outside the rectangle) to find a minimum (valley outside the rectangle); initial value = 24 hrs.
- The algorithm selects all peaks (valleys) outside the rectangle, and find all valleys (peaks) within *LookAheadHrs* (-*LookAheadHrs*) hours. These valleys and peaks are then stored in the first half of the timeslices, in ascending order depending on the value of AVDiff (hence first the valleys then the peaks). The remaining hours are stored in the rest of the timeslices, in ascending order depending on the value of AVDiff.
- All parameters can be adjusted in the model via the user interface, at the page 'TS Indicators - overview'.

The algorithms allows to isolate the hours where an excess of intermittent supply is likely to occur and a use for this excess is likely to arise in the near future. Analogously, the algorithm isolates the hours where a shortage of intermittent supply is likely to occur and this shortage can be "filled" with an excess supply from the near past. Depending on the degree of likely excess (shortage) and on the total number of timeslices, these hours are allocated within a certain timeslice.

Appendix B. SWOT analysis of P2G in the Eemshavendelta region

The Eemsdelta region is considered a suitable location for the implementation of P2G technology given the characteristics described earlier. Apart from an indicative, quantitative analysis on the near term P2G business case perspective for this region, a SWOT analysis was performed to identify the set of possible other drivers and bottlenecks. Herein the focus is on specific regional issues. The value that could be attached to the different elements highlighted in the SWOT-analysis is arbitrary. The sources used in performing this SWOT analysis include available documents and studies and implementing P2G in the Netherlands (CE Delft, 2012; Royal Haskoning / INTIS, 2013)[53] and insights gained at various meetings with representation of stakeholders that are interested or involved in P2G initiatives.

Strengths

- The location of the Eemsdelta region and the nearby border crossings of gas transmission pipelines and electricity transmission lines, as well as the position for national gas and electricity transmission;
- Growing capacity of electricity from wind parks connections coming to land in the Eemsdelta region;
- Electricity grid value retention and no specific need to discontinue operation of the existing (conventional) electricity plants in the Eemsdelta region;
- Local social acceptance for performing industrial activities in the Eemsdelta region
- Province of Groningen has an active and well developed knowledge infrastructure on innovations, focusing on energy and specifically on gas innovations;
- Social resistance for transmission line reinforcements as a result of high populated areas;
- Social acceptance for sustainability related projects to replace natural gas as a results of the recent earthquakes in the Province of Groningen;
- Solid financial position of the local authority Groningen Seaport which enables investments in the Eemsdelta region.

Weaknesses

- The addition of hydrogen to natural gas is restricted due to end-use requirements, which are generally the most restrictive conditions on increasing hydrogen blend levels;
- The benefits for hydrogen depend on the price levels and price volatility. Products as hydrogen with unstable demand, caused by the production character related to the level of curtailment, will experience price fluctuations;

[53] Groningen Sea Ports: http://www.groningen-seaports.com/LinkClick.aspx?fileticket=4axCbGgDZQ8%3D&tabid=2212&language=nl-NL

- The chicken-and-egg problem is likely to occur for hydrogen application in the mobility sector. Car manufacturers need to build vehicles that are affordable for hydrogen purposes. At the same time, an infrastructure of refilling stations is required for motorists;
- The hydrogen market for the industry is very specific and requires a certain purity, which is strict and may influence the supposed guaranteed demand;
- The CO_2 sources in the Eemsdelta region might not be able to provide sufficient purity and capacity and investments may be needed for capture and conditioning of CO_2.

Opportunities

- To develop a sustainable society the industry aims to develop knowledge and tools that help accelerate the transition towards a sustainable industrial system, whereof the derivate from P2G plants could be supportive;
- Hundreds acres of greenfield are available in the Eemsdelta region for the construction of P2G plants;
- The Eemsdelta region is appointed as potential site for geothermal applications, creating a sustainable demand for generated heat in P2G plants;
- The Eemsdelta region has a pool of well-trained and available multi-skilled and operational staff;
- The seaside location of the Eemsdelta region ensures cooling water capacity and water availability. Besides, this enables the connection to the maritime sector for hydrogen application;
- The construction of a biomass refinery plant (Woodspirit) is planned for the Eemsdelta region in which biomass will be torrified and gasified. The product of gasification is amongst others hydrogen, which is further processed to bio-methanol. Hydrogen as derivate from P2G plants can ensure the supply of hydrogen for a constant bio-methanol production;
- P2G could accelerate the installation of a hydrogen supply infrastructure and thereof solving the chicken-and-egg problem of the car manufacturers who need to build vehicles that are affordable for hydrogen purposes;
- The Eemsdelta is highly intensive industrial area resulting in a potential demand for oxygen to valorise the electrolysis step in P2G;
- The Eemsdelta region collaborates to sustain the harbor and the industry resulting in a strong incentive and contribution to regional CO_2 footprint reduction;
- The foundation of a specific and specialized organizational cluster focusing on the further development and deployed of P2G in North Netherlands, as part of SWITCH: the region specific energy plan;
- High social acceptance for P2G as a result of the recent earthquakes and the proposal to replaced natural gas production by sustainable gas production, like P2G.

Threats

- The recent constructions of electricity generation plant in the Eemshaven delta influence the location perspectives for P2G in these regions;
- Occasionally, earthquakes take place in the Groningen region as a result of gas production and exploration which can affect the secured operability of gas pipelines;
- Increasing the electricity grid net capacity from the Eemsdelta region to supply side areas;
- No or relatively small incentive for ‘green’ derivates of P2G as a results of the unclearness of the EU-ETS system concerning CH_4 via P2G;
- Existing SMR plant for baseload and relatively low-cost production of hydrogen.

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