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

D7.6

Full CBA analysis of power-to-gas in the context of various reference scenarios

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Content

Executive Summary

Research question

Power-to-gas (PtG) is a promising technology that could be useful in the transition to a much less CO_2 intensive economy. However, given current technological levels and market conditions, PtG technologies might not get adopted sufficiently from a societal perspective. Current market conditions, including the regulatory regime and CO_2 prices, do not favour the implementation of PtG. Furthermore, PtG requires further technological progress to reduce its cost and to bring it to a higher technological readiness level. Such technological progress may still take several years, since the general nature of innovation processes mean that i) the revenues for individual projects are quite uncertain (the risk for investors is high) and that ii) knowledge spill-overs prevent the benefits of the R&D to fall entirely to the investors. In order to overcome these barriers, public support will be necessary to bring the PtG technology to the market.

The current report presents a social cost benefit analysis based on energy system modelling for the European Union until 2050 for various scenarios. Both external effects (security of supply and environmental impacts) and private costs and benefits (energy system costs) are analysed and combined. The report focusses at the following research question: *What are the social costs and benefits of PtG in the European context under various scenarios?*

PtG is defined here as transforming electrical power via electrolysis into hydrogen and subsequently deploying methanation for making synthetic natural gas. The process without methanation, i.e. only electrolyzing water to generate hydrogen, is not studied separately, although it is of course part of the future energy systems analysed.

Research method

A social cost benefit analysis (SCBA) quantifies and monetarizes (values) all effects for the whole society. If benefits exceed the costs the project is welfare improving. Crucial is that the effects for the whole society are considered and not only the effects for the investor. Effects are the difference between the development *with* the project i.e. deployment of PtG and development *without* the project i.e. without PtG (the counterfactual). Negative effects are costs and positive effects are benefits.

Crucial in evaluating long run projects, like this one, is the height of the discount rate since future benefits and costs are made comparable to current benefits and costs by discounting. Since effects for the whole society are considered in a SCBA, in this case a social discount rate is most suited. Hence, we do not apply a private discount rate, which lies usually above the social discount rate. The social discount rate chosen is based on the European guideline for cost benefit analysis. That is, a discount rate of 4% is used which is the unweighted average of the discount rate for cohesion and other EU member states.

The report builds upon earlier contributions of the European research project STORE&GO, especially the energy system modelling and scenario analysis of [1], the environmental analysis using Life Cycle Analysis of PtG technology [3], and the security of supply study [4]. References [3] and [4] build upon the quantification of effects by JRC-EU-TIMES model in [1] as well, making all diverse inputs in the SCBA consistent.

Four different scenarios for Europe until 2050 are analysed: a positive scenario concerning the deployment of PtG, a so-called realistic scenario with still favourable conditions for PtG, an alternative scenario, and a pessimistic scenario. All scenarios studied target at 95 percent CO_2 emission reduction in 2050. Note that the scenario names are logical from a technology perspective rather than from a system perspective; optimistic thus means that PtG is applied most, while for most observers this would be the most pessimistic scenario as it is characterised by many system constraints and energy system costs that are the highest of all scenarios (the probability that these all happen simultaneously is relatively low). Thus if circumstances are the most detrimental to achieving 95% GHG emission reduction, having PtG available is the most advantageous.

These scenarios are quantitatively analysed with the JRC-EU-TIMES model, which contains an extensive energy system representation for the EU28+ and distinguishes six sectors; the power, commercial, industry, residential, transport and agriculture (only energy consumption) sectors respectively. Given system optimization, the model shows how the transition to a low carbon system could develop until the year 2050 with a focus on technology choices and associated costs. For each scenario, two versions were investigated, one with PtG technologies (i.e. methanation) in place and one without methanation. Comparing these two scenarios delivers the quantitative energy system effects i.e. costs and benefits of PtG.

Apart from energy system costs and benefits, societal effects such as effects on energy security, the environment, employment, and economic growth are analysed. Subsequently, if possible, effects are valued using (shadow) prices. Valuation of effects is where relevant based on market prices (the energy system costs), and if those are not available either non-market valuation techniques or non-market values from the literature are applied. Compared to D6.3 [1] instead of a private discount rate deployed from the business perspective the much lower societal discount rate is applied. This increases the deployment and utilization of PtG.

Main effects and results

The main effects of PtG deployment are:

- PtG lowers the total costs of the energy system with € 68 billion annually in the optimistic scenario in 2050 (2 percent of the total costs of the energy system), that is it prevents more expensive investments or higher operational costs in other parts of the energy system;
- PtG increases the energy security of the energy system by lowering price sensitivity or lowering the probability of shortages of energy during periods of low wind and solar energy production in Europe (“Dunkelflaute” i.e. dark doldrums);
- Deploying PtG in the energy system increases some environmental effects (like land use) while it reduces the impact on other environmental aspects (like climate change effects outside the energy system). When the quantities are valued, mostly using 2015 prices, except for CO_2 emissions, the environmental benefits of PtG exceed the costs.
- There are no benefits in terms of employment or demand induced stimuli of the economy. Both effects are often mentioned as benefits of energy transitions. However, these are most likely offset by countervailing reductions in employment and economic activities via markets. In addition, the economic stimulus of adding PtG to the system is negative, i.e. the savings in the energy system exceed the extra expenses on PtG technologies.
- PtG could ease bottlenecks in the electricity grids and allow inclusion of renewable energy at lower costs.
- Finally, there are two other potential effects. The first is the effect on economic growth via technological improvement and the second are the costs of government action to stimulate the development and deployment of PtG. The first effect is positive for European social welfare, the second negative. These effects could neither be quantified nor monetarized. Both effects are likely to be small, and without impact on the overall conclusion.

Table S-1 contains the main results of the CBA for 2040 and 2050 (each year is representative for the decade around it). It shows that:

- PtG has a positive contribution to European welfare in 2040 and especially 2050 in two possible scenarios, with the total effect in the optimistic scenario substantially exceeding the effect in the realistic scenario. PtG has a slightly negative welfare contribution in the alternative and the pessimistic scenario, since the government invests a bit in developing PtG technologies before it is known how the future evolves, i.e. which scenario is reality. Government backed investments in PtG are likely to be a fraction of the total net benefits in the optimistic and realistic scenario. Therefore the PtG technology should be part of the portfolio of technologies to be further developed, especially to hedge against conditions where it is hard to achieve 95% GHG emission reduction. The analogy with an insurance is strong: people buy an insurance to use under adverse circumstances, not under all or under favourite circumstances.
- Note that there are no cost quantified in the table. The R&D costs necessary to further develop PtG technologies cannot be quantified, therefore they are only included in a qualitative way. Only quantified benefits might seem surprising, is partly inevitable and partly simply the result of the analysis. That PtG leads to cost savings in the energy system is logical given the cost minimizing nature of the model used and the addition of a technology. That PtG also has benefits for security of supply and the environment is a consequence of the analysis, and could have been different given that these are external effects for the energy system.
- The total effect in 2050 is substantially bigger than in 2040, which is in line with the late adoption of this technology in the energy system in earlier STORE&GO analyses.
- The net environmental benefits of PtG in the energy system can be substantially larger than the effects of PtG on the energy system costs. The benefit PtG has for the security of supply is likely to be smaller than the reduction of the energy system costs caused by PtG.
- Two other effects that could not be quantified or monetarized (the growth effect and the costs of government action) are both likely to be small, and without impact on the conclusion.
- The distribution of effects cannot be shown in detail (that requires much more detailed modelling of pricing and government intervention than currently possible). However, it is clear that much of the benefits of PtG end up with other parties than the investors, giving rise to substantial external effects. This is most obvious from the security of supply benefits and the environmental effects that end up with society (via the economy and the environment respectively). Since quite some of the benefits do not end up with the investors in PtG, it is likely that investments in PtG are lower than socially optimal and that government policy aimed at increasing the development and adoption of PtG technologies is welfare improving, especially if scenarios with many constraints for achieving 95% GHG emission reduction become reality.

Table S-1: CBA – midpoint estimate, 2040 and 2050, in billion euro per year

	2040				**2050**			
Effects	Opti-mistic	Real-istic	Alter-native	Pessi-mistic	Opti-mistic	Real-istic	Alter-native	Pessi-mistic
System cost savings	7	0	0	0	68	4	0	0
Security of supply benefits	5	0	0	0	28	3	0	0
Environmental effects	17	0	0	0	93	31	0	0
GDP and employment effects	0	0	0	0	0	0	0	0
Grid effects	+	0	0	0	++	+	0	0
Growth	+	0	0	0	+	+	0	0
Cost of government action	-	-	-	-	-	-	-	-
Total	28 ++-	-	-	-	189 +++-	38 ++-	-	-

Note: Due to rounding, some totals may not correspond with the sum of the separate figures.
Note: In the bottom row the '+' and '-' signs just aggregate the same signs in that column without weighting these unquantified effects.

In addition, a sensitivity analysis is performed given lower and higher estimates for all identified effects. This sensitivity analysis does not change the main conclusion of the analysis based upon midpoint values; PtG contributes positively to European welfare in 2040 and especially in 2050 in the optimistic scenario and to a lesser degree in the realistic scenario. The effects increase over time with the deployment of PtG. The alternative and the pessimistic scenario have a slightly negative outcome because of the cost of government action to develop PtG is an expense before if and when it is known which scenario becomes reality.

This sensitivity analysis also shows that the uncertainty regarding the outcomes is substantial. The magnitude of the uncertainty is substantial, however, the sign does not change, so the impact on the conclusion is limited. The uncertainty is coming from price (or value) uncertainty; with no quantity uncertainty being present since JRC-EU-TIMES only gives a best estimate for each scenario. In reality the quantities are uncertain as well, so the uncertainty of the outcome is larger than can be depicted.

Finally, note that the estimation of especially security of supply benefit and the environmental impacts depends crucially on assumptions and on extrapolating methods to different countries and time periods. Sometimes these extrapolations and assumptions were stretching the boundaries of what could be done reasonably. However, otherwise arriving at a value for these effects would be impossible. The fact that the outcome is always positive provides confidence in the outcome. Still, the outcomes should serve as an indication, whereas future research and additional insights are necessary to perform more detailed estimates once PtG technology develops further.

Policy implications

Before PtG can contribute to European welfare, it has to overcome two clear bottlenecks. First, the existence of external effects make that private investors have a too small incentive to invest. External effects identified are security of supply benefits and environmental benefits, but also quite some of the benefits in the energy system do not fall with investors in PtG. Second, application of PtG requires, in comparison to the current situation, substantially improved efficiency in both production of hydrogen and in the methanation phase.

In order to overcome these bottlenecks, policy measures are necessary. The first set of policy measures should stimulate private investors to take into account positive and negative societal effects in private decisions ('internalization of external effects'). The government should stimulate this through subsidizing positive external effects i.e. effects on security of supply and the environment, and taxing negative external effects (for instance, on the environment). One other option to consider when designing these measures in detail is to create a standard. For example, requirements on back up capacity for more variable and less predictable renewable energy might create an incentive to develop more storage with PtG being one of the useful technologies.

The second set of measures should target the required improved efficiency of the production of hydrogen and methanation. Improving efficiency requires more research and development, pilot projects, and initial production at non-market based conditions. Partly this falls under the general R&D stimulation policies in European countries (like existing tax credits for R&D expenditures), but also specific subsidies, public funding or co-funding of research projects aiming at increasing efficiency of the PtG technologies will be necessary.

1 Introduction

Power-to-gas (PtG) is a promising technology that could be useful in the transition to a much less CO_2 intensive economy. However, given current technological levels and market conditions, PtG technologies might not get adopted sufficiently from a societal perspective. Current market conditions including the regulatory regime and CO_2 prices, do not favour the implementation of PtG. Furthermore, PtG requires further technological progress to reduce its cost and to bring it to a higher technological readiness level; PtG has currently a TRL 5 level, and is reaching TRL 6-7. Such technological progress may still take several years, the general nature of innovation processes mean that i) the revenues for individual projects are quite uncertain (the risk for investors is high) and ii) has knowledge spill-overs preventing the benefits of the R&D to fall entirely to the investor. To overcome these barriers public support will be necessary to bring the PtG technology to the market.

In order to analyse whether PtG technologies contribute to European welfare and under what circumstances, the current report presents a social cost benefit analysis based on an energy system modelling for the European Union until 2050 for various scenarios. Both external effects (security of supply and life cycle impacts) and private costs and benefits (energy system costs) are analysed and combined. Based upon the SCBA this report should answer the following research question:

> *What are the social costs and benefits of PtG in the European context under various scenarios?*

PtG is defined here as transforming electrical power via electrolysis into hydrogen and subsequently deploying methanation for making synthetic natural gas. The process without methanation, i.e. only electrolyzing water to generate hydrogen, is not studied separately, although it is of course part of the future energy system analysed. Therefore, PtG and Power-to-Methane (PtM) are interchangeably used in this deliverable.

The report builds upon earlier deliverables of the STORE&GO European research project, especially D6.3 on the energy system modelling and scenario analysis of [1] and the following publication [2], D5.8 on the Life Cycle analysis of PtG [3] and D7.4 on security of supply study [4]. [3] and [4] are based on [1] as well, making all diverse inputs in the SCBA consistent. Quantification of effects is based on JRC-EU-TIMES, the LCA analysis supplemented with additional estimations to fill in gaps (mostly in the security of supply estimation). Valuation is where relevant based on market prices (the energy system costs), and in other cases based on non-market valuation techniques and if possible non-market values found in the literature. The current deliverable extends the previous deliverables in several ways. First, it creates an overview by integrating the separate elements. Second, it adds a valuation to the environmental analysis. Third, it has a clear focus and shows the impact of PtG by comparing the scenarios with and without methanation.

The scenarios used all target 95 percent CO_2 reduction in 2050 in line with the current EU 2050 energy strategy.[1] The calculations are based upon outputs from the JRC-EU-TIMES model, which contains an extensive energy system representation on European scale.

The report is structured as follows:

- Section 2 is devoted to the research methods applied. First, social cost benefit analysis is discussed followed by the choice of the social discount rate used. Next, the energy system model (JRC-EU-TIMES) and the scenarios are discussed.
- Section 3 discusses the main effects of having PtG versus not having PtG, and quantifies and values the effects.
- Section 4 presents the main results, discusses the policy recommendations and gives suggestions for future research.

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[1] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy

2 Research methodology

This chapter describes first the research methodology of social cost benefit analysis (Section 2.1) and the discount rate, which is a key parameter in these calculations (Section 2.2). This is followed by a short description of the energy system model used (JRC-EU-TIMES; Section 2.3), and the scenarios that are analysed using this model (Section 2.4).

2.1 Social cost benefit analysis

Social cost benefit analysis is a valuable tool for assessing the impact of a specific policy measure on welfare. A social cost benefit analysis (SCBA) quantifies and monetizes as far as possible all effects of the policy measure on society as a whole.

Important contributions to the SCBA literature include Brent (2006[5]), Salanié (2000[6]), and especially Layard and Glaister (1994[7]). Eijgenraam et al. (2000[8]) and the European Commission (2014[9]) compiled useful handbooks for SCBAs concerning infrastructural projects. Romijn and Renes (2013[10]) generalized the framework towards other policy measures.

SCBA is not always clearly defined. The definitions employed in the literature often vary and are sometimes even complementary. Layard and Glaister (1994, p. 1[7]) propose a basic definition of the SCBA: 'If we have to decide whether we do A or not, the rule is: Do A if the benefits exceed those of the next best course of action and not otherwise. If we apply this rule to all possible choices, we shall generate the largest possible benefits, given the constraints within which we live.' Aspects frequently recurring in the definition are ([11]):

(i) that the SCBA orders possible projects in a way that is informative about desirable social choices for decision makers;

(ii) that the SCBA finds that a project is attractive if its benefits exceed its costs;

(iii) that the SCBA includes the effects on society as a whole, not just the isolated effects on the decision maker;

(iv) that the SCBA uses the concepts of willingness-to-pay and willingness-to-accept to quantify costs and benefits (which tend to deviate from market prices)[2];

(v) that the SCBA uses the concept of opportunity costs[3];

(vi) that the SCBA focuses on monetary values because monetary values help aggregating and comparing effects;

(vii) that the SCBA uses the social discount rate rather than the interest rate to aggregate effects over time.

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[2] The Willingness to pay (WTP) is the maximum price at or below which a consumer (or company) will buy one unit of a product. The willingness to accept (WTA) is the minimum amount of money that a person (or company) is willing to accept to abandon a good or to put up with something negative, such as pollution. The price of any transaction will thus be any point between a buyer's willingness to pay and a seller's willingness to accept. The net difference between WTP and WTA is the social surplus created by the trading of goods. (see https://en.wikipedia.org).

[3] The opportunity cost of a choice is the value of the most valuable alternative choice that cannot be enjoyed if this specific choice is made.

Mathematically, an SCBA reduces to calculating the net present value (NPV) of all benefits (B) and costs (C) for the entire society occurring in year *t*, discounting future costs and benefits at the discount rate *d* since future values are worth less than current values. The resulting Net Present Value (NPV) is given by the equation below.

$$NPV = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+d)^t}$$

If the NPV is positive, the policy alternative is a welfare improvement compared to the counterfactual: a society in a given region or country gains from the project because the project's benefits exceed its costs. However, in practice there are several good reasons why politicians may choose to act differently, for example distributional effects and budget constraints requiring a choice between several positive projects. The process of doing an SCBA is broken down into varying sequences of steps. The general procedure (illustrated in Figure 2-1) is that before a SCBA is carried out, it should be made clear (i) why there is a market failure that needs to be addressed by public policymaking in the first place, what causes the market failure, and which solutions are available to address it. The latter implies that it should be made clear which alternative policy measures are available to address the issue at hand. In the context of PtG a lot of technological progress is required with potential positive external effects (knowledge spillovers) [12] and long-time horizons in combination with substantial uncertainty, potentially leading to private investors underinvesting in the technological development and thus making the case for potential government policy [13]. In the next step (ii), these alternative policies should be defined along with, as well as a base case (also referred to as the counterfactual) in which no new policy is in place. All potentially relevant project alternatives should be included in this process. In doing the actual analysis (iii), the effects should be assessed in terms of the difference between the counterfactual, and how the world will most likely develop with a particular project alternative in place. This might also involve taking market responses into account, for example resulting in price changes. Next, each identified effect should be monetized, aggregated by actor and over time. Finally (iv), a sensitivity analysis to assess the impact of the key assumptions made in the process and a discussion of the distribution of effects over different actors are useful extensions of the SCBA.

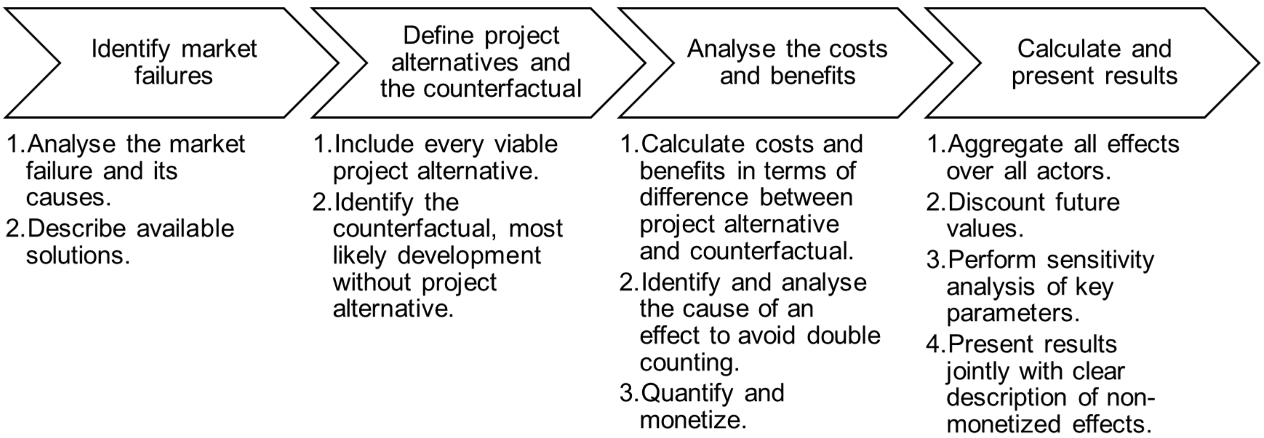

Figure 2-1: General SCBA process[4]

[4] Source: authors, based on the literature mentioned in the text.

2.2 Discount rate

One of the key parameters in a SCBA with a large impact is the discount rate. In a SCBA costs and benefits in different years are aggregated into one number. The further values (costs or benefits) are in the future, the less valuable they are today, i.e. they are discounted. That future values are less valuable than current ones has a number of reasons, like the pure time preference (current values are worth more than future ones), the opportunity costs of capital (current monetary values can be invested and have a positive return), and risk aversion. The factor with which future values are discounted is the discount rate (sometimes also referred to as the interest rate).

Crucial in this discounting is the level of the discount rate. It is one of the parameters with the highest impact on the outcome of a social cost benefit analysis, especially if long time periods are studied. For example if € 100 in 30 years from now is discounted at 3 percent the present value is € 41, at 5 percent the present value is € 23, at 7 the present value drops to € 14 and at 10 percent the present value is € 6.

In determining the correct discount rate there are two questions relevant:

1. Should the private or the social discount rate be used?
2. Given the type of discount rate chosen, what is its correct level?

Both questions will be discussed below, followed by the discount rate to be used in this study.

Private or social discount rate?

The aim of this full CBA analysis of power-to-gas in the context of various reference scenarios is to show what the cost and benefits for society are of having developed power-to-gas technologies versus the situation that these technologies are not developed. This approach is applied to various scenarios and by minimizing the costs of the energy system given technical and economic constraints as included in the energy system model [1]. The aim is to provide policy makers with a compass to steer and adjust their PtG policies. The same approach is also followed by EU (2015) [19] in the context of option analysis as part of the feasibility analysis which in fact is the fourth and fifth step of the CBA methodology outlined elsewhere i.e. determine effects, benefits and costs. It starts off by stating that “option analysis is performed to assess and compare different alternative options which are found generally feasible to meet the existing and future demand for the project and to find the best solution.” Key aspects of selecting the best option include that “if the output and externalities are different in different options (assuming all share the same objective), the Member State is encouraged to undertake a simplified CBA for all main options to select the best option *by determining which option is more favorable from a socio-economic point of view and the selection should be based on economic parameters of a project, including its Economic Net Present Value (ENPV)*.” [emphasis added]. EU (2015 [19]) distinguishes between financial and economic indicators highlighting the project economic performance from a private and social (economy wide) perspective respectively. The ENPV constitutes the NPV from an economy wide or social perspective. Hence, the social costs and benefits as a result of social optimal actions are the input we need for our social cost benefit analysis. These social cost arise because of the social costs of capital and the social costs of time preference. These social benefits and costs can only be determined using a social discount rate.

As a next step, the private discount rate can be used in the simulations. Using the social discount rate may give a result that leads to either underestimating the costs or not achieving the target for deployment of a technology since private actors are governed by private discount rates rather than the social one. The private discount rate exceeds the social one since the former includes market risks, taxes, and higher premia for default risk.[5] However, applying a private discount rate in first instance would answer a different type of question; it primarily provides insights in what actions should be taken by private actors to optimize their profits simultaneously ('simulation perspective'), rather than what should happen to achieve a certain goal to maximize social welfare ('optimization perspective'). The simulation with private discount rates can then be compared with the optimization with the social discount rate to see whether the government should change its policies (taxes, subsidies, norms, rules, regulations, etc.), and if yes, which one. Analyses with the private discount rate are performed as part of other parts of STORE&GO (WP8) and are not discussed here.

These two steps mimic the policy process as well. Policy makers often aim about minimizing social costs, and then look at which policies it should apply to achieve this result. Minimizing social costs is therefore a useful input in the policy decision.

As a conclusion for the social cost-benefit analysis aiming for achieving GHG emission reduction against lowest social costs ('cost optimization') application of social discount rates is strongly preferred above using private discount rates.[6]

Appropriate level of discount rate: theoretical background and application in practise

Given the need for deployment of a social discount rate, the next question is about its appropriate level for our analysis. Determining the level is difficult from a theoretical and practical perspective. We first highlight a few theoretical issues, followed by a description of the actual approach followed in various countries. This shows a wide range of values applied. In the next section we derive, based on these values in use, the optimal discount rate for this study.

From a theoretical perspective, Brent [5] discusses how setting the social discount rate involves intertemporal weighing. The market rate of interest cannot be used to measure the social discount rate, hence the social opportunity costs rate (SOCR) and the social time preference rate (STPR) are the main candidates. The social opportunity costs rate (SOCR) is the alternative return that investments in the project might have elsewhere in the economy, either using the return on capital (i.e. producer rate of interest) or the government interest rate. The social time preference rate is the social marginal rate of substitution as defined by a social welfare function. The social marginal rate of substitution is the rate at which society can give up some amount of one good in exchange for another good while maintaining the same level of utility. For more in depth treatment of these concepts see [5], [7]. Brent concludes that the STPR approach is to be preferred. However, the debate is not concluded and discounts rates advised can vary widely, say between 3 to 20 or 25 percent ([5], p. 365) with the low values based on the STPR approach and the high values based on the SOCR approach; in practice the rates used are on the lower part of this range (0-12 %).

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[5] From a private perspective the corporate taxes paid increase the costs and thus the required discount rate, while these taxes are a transfer from societal point of view and thus do not impact the social discount rate.

[6] At the same time, this is rather difficult and complicated task for two reasons;

a. All factors that influence decision of private partners need to be estimated (taxes, subsidies, norms, rules, regulations etc.), and these factors need to be set very precisely in order to simulate realistic stakeholder behaviour. This is often an insurmountable task, even with huge efforts. This holds especially when looking at large policy changes (like decarbonization of the economy) over a long time period. Hence, in practice private discount rates are often fairly subjective set at artificial values for which it is unclear how they relate to existing barriers and policies. It is an easy button to smuggle all type of considerations which are not yet explicitly modelled in a model, however it blurs modelling results and therefore distorts SCBA results.

b. Taxes and subsidies imply redistribution between system users, they do not induce any welfare gains, as such minimizing private costs does not result in a societal optimum. Also end-user prices for different demand sectors usually include taxes or subsidies, and therefore bring redistribution components in the analysis that are inconsistent with an optimization from a societal perspective.

Stiglitz [14] in a more in-depth analysis shows that the social discount rate does not need to be equal to (i) the consumer rate of interest based on the consumers' marginal rate of substitution, and perfect capital markets (ii) the producer rate of interest based on the producers marginal rate of transformation, (iii) social rate of time preference. He analyses the effects of several potential market failures on the social discount rate. Examples of the market failures analysis are the fact that the output of public project is often a public good, and the marginal rate of substitution of public goods at different moments might well differ from that of private consumption goods, limitations to the (lump sum) taxation possible, constraints on savings, and imperfections in the risk markets. Stiglitz concludes that no general validity of any simple rule might exist.

As a result from a theoretical point of view the perfect discount rate might not exist.[7] From a practical point of view choosing a discount rate is inevitable. As can be expected, given that lack of theoretical consensus, a wide variation of discount rates is used.

The US Office of Management and Budget (OMB) recommends since 2003 the use of two discount rates of 3 and 7 percent. The lower rate is an estimate of the social rate of time preference, proxied by the average return to 10 years government bonds (In US : treasury bonds). The 7 percent discount rate is the estimate of the opportunity costs of capital, proxied by the average before tax rate of return to private capital ([15][16]). Sometimes the discount rate prescribed depends on the topic analysed: the OMB guidelines recommend a base discount rate of 7% for investment analyses but recommend both 3% and 7% for regulatory analyses ([17]).

In the United Kingdom, the discount rate is based on the Ramsey formula[8] and estimated at 3.5 percent during the first 30 years and declining after that period. The French discount rate is based on the same Ramsey formula, but estimates for the French economy yield a discount rate of 4% for the first 30 years ([15]). In Europe many different discount rates are used see for example Hermelink and De Jager (2015) ([18]).

The EU (2015, p. 50, [19]) prescribes the application of a social discount rate of 5% in cohesion countries (Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia, Slovenia) and 3% in other Member States (Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Spain, Sweden, United Kingdom).[9] These percentages have been calculated on the basis of the social rate of

[7] A further complication is that for specific public projects the discount rate will also be influenced by uncertainty. The more uncertain future amounts are, the larger should be the compensation for the public investor(s), and thus the mark-up on top of the risk free discount rate. In order to determine an appropriate mark up for the risk a distinction should be made between two types of risks; macroeconomic risks and project specific risks. Risks that can be diversified away have no impact on the welfare in a country whereas risks that cannot be diversified away reduce the welfare. Ideally the risks should be determined separately for each cost and benefit stream, because benefits and costs can correlate differently with macroeconomic movements as reflected in so-called beta's. However in practice this is impossible. Since risks will be project or sector specific, the risk premium is usually set on a project-by-project or sector-by-sector base. Hence, costs and benefits of a project or sector correlate differently with macroeconomic movements as reflected in so-called bèta's. Consequently, given the Capital Asset Pricing Model (CAPM) a standard risk premium given a certain bèta is added to the risk free discount rate. Practically determining the bèta for public policy is complicated for public policy; in the Netherlands the simplifying assumption is used of beta equal to one ([10][10]).

[8] The Ramsey formula connects time preference, marginal utility of income and consumption in its most fundamental form.

[9] EU (2014 [9]) states that Member States may establish a benchmark for the SDR which deviates from the discount rates mentioned if (i) justification is provided for this reference on the basis of an economic growth forecast and other parameters; and (ii) their consistent application is ensured across similar projects in the same country, region or sector.

time preference (SRTP) method. Using estimates of preferences of consumers and an estimate of the long term economic growth, the Ramsey rule (Ramsey, 1928, [20]) can be applied to derive an estimate for the discount rate (EU, 2014[9]; Dutch Ministry of Finance, 2015[21]).

Moreover, for environmental regulations or analyses that span multiple generations, such as climate change or ozone depleting substances, should be treated differently. Indeed a positive discount rate implies that preferences of current generations are higher valued than preferences of future generations which should be prevented. Accordingly, for analyses of long lasting intergenerational effects sometimes lower discount rates are applied or discount rates that decline over time, the latter being the case in the UK and France, amongst others ([17]). In the context of climate policy (Drupp et al. 2018 [22]) survey what economist would recommend as a discount rate for long time horizons (>100 years) and find a mean recommended social discount rate of 2.27 percent, with a range from 0 to 10 percent. Over three-quarters of experts are comfortable with the median social discount rate of 2 percent, and over 90 percent find a social discount rate in the range of 1 to 3 percent acceptable. This is not yet a standing practice, so we do not follow this approach here.

Concluding remarks and discount rate chosen

The discount rate differs between countries; this is partly the effect of economies being differently, partly the result of a different application method (CAPM versus Ramsey, and all the details in the actual application). Since the current study and the TIMES model covers Europe as a whole it seems reasonable to pick a discount rate in line with this territory. This study therefore applies the EU discount rate, which is both more or less in line with at least the UK, French and Dutch values, and which is consistent with the EU being one of the funders of this project. That is, we use the unweighted average of the discount rate for cohesion and other EU member states[10], that is a discount rate of 4% for entire Europe.

2.3 Model used: JRC-EU-TIMES[11]

In order to understand the role that PtG plays in alternative future scenarios, this deliverable uses an energy system model. This model, JRC-EU-TIMES (D6.3 see [1], [24] and [2]), minimizes system costs given GHG emission reduction targets and other constraints related to potentials of biomass and other technologies, levels of gas and oil prices, learning effects of PtG technologies, and availability of alternatives such as CCS and power-to-liquids (PtL).

The model covers six sectors (power, commercial, industry, residential, transport and agriculture (of the last only energy consumption)) and has a European scale (EU-28 plus Switzerland, Norway and Iceland; EU-28+ in short). The time horizon of the model is from 2010 to 2050 (although it can be used beyond this timeframe). The richness of the model is in the variety of technologies included.

Technology representation is achieved by using a Reference Energy System (RES), which provides the links between processes. Each process is represented by its efficiency (input-output), cost and lifetime. Prices are endogenously calculated through supply and demand curves. Several policies can be added including CO_2 tax, technology subsidy, regulations, targets, energy efficiency, feed-in

[10] If we would apply weighing based on population, the discount rate would be 3.5% (=0,25*5%+0,75*3%). In case of weighing based on GDP the discount rate would be even closer to 3 percent as currently the cohesion countries are about a quarter of EU population and about one eight of EU GDP. However, weighing is complicated since one of the reasons of higher discount rate in the cohesion countries is the higher expected growth rate, increasing the share in European GDP over time.

[11] This section strongly borrows from [1], which is also the key reference for more details on the model. Further details can also be found in [24].

tariffs, emission trading systems and energy security, among others. The model allows obtaining both optimal generation and network capacity additions and associated costs.

In the cost optimization exercise, costs included are investment, other fixed costs, annual operating costs, decommissioning costs, taxes, subsidies and salvage value. Given the capacity expansion component and scope further than power (commercial, residential, industry and transport), it is necessary to limit its temporal (12 time slices for a year and 24 slices per year for the power sector) and spatial (one node per member state) resolution to keep the model tractable and the calculation time acceptable. Therefore, hierarchical clustering is applied for factoring representative hours of a year into time slices. The software used is TIMES (The Integrated MARKAL-EFOM System).

Cost optimization is done for the entire energy system looking at the longer term (2050) and covering EU-28+. The reasons for this selection are: a) only in the long term low carbon scenarios will be achieved, b) most of previous studies focus on a local or national scale with few considering the dynamics of the entire EU region, c) cost optimization is the first step to identify the best routes to satisfy energy needs, and d) PtG is a technology connecting various sectors and there lies the importance of looking beyond power. Amongst others, the model solves the amount of PtG deployed in different scenarios (capacity and energy) that minimizes the cost in that scenario.

The model is suited to analyse low CO_2 emission scenarios (with reduction targets exceeding 80%) and to understand better the drivers for the role of the technologies and especially the circumstances that influence the use of PtG in the energy system. The circumstances that influence PtG deployment are the attractiveness of PtG versus the costs for the complete energy system of other flexibility options such as Demand Side Management, grid expansion, excess of generation capacity and storage technologies. To this aim, amongst others different production routes for PtG have been added to the model, as detailed in [1].[12]

Since the drafting of [1] JRC-EU-TIMES has been further developed. The main changes are:

- Geothermal potential is limited to maximum 300 TWh in EU28. The effect in the optimistic scenario is that more PtM is needed increasing capacity to almost 660 GW (vs. 550 GW).
- Interconnection capacities are limited to twice the capacities in the 10-year network development plan (TYNDP) from ENTSO-E. Following [23] in an earlier model version it was assumed that interconnection capacity should be 15% of the installed generation capacity of a Member State by 2030. This resulted to very large interconnection capacities in the future with unrealistic low capacity factors. The effect of this correction on the deployment of technologies is limited.

Strengths and weakness of JRC-EU-TIMES[13] for studying costs and benefits of PtG

Not all costs and benefits can be realistically simulated with JRC-EU-TIMES, for several reasons. First of all, since the model simulates long term developments and to reduce the time required to run the model, it minimizes the costs of the energy sector with one year representing a decade. It thus provides insights in the planning of energy systems that operate for multiple decades. However, this type of analysis does not account for the benefits from more efficient operations of infrastructures,

[12] Originally three ECN models (OPERA, COMPETES and ECN-TIAM) would have been used, with all three models requiring substantial extension, for example to include an European dimension in OPERA which is a technology rich model, but only with data for the Netherlands. D6.3 ([1]) showed that the JRC-EU-TIMES model is suited for the analysis necessary for this deliverable and D7.4, and that using this model would ensure consistency with other deliverables. Therefore the switch of models used (as agreed with the project coordinators) is seen as an improvement.

[13] For a more general discussion of strengths and weakness of JRC-EU-TIMES, see section 3.1 of [24] , model description.

or broader energy systems [25], within the optimization period of about 10 years, i.e. it does not identify the full need for (seasonal) flexibility.

Secondly, grids are represented as one zone per country. JRC-EU-TIMES accounts for the extra cost to expand the grid if electricity demand increases (see Section 3.10 of D6.3 [1]), but it does not account for potential line congestion (since this is directly linked to spatial analysis). Therefore, effects from PtG on the grids within countries, especially on regional or spatial level, cannot be analysed.
Another technical restriction is that flexibility and storage options are not evaluated separately. For instance DSM or batteries are no options for long term shifting of energy. Thus they cannot be compared directly with PtG.

Thirdly, Gross Domestic Product (GDP) is given, as a result shocks or constraints to the economy (like a strict CO_2 emission reduction) that actually reduce economic growth cannot be calculated.

Another important drawback for the study of energy security based upon JRC-EU-TIMES model outputs is that the energy supply from outside Europe is supplied from the world market. JRC-EU-TIMES assumes that the world market functions according to the status quo i.e. it is impossible to import on large scale hydrogen or synthetic fuels from places outside Europe (e.g. from the MENA region) with higher availability of renewable energy sources due to e.g. more solar irradiance or higher wind speeds.

At the same time the technological richness of the model, and its EU-wide geographical coverage make it an ideal model to study energy security implications of PtG in the European context.

Compared to the earlier deliverables using this model ([1], and [3]), the use of the model is different here. In [1] and [3] several scenarios are analysed and described without being explicit on what the impact is of PtG on the developments. In this deliverable the focus is explicitly on the effects of PtG, therefore for each scenario two variants are calculated and compared: one version with methanation technologies and one version without methanation technologies in place. This enables answering questions on whether PtG contributes to European welfare and if so how much.

2.4 Scenarios

Given the uncertainty about how the future will develop, the SCBA uses several scenarios. For each scenario two versions are compared: a baseline alternative (also reference scenario or counterfactual) describing the development of the energy sector and the economy without PtG, and a project alternative with PtG (see also EU, 2014, p. 26 [9]). The baseline alternative is the most feasible situation that would occur in the absence of the project, i.e. development of PtG technologies. The differences of the 'situation with PtG' and the 'situation without PtG' are the costs and benefits of developing PtG technologies.

In JRC-EU-TIMES scenarios have been executed as a parametric variation. In Blanco [1] 22 parameters that are related to either the system (e.g. CO_2 storage) or the technology (e.g. PtG capital expenditures (Capex)) were varied to create over 120 different scenarios, out of which 55 were selected for more detailed analysis. This allows identifying on one hand which critical parameters do promote PtG deployment and on the other the role (capacity and activity) that the PtM technology has in different alternative configurations of the energy system. Blanco showed that PtG potential arises for cases with 95% CO_2 reduction target, no CO_2 underground storage and low Capex figures (75 €/kW only for methanation).

The ‘situation with PtG’ and the ‘situation without PtG’ will only differ for scenarios where PtG technologies are applied. Nevertheless, the scenarios in D6.3 [1] where no PtG is applied although the technology is available are relevant and straightforward. These scenarios where it is economically unattractive to apply PtG are relevant as they describe possible manners in which energy systems could develop in the coming decades. Besides they are straightforward as, for the current analysis, they require no calculations.

Therefore the following scenarios from [1] are used:

- *Pessimistic scenario*. Blanco presents four scenarios with PtG not being chosen in the cost minimizing mix of technologies. These are the basic 80 and 95 percent reduction scenarios with only the CO_2 target as constraint. There are no restrictions to the realization of technological potentials. Two other scenarios have the same emission reduction and the additional constraint that CO_2 underground storage is impossible. This can be the result of limited social acceptance or a general ban of fossil fuels.
- *Realistic scenario*: the scenario with what is perceived (by Blanco) as likely constraints that favour PtM. This includes 95% CO_2 reduction, no CO_2 underground storage, low Capex (75 €/kW) for the methanation step, and high potential for variable renewable energy (VRE) such as solar PV and wind.
- *Alternative scenario* (in [1] this is denoted the constrained scenario). This is a scenario with a different set of constraints that are also likely, but that do not favour PtM. This aims to show that it is also possible that the system evolves in a direction where PtM plays a limited role. The scenario is characterized by 95% CO_2 reduction, no restriction to CCS, high biomass potential, high VRE potential, high hydrogen production due to high Proton Exchange Membrane (PEM) performance, no restriction to electric heavy-duty transport, and low LNG efficiency in ships (25 gCO_2/ton*Nm).
- *Optimistic scenario*. This covers the most favourable set of conditions for PtM and establishes an upper bound for the technology activity. This includes the set of conditions in the “Realistic” scenario plus low biomass potential, high gas price, high electricity network costs, high PtM efficiency, high PEM performance, low Power-to-Liquids (PtL) performance, hydrogen production with Solid Oxide Electrolysis (SOEC) technology possible and high LNG efficiency in ships (12 gCO_2/ton*Nm).

Note that the naming of the scenarios is in line with Blanco (2018 [1]). The scenario names are logical from a technology perspective rather than from a system perspective; optimistic thus means that PtG is applied most, while for most observers this would be the most pessimistic scenario as it is characterised by many system constraints and energy system costs are the highest of all scenarios. Thus if circumstances are the most detrimental to achieving 95% GHG emission reduction, having PtG available is the most advantageous. This scenario has more than 10 drivers in favour of methanation, which reduces its likelihood of happening. See the appendix and [1] for more details on the assumptions used in the scenarios.

3 Costs and benefits of power-to-gas

This chapter discusses the societal costs and benefits of PtG. For each scenario the costs and benefits are the difference of the calculations based on JRC-EU-TIMES with PtG technologies (i.e. methanation) enabled, versus the calculations without PtG technologies. The costs of the energy system are discussed first followed by two sections on non-market effects i.e. energy security and environmental effects. The remaining sections discuss the GDP and labour market effects, the effects of PtG on grids, and some other effects.

3.1 Costs of the energy system

JRC-EU-TIMES calculates the cost minimizing energy system. While doing so the following costs are distinguished:

- Capex: Annuity for Capex with discount rate and lifetime by technology
- Fixed Opex: Annual costs fixed regardless of production (e.g. staff salary) and usually taken as percentage of Capex
- Variable Opex: Annual costs that are a function of production, but other than feedstock costs
- Flow costs: Extra costs associated to commodities in or out of a process. Most of these are associated to import/export (e.g. crude oil or jet kerosene) with some additional cost penalties based on flows. Overall this cost item is minor compared to the other cost items.
- Elastic demand cost term: Cost resulting from the loss of welfare due to the reduction (or increase) of demand in a given scenario compared to the baseline scenario. That is JRC-EU-TIMES estimates the loss in consumer utility if relative prices change, as a result of GHG emission reduction policy.

Below we present the annual costs, since the CAPEX are calculated as annuities the CAPEX and other cost items are directly comparable. Table 3-1 to Table 3-3 show the development of the annual costs of the energy system for the years 2030, 2040 and 2050 respectively. For the optimistic scenario and the realistic scenario the cost with PtG and the costs without PtG are shown. The differences are included in the column ‘delta’. The alternative scenario without PtG is not calculated here (with the social discount rate) since it hardly deploys any PtG, so the differences are small. And the pessimistic scenario is not shown, since PtG is not deployed in the scenario in any year. The difference in the pessimistic scenario with and without PtG is therefore zero.

Table 3-1 shows the costs of the energy system in the year 2030. In this year the costs of having PtG are nil compared to the situation without PtG.[14]

[14] Or more precise in the five years before and after that year for which the target year (2030 in Table 3-1) calculations are representative.

Table 3-1: Annual costs of the Energy System 2030 (billion Euro)

	Optimistic			**Realistic**			**Alterna-tive**
	with PtG	**without PtG**	**delta**	**with PtG**	**without PtG**	**delta**	**with PtG**
Capex	1,055	1,055	0	985	985	0	988
Fixed Opex	270	270	0	287	287	0	291
Variable Opex	156	156	0	384	384	0	408
Flow costs	443	443	1	418	419	-1	375
Elastic demand cost term	39	38	0	-52	-52	0	-75
TOTAL	1.963	1,963	0	2,023	2,022	0	1,987

Table 3-2 shows the relevant costs of the energy system for the year 2040. The effect of PtG on the total annual costs increases with the deployment of PtG. In the optimistic scenario deploying PtG decreases costs marginally. In the realistic scenario developing PtG adds to the costs, but the difference in costs of this scenario with and without PtG are still negligible.

Table 3-2: Annual costs of the Energy System 2040 (billion Euro)

	Optimistic			**Realistic**			**Alterna-tive**
	with PtG	**without PtG**	**delta**	**with PtG**	**without PtG**	**delta**	**with PtG**
Capex	1,585	1,591	-6	1,538	1,538	0	1,334
Fixed Opex	448	452	-4	467	466	0	399
Variable Opex	163	163	0	185	185	-0	222
Flow costs	314	311	3	253	253	1	326
Elastic demand cost term	216	215	1	89	89	-1	-76
TOTAL	2,726	2,733	-7	2,532	2,531	1	2,205

Table 3-3 shows the costs for the three scenarios in the year 2050. Here the cost differences (column ’delta’) are larger, up to € 68 billion annually for the optimistic scenario. This is about 2 percent of the total costs of the energy system. Note that a large part of the cost saving is in the elastic demand cost term. That is PtG lowers some of the end user prices to such extent that welfare losses due to the reduction (or increase) of demand in a given scenario compared to the base scenario is diminished. Thus JRC-EU-TIMES calculates the dead weight loss (what is a cost to society) of prices being different compared to the base scenario (i.e. the EU Reference scenario).

Table 3-3: Annual costs of the Energy System 2050 (billion Euro)

	Optimistic			**Real-istic**			**Alterna-tive**
	with PtG	**without PtG**	**delta**	**with PtG**	**without PtG**	**delta**	**with PtG**
Capex	2,360	2,377	-17	2,280	2,273	7	1,835
Fixed Opex	544	541	3	537	533	4	398
Variable Opex	205	205	-1	217	217	-0	237
Flow costs	232	230	2	192	200	-9	317
Elastic demand cost term	248	303	-55	180	186	-6	-105
TOTAL	3,588	3,656	-68	3,405	3,408	-4	2,681

The effect of PtG on prices can also be shown by looking at the CO_2 prices[15]. Table 3-4 shows the prices per ton CO_2 for the optimistic, realistic and alternative scenarios. The more PtG is applied in a scenario, the bigger is the difference of the CO_2 price between the scenario with PtG and the scenario without PtG. In the optimistic and the realistic scenario the CO_2 price towards 2050 is around € 1,000 €/ton. These high prices clearly show that under the conditions of these scenarios the constraints are so severe that in the absence of PtG more expensive measures (including PtG) are necessary to reduce CO_2 emissions to reach the 95 percent reduction target. Especially in the optimistic scenario (with most PtG deployment) the effect of PtG on the marginal CO_2 is substantial: in the optimistic scenario having PtG lowers the marginal CO_2 price with over 20 percent compared to the situation of not having PtG in this scenario. In the realistic scenario PtG uptake is much less, as is the effect on the marginal price. The CO_2 price in the alternative scenario is low precisely because this scenario is meant to show that there is a low carbon pathway where emission reduction is relatively cheap and PtG does not play a role.

Table 3-4: CO_2 prices (€/tonCO_2; note that these are the marginal prices)

	Optimistic		**Realistic**		**Alterna-tive**
	with PtG	**without PtG**	**with PtG**	**without PtG**	**with PtG /without PtG**
2015	0	0	5	4	6
2028	73	72	66	66	43
2040	482	466	420	420	92
2050	990	1,262	1,188	1,208	141

[15] This price represents the cost to reduce an additional ton of CO_2. This is not to be confused with the average cost to achieve the lower CO_2 emissions.

3.2 Security of supply

The welfare effects of society being less vulnerable to supply side shocks of energy when PtG is deployed are estimated using three different methods. These three methods are identified in the literature, and all three are applied to estimate an energy security benefit of Power-to-Gas (for one method two estimations are made). Applying each method to value the effect of PtG on energy security until 2050 requires assumptions, amongst others for applying a method developed for a specific case to another case (country, fuel type, time period). This was critical in arriving at estimates of the value of PtG for energy security in 2050. None of these methods has originally been designed for this purpose, making the application unavoidably crude, however better methods so far do not exist. Therefore the outcomes should be interpreted with care. In the social cost benefit we use the average of the three methods. In the following the methods are shortly described, for more detail see [4].[16]

Sensitivity to price increases: the oil import premium method, based on Leiby [26]

This method estimates the economic damage of an unexpected and exogenous substantial change (shock) in import dependence or of a change in import prices of main fuels (like oil, gas or biomass). A substantial increase in the price of fossil fuels requires changes in producer and consumer behaviour. Producers, and especially those that are fossil fuel intensive, see their cost rise due to the higher fuel prices while consumers experience a real budget decrease due to inflation. This impacts the economy, since the time needed to adjust is often substantial and large price increases can lead to a recession. The key reference in this method is [26], for a later application see [27].

Applying the Leiby approach in 2050 is challenging, oil import and oil consumption will be substantially reduced by 2050, given the CO_2 reduction target of 80 or 95 percent depending on the scenario. While studying the effect of the import price of oil on the economy, Leiby and later Brown basically studied the effect of the energy price on the economy. Oil and gas prices were strongly correlated, the same holds to a lesser extent to coal prices. Thus if the oil price increased substantially, basically the price of gas increased, and overall the price of energy increased. Therefore, the Leiby and Brown estimates can be understood as an estimate of the effect of the energy price on the economy. Note that from an economic point of view price increases mean increased scarcity. In 2050 in most scenarios oil and gas play a marginal role, most energy is supplied by renewable energy with especially wind and solar being sensitive to supply fluctuation. So, price fluctuations will remain, however with a different source (periods with strong reductions in production of wind and solar power caused by weather fluctuations versus oil market events), and different timing (more regular, shorter lived). Predicting how energy price fluctuations will be in the future requires pricing models using strong assumptions on market mechanisms in place. This is outside the JRC-EU-TIMES model, because that does neither include price nor supply fluctuations. It is also outside the scope of other long term models. Consequently, below we make a first crude approximation, especially since we apply a study done for the US to Europe.

Scenarios with PtG will see more storage and thus less scarcity during a period of low intermittent renewable energy generation, than if PtG would not be developed. Therefore with PtG technologies in the energy system, price fluctuations and price uncertainty will be less than without PtG technologies. The price shocks will in the future likely be stronger but shorter lived than the past oil crisis. We therefore expect a similar welfare economic loss due to price fluctuations. Furthermore PtG lowers the price fluctuations, because it increases energy supply during periods that variable and intermittent renewables are scarce and reduces demand when intermittent renewables are abundant.

[16] Compared to that earlier deliverable, the security benefits for the alternative scenario are zero here always, whereas in [4] they sometimes were positive, but very small. So they are here treated as nil.

The estimation basically applies Leiby's estimate, corrects it for inflation (from 2007 until 2013), GDP and population difference between US in 2007 and the EU in 2050, and estimates the contribution of PtG to more security of supply based on the ratio of 'conversion of H_2 to CH_4' and electricity production. Each estimate is made for a low, midpoint and a high estimate to include uncertainty about key variables. For details see [4].

Value of lost load and expected energy unserved

The second approach for valuing the supply security value of PtG is based on the vulnerability of the electricity system. Within this approach, two different valuations are developed: one based on the need for rationing and the social cost of that, and one based on the need for more reliable back up power and the costs of those.

Both approaches start with an estimation of the expected energy unserved. This measure captures in a single figure the probability of involuntary interruptions and the likely size of those interruptions. It is used mostly for electricity. The assessment depends upon a set of underlying assumptions about possible supply and demand options and the probability distributions applied to them (see [28] for a more detailed overview). The first method assumes that the shortage in supply is solved by rationing users and calculates the damage of that, while the second method calculates the back-up facilities necessary to prevent such rationing. So the method focusses on situations when based on variable renewable energy production (solar and wind energy) further electrification increases the possibility of a dark doldrums. A dark doldrum is a period when it is both dark (not sunny) and without wind leading to substantially reduced solar and wind energy production, while at the same time demand will be relatively high. Dark doldrums are also known under the German term “Dunkelflaute” a combination of 'Dunkelheit' and 'Windflaute'. One could also speak of cold doldrums ('kalte Dunkelflaute'), because dark doldrums occur mostly while it is also relatively cold. This would occur while it is not windy in most European countries and clouds reduce solar irradiation and thus production. Mostly when it is not windy in one country this can be compensated with production in other countries, however sometimes the reduction in renewable power will occur in several or all European countries at the same time (see for example [29]). If PtG technology can be deployed this will reduce the effect of such dark doldrums; during the dark doldrums PtG can increase supply of energy from the stock of synthetic methane, while temporarily reducing demand for electricity because it can reduce production of CH_4 for a short period.

The estimation of the damage of reduction in demand starts with the expected days per year when power is insufficient. This means in the midpoint estimate a two weeks shortage period once every five years and a four week shortage period once every 10 years (the low estimate is 50 percent lower, while the high estimate is double the midpoint estimate). Based on expected electricity production of wind and solar in 2050, and the reduction in production during a dark doldrum, the reduction in total power production is calculated. Using EU GDP in 2050 and the stylized fact of [30] found for the Netherlands in 2003 that the value of leisure is about the same as the value of GDP, the total value generated in Europe per year and per day is calculated. Next demand reduction and additional import from outside Europe are estimated, and applied to calculate the remaining shortage. Reducing the expected damage with 50 percent because the outages are not unexpected, the damage per year is calculated. PtG helps to solve this shortages perfectly in the optimistic scenario (with the most PtG). In the other scenarios, the contribution of PtG is limited since it scales with the ratio of PtG usage in that scenario and PtG usage in the optimistic scenario in 2050.

The other estimation based on supply interruptions uses the same electricity shortages in 2050 as the first method, but now calculates how many gas fired peaking power plants are necessary to prevent rationing electricity demand. Using a € 1000 per MWh long run marginal costs in 2050 (for power plants used 5 days a year on average and with very high CO_2 permit prices) the security of supply benefits of prevented rationing is estimated.

Willingness-to-Pay for Security of Supply, based on work by Bollen et al. [31]
[31] estimates the value of security of supply based on the revealed willingness-to-pay of society as a whole. They look at a number of cases, most information they utilize is from the French program to build many nuclear power plants to be less reliant on oil imports, in order to reduce the availability and price risk. They do so while analysing integrated approaches that resolve problems relating to global climate change, local air pollution and security of supply at the same time. Hence, an integrated assessment of energy-economy-environment interactions is carried out with the MERGE model [31]. The objective of the MERGE model is welfare optimisation and it is able to simulate both environmental and economic impacts as input for a cost-benefit analysis. To this aim, it has been expanded with a function to include security of energy supply, notably energy savings and diversification of energy systems. Bollen et al. estimate the willingness-to-pay with a function based on amongst others import ratio of energy, energy intensity, and the share of the fuel at hand in the total primary energy supply.

They approximate the willingness-to-pay for large national projects, dedicated to ensure energy supply security, and find that they typically amount to a couple per mille up to, at most, 1% of private consumption ([31], p. 31). Based upon the example of the nuclear program in France, they take 0.5% as central value for the willingness-to-pay, and take a sufficiently large range of values for the concomitant sensitivity analysis i.e. from 0.1% to 1% (op cit. p. 32). Note that private consumption is 75-80% percent of GDP (the difference are investments and transfer abroad; [31], p. 9).

While looking at Europe in 2050, import ratios are hardly interesting anymore, since much more energy is generated within Europe than currently is the case. However, society remains sensitive to changes, for example in case of a dark doldrum. PtG may help to increase security of supply by adding more storage possibilities to the system. Therefore their willingness-to-pay formula is not replicated. Our estimate starts with the willingness-to-pay range of [31] followed by the GDP estimates for 2050, and the private consumption ratio. From this, a willingness-to-pay for security of supply is calculated. Some of the assumptions made while estimating the security of supply benefit of PtG are: the contribution of PtG to total security of supply ranges from 10 to 50 percent of the total willingness to pay for security of supply; and the benefits for security of supply relate to the deployment of PtG, with the deployment of PtG in 2050 in the optimistic scenario being normalized at 100 percent. For further details see [4].

Results
Table 3-5 presents the estimates of the total value of energy security for the methods discussed above for the years 2040 and 2050. The first four rows of the table show the results for the optimistic scenario, with in the last three columns the results for 2050 (low, midpoint and high estimate respectively based on the different assumptions as discussed in [4]). The fifth line is the average of the four estimates. The three blocks below the optimistic scenario have the estimation results for the three other scenarios as described in section 2.4.

There are three blocks with results substantially different from zero; the optimistic scenario in 2040 and 2050 and the realistic scenario in 2050. Here, the bandwidth of each estimate is substantial, whereas the difference between the four estimates is relatively small. Therefore the average of the four methods seems a good first approximation of the welfare effect on energy security of PtG.

It is visible that the value of PtG for supply security is especially substantial in the optimistic scenario. In the other scenarios is about one seventh of the value in the optimistic scenario in 2050 or zero. In addition, only in the optimistic scenario PtG has a positive energy security value in 2040. This is the result of predictions of JRC-EU-TIMES about the use of PtG in the other scenarios and before 2040. If no PtG is deployed it cannot contribute to energy security.

Table 3-5: Annual security of supply benefits of PtG, billion euro

Scenario	Method	2040 low	2040 midpoint	2040 high	2050 low	2050 mid-point	2050 high
optimistic	Leiby	3	4	12	11	18	51
optimistic	Rationing of demand	3	10	17	13	43	79
optimistic	Back-up power	2	6	18	7	27	82
optimistic	Bollen	0	0	1	2	23	90
optimistic	**average**	**2**	**5**	**12**	**8**	**28**	**76**
realistic	Leiby	0	0	0	2	3	7
realistic	Rationing of demand	0	0	0	2	4	11
realistic	Back-up power	0	0	0	1	2	12
realistic	Bollen	0	0	0	0	3	12
realistic	**average**	**0**	**0**	**0**	**1**	**3**	**11**
alternative	Leiby	0	0	0	0	0	0
alternative	Rationing of demand	0	0	0	0	0	0
alternative	Back-up power	0	0	0	0	0	0
alternative	Bollen	0	0	0	0	0	0
alternative	**average**	**0**	**0**	**0**	**0**	**0**	**0**
pessimistic	Leiby	0	0	0	0	0	0
pessimistic	Rationing of demand	0	0	0	0	0	0
pessimistic	Back-up power	0	0	0	0	0	0
pessimistic	Bollen	0	0	0	0	0	0
pessimistic	**average**	**0**	**0**	**0**	**0**	**0**	**0**

3.3 Environmental effects

Changes in the energy system have many different environmental effects, like changes in water usage, changes in air and water pollution, and use of exhaustible resources. In deliverable D5.8 of the STORE&GO project the environmental impact of PtG in the energy system was analysed by performing a Life Cycle Analysis (LCA) of the Energy System with PtG [3]. That is for each scenario for 2050 an estimate is made of the effect on 15 different environmental categories. The same methodology is applied to analyse the optimistic and the realistic scenario with a 4 percent discount rate, for cases with and without PtG. The alternative and pessimistic scenario are not analysed in the LCA because PtG is not used in those cases, hence there will be no differences between the situations with and without PtG technology deployed. Making an LCA for a complete energy system is a challenging task, because it requires information about many technologies. For [3] the more than 3000 individual processes in JRC-EU-TIMES (including import, mining, duplication for fuels) representing over 450 technologies had to be reduced to a smaller, workable number of technologies. For the aggregated technologies data was required on their Life Cycle impact over a number of impact categories (like effect on land use, effect on fossil depletion and so on, see the tables below for all categories).[17] The LCA analysis uses the ReCiPe LCA methodology and classification [33]. A further complication and uncertainty is the focus of the analysis on future energy systems, with substantial uncertainty about the technological progress (and associated learning curves) of specific technologies. Predicting the 2050 LCA impact of PtG in a complete energy system is already an immense task and achievement. This imposes a few limits on the output available for this analysis: the years 2030 and 2040 are missing, and no sensitivity analysis on the LCA outcomes could be done. The LCA analysis provides for each scenario output that looks like Table 3-6 for the optimistic scenario. For the realistic scenario a similar table is available in the appendix of this deliverable (Table A1-2), the biggest difference being that the difference between the situation with PtG and the situation without PtG is much smaller. This suits the fact that in the optimistic scenario PtG is deployed substantially more than in the realistic scenario.

Table 3-6: Environmental impacts in 2050 for the optimistic scenario

Impact category	**Unit (*x* millions)**	**Optimistic - CBA - with PtG**	**Optimistic - CBA - without PtG**	**Comparison**	**Comparison in percentage**
Land use	m2a	1,035,126	854,668	180,458	21%
Climate change	kg CO2-Eq	836,140	1,070,405	-234,265	-22%
fossil depletion	kg oil-Eq	184,237	258,673	-74,436	-29%
Freshwater ecotoxicity	kg 1,4-DB-eq.	859	902	-43	-5%
Freshwater eutrophication	kg P-Eq	97	91	7	7%
Human toxicity	kg 1,4-DB-eq.	395,444	388,858	6,586	2%
Ionizing radiation	kg U235-Eq	237,156	237,759	-603	0%
Marine ecotoxicity	kg 1,4-DB-eq.	3,333	3,217	116	4%
Marine eutrophication	kg N-Eq	317	304	12	4%
Metal depletion	kg Fe-Eq	467,645	417,361	50,284	12%
Natural land transformation	m^2	141	186	-45	-24%
Ozone depletion	kg CFC-11.	0	0	0	-9%
Particulate matter formation	kg PM10-Eq	2,347	2,237	110	5%
Smog formation	kg NMVOC	6,072	6,012	60	1%
Acidification	kg SO2-Eq	4,372	4,151	222	5%
Terrestrial ecotoxicity	kg 1,4-DB-eq.	312	287	25	9%
Urban land occupation	m^2a	51,137	49,129	2,007	4%
water depletion	m^3	11,497	10,722	775	7%

Given the complexity of the underlying energy system (both in the models and in reality) it is hard to understand the size of the changes. That some of the changes are substantial can be understood

[17] Note that this LCA includes many more technologies than most LCAs on Power to Methane or Power to Hydrogen, see for example [32].

as an effect of PtG capacity being 660 GW, which is substantial compared to the current total electricity installed capacity of 1000 GW.

It should be noted that not all large physical impacts result later on in large financial effects.

There is one effect that deserves further clarification: the effect on climate change. JRC-EU-TIMES is an energy modelling system covering about 70 percent of all CO_2 emissions. These are reduced by 95 percent. The LCA analysis shows that with PtG more emissions outside the energy system and the model) are reduced than without PtG. Consequently, including the effect on climate change is not a double counting.

Careful interpretation is necessary, which is illustrated with two related examples. First, if a quantity shows an unfavourable development (like human toxicity), specific policies will address this issue to reduce this compared to the levels currently predicted. Second, prevention of climate change is also needed to save human lives, so there is overlap between both categories, which makes it hard to draw hard conclusions on specific categories.

Finally, note that there is quite some uncertainty about for example the LCA impact of the methanation phase. The current impacts are based on the demo-sites, which is the best knowledge available. However these values might not provide accurate predictions of the 2050 impact.

The inclusion of the effects discussed above in the SCBA requires monetisation (valuation). This step requires a valuation figure per unit for each of the categories. LCA analysis use different classifications, each with pros and cons (see for example [34], [32]). The most relevant study here is [35], which contains amongst others a valuation of most of the ReCiPe categories.

Table 3-7 depicts these values. There is quite some uncertainty on the value or price per unit, accordingly for most categories a midpoint estimate as well as a low and a high value are reported for adequately taking into account uncertainty in the SCBA. These are values for 2050.

Table 3-7: Value per unit (2050)[18]

Impact category	Unit	Low	Midpoint	High
Land use	€/m2 a	0.0255	0.0845	0.685
Climate change	€/kg CO2-eq.	0.2	0.5	1
Fossil depletion		0	0	0
Freshwater ecotoxicity	€/kg 1,4 DB-eq.	0.00485	0.0361	0.0409
Freshwater eutrophication	€/kg P-eq.	0.25	1.86	2.11
Human toxicity	€/kg 1,4 DB-eq.	0.0725	0.0991	0.153
Ionizing radiation	€/kg kBq U235-eq.	0.0297	0.0461	0.0598
Marine ecotoxicity	€/kg 1,4 DB-eq.	0.000992	0.00739	0.00837
Marine eutrophication	€/kg N	3.11	3.11	3.11
Metal depletion	kg Fe-Eq	0.026	0.052	0.104
Natural land transformation	€/m2 a	0	0	0
Ozone depletion	€/kg CFC-eq.	22.1	30.4	45.7
Particulate matter formation	€/kg PM10-eq.	28	39.2	60.4
Smog formation	€/kg NMVOC-eq.	0.84	1.15	1.84
Acidification	€/kg SO2-eq.	0.526	4.97	5.66
Terrestrial ecotoxicity	€/kg 1,4 DB-eq.	1.17	8.69	9.85
urban land occupation	€/m^2 a	0	0	0
water depletion	€/m^3	0	0	0

A few values should be highlighted:

- The value of less fossil depletion is zero because with very stringent climate policy it is unlikely that fossil fuels will be exhausted, hence the marginal value is zero. Furthermore fossil depletion might already be partly included in the value for climate change.
- Natural land transformation and urban land occupation have a value of zero to prevent double counting with the first category (land use).
- Water depletion is estimated at zero because its value already seems included in the normal cost price of water, so including a positive value here would mean double counting. Besides, [36] mentions the lack of reliable estimates as reason why a value of zero is included there. The same problem applies here as well.
- The monetisation value for metal depletion is based on [36]. The more recent [35] does not give a value here, this could either be a too uncertain number or the question whether this metal is going to be exhausted and thus whether a positive value in a CBA is justified.
- The biggest challenge is the determination of the value for climate change. [35] shows a midpoint value of 0.057 €/kg, although the accompanying text states that this value holds for 2015, is derived backwards from 2050, and future values require a 3.5% price increase per annum. This boils down to a midpoint value of € 190/ ton in 2050.[19] However, in the energy

[18] The midpoint values for most impact categories reflect the individualistic perspective for decision making i.e. a time span of 20 years. Exceptions are land use, human toxicity, eco-toxicity, and climate change which are all (either the midpoint or upper value) based upon the hierarchic perspective for decision making with a time span of 100 years.

[19] Note that some of the literature does not make predictions beyond 2030, see [9] (p. 63) for CO_2 prices up to 2030 required for European infrastructural projects.

system in the realistic and the optimistic scenario the CO_2 price is € 1000/ton or above (see Table 3-4).

- At first sight, it seems unlikely that the energy system reduces CO_2 up to € 1000/ton whereas outside the energy system the abatement costs are just € 190/ton as in [35]. However, such low CO_2 prices are unlikely in a 95% emission reduction scenario for 2050. Two Dutch government based research organizations made, in a large scenario analysis for the Netherlands, predictions for energy prices and CO_2 prices for 2030 as well as 2050 ([34][38]). Based upon the marginal abatement cost approach, the CO_2 price prediction in the 2 degree scenario ranges from 200 to 1000 €/ton in 2050. In this scenario the emission reduction in Europe varied between 80 and 95 percent, with the higher prices corresponding to the higher emission reduction targets. This is supported by international estimates of the monetary value of greenhouse gases; based upon the damage cost approach [39] provides a higher estimate for the social cost of carbon for 2050 of 1215 $€_{2015}$/ton CO_2, assuming a low discount rate, high climate sensitivity i.e. the long-run temperature increase expected from a doubling of the CO_2 concentration in the atmosphere is significant, and damage estimations taking into account catastrophic climate change. Furthermore, the applied integrated assessment model had a fairly conservative treatment of potential catastrophic climate change. Moreover, as outlined by [39] there exist several studies which report a much higher value than 1215 $€_{2015}$/ton CO_2.[20] Apart from that, the CO_2 prices in the JRC-EU-TIMES model of € 1000/ton or above can be explained by the fact that the energy systems in the model are quite constrained by several assumptions and adverse system-wide conditions in the realistic and optimistic scenarios (e.g. no CCS, low biomass potential, and low PtL performance in the optimistic scenario); these constraints force the model to deploy the remaining, more costly technology options to reduce CO_2 emissions. Given all reasons, for climate change the CO_2 price of € 1000/ton is applied as upper value, and a price of 200 €/ton as lower value.

Note that most of the prices are based on current estimates, so valid mostly for current effects, not for effects in 2050. However the prices or values for 2050 are unknown. Only for climate change predictions for 2050 are available (but with a wide bandwidth).

Two observations are relevant. First, the prices are based on current pollution levels. Some pollution is likely to diminish (particulate matter formation) since less fossil fuels will be burnt (although biomass will be burned more) and specific policies aiming at these pollution will be effective in the long run. Thus the quantity of pollution will decrease, leading to lower marginal damages and thus lower prices. Second, prices are based on current welfare levels. If welfare increases the relative price of non-reproducible nature might increase. The Dutch government rules on discounting include a 1 percent relative price increase of non-reproducible nature since its supply decreases relative to an increasing GDP (see [39], [41]). That would correspond to about a 40 percent increase in prices in 2050 compared to the figures in

Table 3-7 which, apart from climate change, are supposed to remain the same until 2050 [35]. As both observations point to developments in opposite directions, we decided to apply the 2015 values also for 2050. A sensitivity analysis for these prices along both observations is not shown in the report but will not change the overall conclusion about PtG.

The next step is to multiply the prices with the quantities as discussed above. Table 3-8 shows the resulting value per category and the total value in the last row. This calculation is performed for the optimistic and the realistic scenario for a low, midpoint and high value. The low and high values show

[20] For a further discussion of CO_2 values we refer to [39]. Note that it is stated that the estimates are under- rather than overestimates.

the uncertainty around estimating appropriate values for the year 2050. The alternative and pessimistic scenarios are not shown, since the quantity (defined as the difference between the scenario with PtG and the scenario without PtG) is zero, and thus all values per category are zero for these scenarios. The bandwidth of effects per scenario result from uncertainty in the price estimation. The quantity of each category is the same for the low, midpoint and high estimate of each scenario.

Table 3-8: Annual benefit per category in billion euros (2050)

	Optimistic scenario			**Realistic scenario**		
	Low	**Mid-point**	**High**	**Low**	**Mid-point**	**High**
land occupation	-4.6	-15.2	-123.6	-0.4	-1.3	-10.6
climate change	46.9	117.1	234.3	12.8	32.0	64.0
fossil depletion	0.0	0.0	0.0	0.0	0.0	0.0
freshwater ecotoxicity	0.0	0.0	0.0	0.0	0.0	0.0
freshwater eutrophication	0.0	0.0	0.0	0.0	0.0	0.0
human toxicity	-0.5	-0.7	-1.0	0.0	0.0	-0.1
ionizing radiation	0.0	0.0	0.0	0.0	0.0	0.0
marine ecotoxicity	0.0	0.0	0.0	0.0	0.0	0.0
marine eutrophication	0.0	0.0	0.0	0.0	0.0	0.0
metal depletion	-1.3	-2.6	-5.2	-0.2	-0.4	-0.7
natural land transformation	0.0	0.0	0.0	0.0	0.0	0.0
ozone depletion	0.0	0.0	0.0	0.0	0.0	0.0
particulate matter formation	-3.1	-4.3	-6.6	0.4	0.6	0.9
photochemical oxidant formation	-0.1	-0.1	-0.1	0.0	0.1	0.1
terrestrial acidification	-0.1	-1.1	-1.3	0.0	0.3	0.4
terrestrial ecotoxicity	0.0	-0.2	-0.2	0.0	0.0	0.0
urban land occupation	0.0	0.0	0.0	0.0	0.0	0.0
water depletion	0.0	0.0	0.0	0.0	0.0	0.0
Total	37.2	92.9	96.1	12.7	31.3	54.0

Based on the table the following lessons can be learned. First of all, the results show that the total environmental impact decreases with PtG; in both scenarios the low, midpoint and high estimates show that PtG decreases the environmental damages; so there are net benefits. Second, the effect on climate change (emissions outside the energy system) is always the largest effect. Third, the effect on land occupation is substantial. This is especially so in the high estimate, because the price of land occupation increases much more between midpoint estimate and the high estimate than the effect on climate change. The land use effect in the realistic scenario is compared to the climate change effect smaller which is the result of the difference in the scenarios in the biomass allocation and because there are differences in consuming processes using different types of biomass with different upstream impact (e.g. BtL uses wood chips, while biomass gasification for hydrogen uses cleft timber).

For 2030 and 2040 no environmental effects are calculated, but these are inferred by assuming environmental effects (in euros) to develop proportionally over time like the security of supply benefits. So for the 2040 values we multiplied the 2050 values with the ratio of security of supply benefits of 2040 divided by the security of supply benefits of 2050. These values are directly used in Chapter 4.

3.4 GDP and employment effects

Developing and employing PtG technologies leads to additional spending, part of which should be government based. Such additional spending could create additional GDP growth and additional employment benefits, which are social benefits that should be included in a social cost benefit analysis. However, in calculating the social benefits a number of issues are relevant. First, the mechanism through which additional spending could create additional GDP or additional employment. This mechanism described is standard economics and can be found for example in [42] (especially chapters 31 and 32). Second, the size of the additional spending, correcting for crowding out of spending. We discuss both issues below.

Could additional spending create additional GDP and additional employment?

Normally, production in an economy is determined by the availability of capital goods, technologies available and the size of the labour force willing to work. These factors of production determine the long run production function. This production does not depend on the price level of the economy. In Figure 3-1 the long run production function is the vertical line at a GDP of 100. Long run production in the economy is of course not fixed, but depends on for example investments in physical capital, human capital, investments in technological development (like R&D expenditures), labor market policies which influence the supply of labor, and natural constraints (natural resources available and choices made with respect to the use of these, like CO_2 emission constraints). Hence, the long run production does not depend on the price level, but also not on demand (in the long run price adjustments imply that the labor market clears and all production capacity is used. In the long run production as large as possible with an efficient use of the production factors labor and capital.

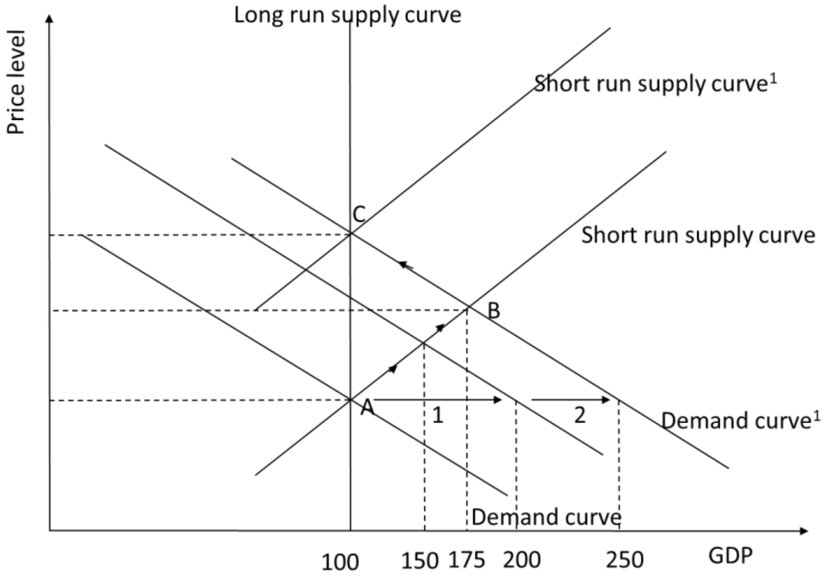

Figure 3-1: The effect of additional spending on the economy

In the short run the production depends on demand and the price level. Starting from an equilibrium point *A* where production is equal to the long run production capacity, the demand curve and the short run supply curve intersect at the same point. Note that the demand curve is downward sloping, since normally a decrease in the prices leads consumers to increase the demand for goods, and that the supply curve is upward sloping since producers are willing to produce and sell more of their goods if they get higher prices. Unexpected demand from abroad or unexpected additional spending of the government might lead to an increase in demand. Such an increase in the demand given the price level, so a rightward shift of the short run demand curve denoted with ‘1’ in the figure, will in the short run lead to increased production (the short run equilibrium is the intersection between the short run supply curve and the demand curve) and lower unemployment. The initial increase is here normalized at 100, leading to an increase of production of 50. The increased production results in increased income which leads to further increases in demand further increasing production. This process will go on but much of the effect will be leaking away (because of taxation, savings and imports reducing domestic demand). The whole process of additional spending is indicated in the figure with ‘2’. Here this multiplier effect is assumed to be 50 percent of the initial stimulus. The demand curve is now dented demand curve[1]. If prices would have remained the same the production (GDP) would have increased to 250. However, given the upward sloping supply curve prices increased to maintain short run equilibrium, so the economy ends in points *B*, with a GDP of 175 and a higher price level.

How much GDP increases due to a sudden, unexpected increase in demand depends amongst others on the state of the economy. In an economic recession an increase in demand will lead to a much greater increase in production, than during an economic boom when most production factors are already used at full (efficient) capacity and further increases in demand result in stronger price increases and lower GDP increases. In terms of the figure, in a recession the short run supply curve is much flatter than during a boom.

The increase in production (GDP) is realized by a more intensive use of existing production factors, for example by working longer days or by unemployment falling below the equilibrium search level. Such more intensive usage of production factors leads to stress on markets of labour and capital goods leading to wage and price adjustments (increases). Price increases reduce demand and reduce production because production becomes more expensive. This makes that the short run supply curve shifts leftwards (denoted short run supply curve[1]). The economy ends back at the original production level, determined by available production factors, at higher prices (point c in Figure 3-1). Total demand will be the same as before, but might have changed in composition.

Determining the multiplier and the adjustment process in practice is complicated. [43] (following [44]) in a social cost benefit analysis of CO_2 emission reduction policy assume that the adjustment period is 10 years, and that each year 10 percent of the initial increase in GDP disappears. They appear to use a multiplier of 0.5 like [44]. Note that the speed of the adjustment might depend on what kind of goods are in more demand because of the increase in demand. If, like in CO_2 abatement policy, the demand for goods requiring engineers goes up, scarcity might be much more immediate leading to higher prices, whereas when the demand is for goods that require unskilled labour the price increases might be much less quickly. So given that the topic here is the energy system, the adjustment of the economy might be relatively quick lowering the effect.

Secondly, the size of the additional spending, correcting for crowding out of spending

The next the question is how big is the initial increase in demand, and how unexpected is this. In all scenarios studied CO_2 emission reduction is substantial (ranging from 80 to 95 percent). This requires substantial investments from companies, households and governments and requires further operational costs (see section 3.1). However, it is hard to see these expenses as additional expenses: companies, households and governments can spend their income only once. So if a company invests in a power-to-gas plant it cannot invest the same amount in another production facility. Borrowing is possible, especially for governments; however this requires that in the future debts have to be repaid. So if a government had borrowed to stimulate demand, than in the future it has to increase the taxes to repay its debt, reducing demand in the future.

Add to this that the increase in demand (shift 1 in Figure 3-1) should be to some degree be unexpected, otherwise producers and consumers will adapt the expectations and prices much quicker. For climate policy with a time horizon until 2050 unexpectedness of the investments is a very hard assumption give the policy and media attention climate policy is attracting.

Therefore, most of the demand for clean technologies is a change in the composition of demand rather than an increase in demand. And where there exists an increase in demand it is unlikely that it is sufficiently unexpected to lead to increases in GDP. So in other words some sectors will grow, but others will decrease, the net effect for the economy (or for gross domestic production; GDP) is zero.

Sign and size of the investment change in the social cost benefit analysis

The text above discussed the effect of an impulse from investing in PtG and that the effect is likely to be zero. So far undiscussed was the size and sign of such an impulse. In the SCBA we compare the situation with PtG with the situation without PtG. With PtG technology the investments in this technology will be bigger than if this technology is ruled out. That suggests a positive spending effect. However, the investments in other technologies that are part of the energy system fall, see Table 3-3. Hence, the net effect of the demand increase of PtG is negative, which is contrary to the direct effect.

Conclusion

An increase in demand could lead to a temporary increase in production (GDP) and employment. However, such an increase will be temporarily due to adjustments via markets where scarcity (like for example labour) will lead to higher prices (i.e. wages). The additional investments in the energy system will most likely lead to a much smaller additional demand because the additional investments crowd out other expenses. Furthermore, the remaining additional investments will not be unexpected. Therefore an additional GDP or employment effect is unlikely. Therefore we estimate these effects to be zero here.

If despite the arguments above, such a demand effect would be deemed likely, the sign would be negative here, since PtG technologies lead to less investments in the energy system compared to the energy system without PtG.

3.5 Grids

PtG might have an impact on grids as it could enable integration of renewable and intermittent sources in the grid and relieve capacity constraints of the electricity grid and thus prevent costly expansions. The JRC-EU-TIMES model includes grids, but given unavoidable modelling constraints the granularity is less than ideal for this issue.

A technical study with more detailed analysis of the effect of PtG on transmission and distribution grids can be found in D6.4 [45]. They analyse whether PtG can compensate for the imbalances of renewable energy due to differences between forecasted and realized production i.e. forecast errors related to the weather. Assuming that PtG is the only source of flexibility, they find that 7.2-10 GW of PtG reduces imbalances in EU transmission networks with simplified network topologies considerably. Unfortunately, PtG benefits for grids have been calculated in technical terms only, although further work within the STORE&GO project is envisaged on future scenarios and the impact of PtG on electricity infrastructures by the end of August 2019 (D6.6).

Hence the question is whether the costs of the grids are not understated in the cases without PtG. TSOs argue that it is technically, economically and socially difficult to build sufficient electricity grid capacity to connect all the renewable energy to the grid. Accordingly some energy should be converted to molecules (either hydrogen or methane). If so PtG has an additional benefit.

Electricity grid operator TenneT ,jointly with gas grid operator GasUnie made a study [46] looking at the grids towards 2050 under a 95 percent emission reduction scenario taking both gas and electricity grids into account. They modelled Power-to-Hydrogen in both countries, but Power-to-Methane only in Germany (see their page 89). They find a small flow of methane coming from Power to Methane in Northern Germany, lowering the connection of wind energy at sea to the German energy system. They focussed at the grids, so their energy system is less detailed than in JRC-EU-TIMES. Moreover they did not include any economic evaluation, investment costs, or commodity prices in their analysis. That makes it hard to generalize their Dutch/German findings to the European context. The study makes clear though that local bottlenecks in grids might be relieved with power-to-gas. Consequently, in the optimistic and the realistic scenarios a plus is included as a positive, but unquantified and valued, effect in the tables in Chapter 4.

3.6 Other effects

3.6.1 Effect on growth[21]

Stringent environmental policy imposes constraints on technologies deployed and thus on production levels (stricter constraints shift the long run supply curve leftwards in Figure 3-1). The current scenarios use the economic development of the European reference scenario with limited greenhouse gas emission reduction as exogenous input. However, the scenarios used here have a much more stringent greenhouse gas policy than the European reference scenario, thus have much less technological possibilities and therefore GDP will in these scenarios be likely less than in the European reference scenario. Note that this is already so in the case without PtG. Having PtG technologies available makes these environmental constraints less stringent. This is also indicated by lower CO_2 prices. Less stringent constraints will lead to an increase in GDP i.e. PtG has a positive effect on GDP. However, it is hard to estimate the magnitude of this effect and the effect is likely to be small (compare the cost savings caused by PtG with the total costs of the energy system in Table 3-3).

3.6.2 Costs of government action

The analysis does not include the costs of the government for reaching the 95 percent GHG emission reduction target. For reaching that target a combination of taxes, subsidies, innovation stimulus, norms, and other policies (like the creation of functioning CO2 permit markets) is necessary. This includes paying for R&D for developing technologies which are still too far from market introduction to be applied and earn back the money of the investors. Such policies are costly, either in the form of direct expenses or in the (distorting) impact they have on decisions of households and companies. Predicting the necessary or actual policy mix for the next 30 years is close to impossible, this makes quantification impossible.[22]

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[21] This section discusses a supply side impact on GDP: the technology used to produces goods and services (measured in GDP). This is different from Section 3.4 which focusses at demand side impact at GDP: how much does GDP increase if demand for goods and services increases through policy. Or in other words technology push versus market pull.

[22] In the literature only one estimate is available ([43]), and this concerns an estimate for the whole climate policy, and not for a specific subpolicy such as PtG.

Note that most of these costs to reach 95 percent CO_2 emission reduction are the same for each scenario with PtG technologies and without PtG technologies. The differences are the cost to develop and adopt PtG technologies in the scenarios with these technologies, and probably a small reduction in cost to develop and adopt other clean technologies. Part of these cost have to be made before it is known which scenario best describes the future. So if a government decides to support PtG development, it is necessary to do so also in the scenarios where the technology will not be adopted in the end.
These costs associated with government action cannot be quantified. However it seems unlikely that it is substantial figure compared to the benefits in the optimistic and realistic scenario. Therefore this effect is mentioned, but not valued in the tables.

4 Results and conclusion

This chapter presents the result of the social cost benefit analysis (CBA) of power-to-gas (PtG; that is including methanation, power-to-hydrogen is not studied separately). Chapter 4.1 presents and discusses the overall outcome of the CBA and sensitivity analysis. Chapter 4.2 presents the main policy conclusion. Section 4.3 discusses some suggestions for future research.

4.1 Main findings

Chapter 3 analyses and monetarizes the main effects of power-to-gas. This section presents the overall result of these effects.
Table 4-1 summarizes the main output for the midpoint estimate for 2040 and 2050. The midpoint estimate is the best estimate of the effects of PtG. Table 4-2 shows the valuations for the low and high valuation in the corresponding years. This shows the bandwidth of plausible outcomes. The midpoint estimate is always between the low and high value, although not always precisely in the middle.

Before aggregating of the single effects was possible, a few more steps were necessary:

- JRC-EU-TIMES calculates a best estimate for each scenario, no low or high estimates are given. Therefore in the low and high estimate, the best estimate of JRC-EU-TIMES is used, since an estimate of the uncertainty around the model estimate for the 2040 and 2050 predictions is impossible.
- All signs are made consistent. The change of the costs of the energy system (Section 3.1) as result of adding PtG to the scenario was negative, meaning less costs, so a benefit. In this section all benefits are positive values, so aggregation and interpretation is possible.
- Security of supply benefits are in the alternative scenario estimated at € 0.2 billion (Section 3.2). This is based on a model run with PtG, however there is no corresponding model run without PtG available, since PtG is hardly applied. For the estimation of security of supply benefits this poses not a problem, whereas the changes of system costs and environmental effects cannot be approximated. However, the deployment of PtG is very small in this scenario, making it likely that the effects for the energy system and the environmental effects are very small too. The effects of the alternative scenario should therefore be read as nil.
- The effects of PtG on the grids and on other effects (growth and government action) are indicated with ‘0’, ‘+’, or ‘++’ with the size of the effect roughly in correspondence to the size of PtG in that scenario and thus in line with the other effects.
- These are annual values representative for the decade around this year (so 2050 is representative for 2045 until 2055).[23]

[23] Most cost benefit analyses present a net present value (aggregation over time taking the time preference into account), hence an aggregation over the lifetime of an investment does have an effect. Here annual effects are presented. These annual effects could have been aggregated over a few decades (assuming a specific growth rate, for example a linear one), but this would only have led to bigger numbers, not to a different sign or different conclusion. Note that the difference between annual effects and net present value as commonly presented is not that large since the investment costs in the energy system are converted into annual costs by calculating annuity values in JRC-EU-TIMES.

Table 4-1 contains the main results of the CBA for 2040 and 2050. It shows that:

- PtG has a positive contribution to European welfare in 2040 and especially 2050 in two possible scenarios, with the total effect in the optimistic scenario substantially exceeding the effect in the realistic scenario. PtG has a slightly negative welfare contribution in the alternative and the pessimistic scenario, since the government invests a bit in developing PtG technologies before it is known how the future evolves, i.e. which scenario is reality. Government backed investments in PtG are likely to be a fraction of the total net benefits in the optimistic and realistic scenario. Note that the scenario names are logical in the STORE&GO project: optimistic means PtG is applied most, while for most observers this would be the most pessimistic scenario as it is characterised by many system constraints and energy system costs are the highest of all scenarios. Thus if circumstances are the most detrimental to achieving 95% GHG emission reduction, having PtG available is the most advantageous. Therefore the technology should be part of the portfolio of technologies to be further developed, especially to hedge against conditions where it is hard to achieve 95% GHG emission reduction. The analogy with an insurance is strong: people buy an insurance to use under adverse circumstances, not under all or under favourite circumstances.
- Note that there are no costs quantified in the table. The R&D costs necessary to further develop PtG technologies cannot be quantified, therefore they are only included in a qualitative way. Only quantified benefits might seem surprising, is partly inevitable and partly simply the result of the analysis. That PtG leads to cost savings in the energy system is logical given the cost minimizing nature of the model used and the addition of a technology. That PtG also has benefits for security of supply and the environment is a consequence of the analysis, and could have been different given that these are external effects for the energy system.
- The total effect in 2050 is substantially bigger in 2050 than in 2040, which is in line with the late adoption of this technology in the energy system in earlier STORE&GO analyses.
- The net environmental benefits of PtG in the energy system can be substantially larger than the effects of PtG on the energy system costs. The benefit PtG has for the security of supply is likely to be smaller than the reduction of the energy system costs caused by PtG.
- There are two other effects that could not be quantified or monetarized. The first is the effect on economic growth via technological improvement and the second are the costs of government action to stimulate development and deployment of PtG. The first effect is positive for European welfare, the second negative. Both effects are likely to be small, and without impact on the conclusion.
- The distribution of effects cannot be shown in detail (that requires much more detailed modelling of pricing and government intervention than currently possible). However, it is clear that much of the benefits of PtG end up with other parties than the investors, giving rise to substantial external effects. This is most obvious from the security of supply benefits and the environmental effects that end up with society (via the economy and the environment respectively). Since quite some of the benefits do not end up with the investors in PtG, it is likely that investments in PtG are lower than socially optimal and that government policy aimed at increasing the development and adoption of PtG technologies is welfare improving, especially if scenarios with many constraints for achieving 95% GHG emission reduction become reality.

Table 4-1: CBA – Midpoint estimate, 2040 and 2050, billion euro per year

	2040				2050			
	Optimistic	Realistic	Alternative	Pessimistic	Optimistic	Realistic	Alternative	Pessimistic
System cost savings	7	0	0	0	68	4	0	0
Security of supply benefits	5	0	0	0	28	3	0	0
Environmental effects	17	0	0	0	93	31	0	0
GDP and employment effects	0	0	0	0	0	0	0	0
Grid effects	+	0	0	0	++	+	0	0
Growth	+	0	0	0	+	+	0	0
Cost of government action	-	-	-	-	-	-	-	-
Total	28 ++-	-	-	-	189 +++-	38 ++-	-	-

Note: Due to rounding, some totals may not correspond with the sum of the separate figures.
Note: In the bottom row the '+' and '-' signs just aggregate the same signs in that column without weighting these unquantified effects.

Table 4-2 shows the results of the sensitivity analysis i.e. upper and lower values for all effects and the total outcome. The left four columns show the estimates for 2040 and the right four columns show the 2050 values. The first seven line show the low estimates, and the bottom seven rows show the high estimate.

- The main conclusion is the same as in Table 4-1: PtG contributes positively to European welfare in 2040 and especially in 2050 in the optimistic scenario and to a lesser degree in the realistic scenario. The effects increase over time as also the deployment of PtG increases over time. In the alternative and the pessimistic scenario, the cost of government action to develop PtG before it is known which scenario becomes reality creates a slightly negative outcome.
- Uncertainty is substantial. One of the factors contributing to this uncertainty is the substantial increased value for land use in the high estimate in the environmental effects.
- Also the estimated values for security of supply benefit and the environmental benefit vary substantially between the low and the high estimate. This uncertainty results from different assumptions and input in the price estimation. No uncertainty is the result of uncertainty of the quantity, since JRC-EU-TIMES only made a point estimate for each scenario. In reality the quantities (given the conditions of each scenario) are uncertain as well (so effects can be larger or smaller). So the uncertainty of the outcome is larger than can be depicted.
- For the total effect the midpoint estimate of the previous table always is between the low and high estimate.
- Finally, note that the estimation of especially security of supply benefit and the environmental impact depends crucially on assumptions and on extrapolating methods to different countries and time periods. Sometimes these extrapolations and assumptions were stretching the boundaries of what could be done reasonably. However, otherwise arriving at a value for these effects would be impossible. The fact that the outcome is always positive provides confidence in the outcome. Still, the outcomes should serve as an indication, whereas future research and

additional insights are necessary to perform more detailed estimates once PtG technology develops further.

Table 4-2: CBA – low and high value, 2040 and 2050, billion euro per year

		2040				**2050**			
		Optimistic	Realistic	Alternative	Pessimistic	Optimistic	Realistic	Alternative	Pessimistic
System cost savings	Low	7	0	0	0	68	4	0	0
Security of supply benefits	Low	2	0	0	0	8	1	0	0
Environmental effects	Low	8	0	0	0	37	13	0	0
GDP and employment effects	Low	0	0	0	0	0	0	0	0
Grid effects	Low	+	0	0	0	+	+	0	0
Growth	Low	+	0	0	0	+	+	0	0
Cost of government action	Low	-	-	-	-	-	-	-	-
Total	Low	16 ++-	-	-	-	113 ++-	38 ++-	-	-
System cost savings	High	7	0	0	0	68	4	0	0
Security of supply benefits	High	12	0	0	0	76	11	0	0
Environmental effects	High	15	0	0	0	96	54	0	0
GDP and employment effects	High	0	0	0	0	0	0	0	0
Grid effects	High	+	0	0	0	++	+	0	0
Growth	High	+	0	0	0	+	+	0	0
Cost of government action	High	-	-	-	-	-	-	-	-
Total	High	34 ++	-	-	-	240 +++-	68 ++-	-	-

Note: Due to rounding, some totals may not correspond with the sum of the separate figures.

Comparison to other studies

[47] shows that studying PtG in an optimized system might give a different outcome than when the private business case is analysed. Their stylized model of the Irish electricity market shows that private investments in PtG are not economically attractive. That model also showed that PtG might increase the benefits of the renewable generation to such extent (by increasing demand at hours with low demand) that the increased profitability of the renewables might make investing in PtG attractive for electricity companies with a significant share of renewable generation in their portfolios. This effect is also illustrated in our analysis; we found substantial external effects leading to less than social optimal deployment. Note that the current simulations with the JRC-EU-TIMES model are not a full social optimum; the external effects (like the security of supply effect or the LCA benefit) are not taken into account in determining the optimum PtG investment. Given these external effects, the estimated PtG deployment here is lower than socially optimal as well.

[48] found PtG to become societally attractive at 200 €/ton CO_2 or above. Our estimation based upon JRC-EU-TIMES is in line with this estimate; no PtG is deployed in the alternative scenario with a CO_2 price below 150 €/ton, while PtG is applied in the realistic and the optimistic scenarios which have CO_2 prices substantially above 200 €/ton (i.e. around or above €1,000 €/ton).

4.2 Policy implications

Before PtG can contribute to European welfare, it has to overcome two clear bottlenecks. First, the existence of external effects make that private investors have a too small incentive to invest. External effects identified are security of supply benefits and environmental benefits, but also quite some of the benefits in the energy system do not fall with investors in PtG. Second, application of PtG requires, in comparison to the current situation, substantially improved efficiency in both production of hydrogen and in the methanation phase.

In order to overcome these bottlenecks, policy measures are necessary. The first set of policy measures should stimulate private investors to take into account positive and negative societal effects in private decisions ('internalization of external effects'). The government should stimulate this through subsidizing positive external effects i.e. effects on security of supply and the environment, and taxing negative external effects (for instance, on the environment). One other option to consider when designing these measures in detail is to create a standard. For example, requirements on back up capacity for more variable and less predictable renewable energy might create an incentive to develop more storage with PtG being one of the useful technologies.

The second set of measures should target the required improved efficiency of the production of hydrogen and methanation. Improving efficiency requires more research and development, pilot projects, and initial production at non-market based conditions. Partly this falls under the general R&D stimulation policies in European countries (like existing tax credits for R&D expenditures), but also specific subsidies, public funding or co-funding of research projects aiming at increasing efficiency of the PtG technologies will be necessary.

4.3 Suggestions for future research

Most quantities and prices used for the social cost benefit analysis are uncertain. Some effects could not be quantified at all in the current project (like the effect of PtG on the grids), even though these effects could be substantial. Hence, more research on these effects is considered to be useful. Preferably, these effects should be derived from dedicated modelling analyses that allow for more precise estimations of effects.

Besides, some research will also be needed to develop future prices of environmental goods. This research should better account for environmental effects of non-reproducible nature and the extent to which recent European and member state legislation aiming for significant greenhouse gas emission reductions in agricultural, commercial, industry, residential, and transport sectors affects the prices of different environmental impact categories.

From the energy security perspective it is important to gain better insights in the contribution that PtG could make towards relieving grid constraints both within and across European countries. This requires a model with a sufficient network granularity.

Furthermore, future security of supply deserves more attention, especially the geopolitical aspects. The effect of PtG on the fossil fuel supplying countries will be limited: these countries lose their business model under scenarios with strict emission reduction; PtG seems to have limited impact on the remaining use of fossil fuels. In addition, in JRC-EU-TIMES it is impossible to import on large scale hydrogen or synthetic fuels from places outside Europe (e.g. from the MENA region) with higher availability of renewable energy sources due to e.g. more solar irradiance or higher wind speeds. In reality this can happen and it might be economically attractive, and might have geopolitical implications which are outside the scope of the current report and of [4].

Besides, from the system cost perspective it would be good to see how the large scale import of cheap energy carriers (including synthetic gas) from outside the EU, e.g. from the MENA region with higher availability of cheap renewable energy sources, would affect the adoption and utilization of PtG facilities in Europe.

These will be quite demanding tasks. However, it seems unlikely that all uncertainty will be resolved (predicting the future is always an uncertain exercise). Furthermore, it is deemed unlikely that new research will alter the main conclusion that PtG can be useful in some circumstances, but not in others, and its development requires government policy given the externalities of PtG and the uncertainty associated with long term technological developments.

There are two further potential benefits of developing and adopting PtG technologies in Europe that are not discussed here. First developing these new technologies might help countries outside Europe in adopting stricter climate policies. If so this might create further climate benefits. Second, if Europe develop these technologies it might take a lead in producing and designing this equipment, creating an comparative advantage for Europe in this industry.

Given that PtG's attractiveness depends both on its own technological progress and the technological progress of other sometimes competing technologies as well as the external circumstances (which scenario becomes reality), future research should evaluate how attractive further development of PtG is given updated conditions.

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Appendix: Additional details

Table A1-1: Detailed assumptions for the scenarios

	Scenario			
Key assumption	**Optimistic**	**Realistic**	**Alternative**	**Pessimistic**
CO2 target	95	95	95	95
CCS	No	No	Yes	Yes
Biomass potential	Low	Ref	High	Ref
VRE potential	High	High	High	High
Geothermal potential	Low	Low	Low	Low
Nuclear	Yes	Yes	Yes	Yes
Coal allowed	Yes	Yes	Yes	Yes
Gas price	High	Ref	Ref	Ref
Oil price	Ref	Ref	High	Ref
Electricity network	High	Ref	Ref	Ref
DSM	Ref	Ref	High	Ref
PtG cost	Low	Low	Ref	Ref
PtG efficiency	High	Ref	Ref	Ref
PEM performance	High	Ref	High	Ref
PtL performance	Low	Ref	Ref	Ref
SOEC	Yes	No	Yes	No
LNG efficiency for ships	High	Ref	High	High
Electric trucks	No	No	Yes	No

Note: For the pessimistic scenario several scenarios of [1] could be used with various assumptions. Here key assumptions from scenario '95' are used as far as possible.

Table A1-2: Environmental impacts in 2050 for the realistic scenario

Impact category	Unit (*x* millions)	Optimistic - CBA - with PtG	Optimistic - CBA - without PtG	Comparison	Comparison in percentage
Land use	m2a	1,058,024	1,042,597	15,427	1%
Climate change	kg CO2-Eq	1,590,678	1,654,698	-64,020	-4%
fossil depletion	kg oil-Eq	306,405	326,435	-20,030	-6%
Freshwater ecotoxicity	kg 1,4-DB-eq.	1,282	1,345	-63	-5%
Freshwater eutrophication	kg P-Eq	312	311	1	0%
Human toxicity	kg 1,4-DB-eq.	749,967	749,524	443	0%
Ionizing radiation	kg U235-Eq	239,146	239,812	-666	0%
Marine ecotoxicity	kg 1,4-DB-eq.	6,827	6,825	2	0%
Marine eutrophication	kg N-Eq	380	380	0	0%
Metal depletion	kg Fe-Eq	681,382	674,420	6,962	1%
Natural land transformation	m^2	221	231	-10	-4%
Ozone depletion	kg CFC-11.	9	9	0	0%
Particulate matter formation	kg PM10-Eq	3,434	3,448	-15	0%
Smog formation	kg NMVOC	7,349	7,394	-44	-1%
Acidification	kg SO2-Eq	7,384	7,451	-68	-1%
Terrestrial ecotoxicity	kg 1,4-DB-eq.	389	387	2	0%
Urban land occupation	m^2a	54,923	54,753	170	0%
water depletion	m^3	14,350	14,329	21	0%