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STORE&GO

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

D7.4

Full socio-economic costs and benefits of energy mix diversification and the role of power-to-gas in this regard

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Executive Summary

Energy mix diversification is a key element of energy security, one of the three main goals of energy policy in the European Union. The more diverse the energy input of a country or region is, the less prone it is to energy security disruptions. In the context of the STORE&GO project therefore one of the societal impacts of Power to Gas (PtG) that has to be accounted for in a social cost benefit analysis (SCBA) is its effect on energy mix diversity, or in a broader sense, energy security. This deliverable analyses *What is the contribution of Power-to-Gas to energy mix diversity and more broadly to energy security? Can this development be quantified and preferably be valued?*

The energy security contribution of Power to Gas is analysed for four scenarios for Europe until 2050, assuming a CO_2 emission reduction of 95 percent. These scenarios are analysed with the JRC-EU-TIMES model, which contains an extensive energy system representation at European scale. 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 calculated, one with PtG technologies in place and one without such technologies. Comparing these two scenarios showed the energy security benefit of PtG. Compared to D6.3 [13] a major change is lowering the discount rate used from the business perspectives towards the much lower societal discount rate. This increases the use of PtG. Taxes, subsidies and regulation are not optimised to maximize the deployment of PtG, whether this will be desirable is the topic of D7.6.

Before presenting the main results, it is important to realize that energy security is a broad and diverse concept. Some of the research on energy security starts from a physical availability perspective, while other research starts from the price volatility perspective. Furthermore it is a broad field with several contributing scientific disciplines. Political scientists approach energy security as an issue of sovereignty, while engineers and complex system analysts consider energy security as issue related to resilience and robustness respectively. Economists and system analysts focus on the resilience perspective, which looks into all types of risks originating from less predictable factors of any nature, such as political instability, economic crises, disruptive technologies, or extreme weather events. Also the time horizon and geographical scope can matter a lot for how energy security is analysed. Ultimately energy mix diversity and energy security is about fulfilling the need of society for energy services. Consequently, energy security is not about the energy sector being distorted but about society being disturbed.

Since there are various ways to look at the issue and the differences matter, there are many different indicators on energy security. Nevertheless, there exist only a few valuation studies on energy security. Therefore this deliverable presents first the evaluation for several indicators and subsequently outlines and applies all relevant valuation approaches on PtG, using the JRC-EU-TIMES for four different EU energy system scenarios (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.

Concerning the first part of the study, the indicators are all related to the sovereignty, resilience and robustness perspectives of energy systems. For these perspectives the main findings for all scenarios are that:

- Overall, all indicators studied in detail, for the sovereignty, resilience and robustness perspective, show an improvement of energy security towards 2050. For all these indicators the impact of PtG is limited, although it should be noted that no indicator covers all (or nearly all) aspects of energy security. The indicators that can be shown might underestimate the relevance of PtG for future energy system. Nevertheless, the total societal impact of PtG can be significant, as shown in the validation estimations below.

- For the *sovereignty perspective* given the 95% GHG emission reduction scenarios the indicators show an improvement in the European energy security from 2015 towards 2050. The imported energy from outside Europe relative to the total primary energy supply (TPES) falls. The imported gas as percentage of all consumed gas and the costs of imported gas decline substantially as well. This picture could change if scenarios are included that import 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, which would lead to a trade-off between lower cost and sovereignty.

- For the *resilience perspective* the energy security indicators show a slightly diverging perspective. The diversity of primary energy sources increases towards 2030, showing an improvement of energy security, while it becomes more concentrated afterwards. Electricity generation shows the opposite pattern. The diversity of electricity generation decreases towards 2030 and then increases again towards 2050 at current levels. Energy intensity (energy used as fraction of GDP) will fall for all scenarios, indicating higher resilience of energy consumption sectors including the transport sector for energy price fluctuations.

- For the *robustness perspective* one indicator could be quantified, that is the spare capacity of electricity generation. Another fundamental indicator of robustness is the ability of electricity networks to deal with the intermittent nature of renewable energy sources, and to balance and stabilize the electricity grids. However, this second indicator could not be investigated due to model constraints. The aforementioned indicator, the spare capacity of electricity generation, increases until 2050. However it is unlikely that this is completely an improvement of energy security, since much of the new capacity will have a relatively low capacity factor. Besides, the indicator does not take into account the possibilities for generation reserve sharing across countries as well as the limitations for generation to meet demand due to grid capacity constraints within countries. Future research may apply more advanced indicators for this perspective e.g. a flexibility margin indicator that provides insights in the extent to which the available electricity system flexibility exceeds the demand for flexibility in energy systems with high shares of variable renewables, including the role of gas storage. Such an indicator should ideally be granular enough to take into account major congestions that would impede that generation meets demand. The latter would require more granular model outputs than were available for this study. A complementary study with more detailed analysis of the grids including the effect of PtG can be found in D6.4 [25].

Most indicators are expressed in physical units, if an indicator is monetary this is not the same as a welfare effect that can be inserted in a cost-benefit analysis. For these reasons, we complemented our study with estimations of the societal value of PtG for energy security, with the valuations being expressed in euros to enable comparison with other costs and benefits in a social cost benefit analysis. The few existing valuation studies of energy security were scrutinized on their merits and for the first time (as far as we know) applied to analyse the contribution of PtG to the energy security of low-carbon energy systems. The following conclusions can be drawn:

- Three methods are elaborated and applied to estimate the societal value of energy security for the European Union: the first method is based on oil price fluctuations and their impact on the economy, the second method is based either on the costs of avoiding outages in periods of very low wind and solar energy production during several weeks or on the costs of outages if no action is taken to avoid outages in periods of very low wind and solar energy production during several weeks, and the third method is based on the willingness to pay for security of supply. Although these methods differ substantially, the outcomes are more or less in line with each other.

- With the same model as above (JRC-EU-TIMES) the same scenarios of possible future developments as above are analysed. In the positive scenario the societal value of PtG is already substantial in 2040 and increases towards 2050. In the so-called realistic scenario, PtG has a positive energy security benefit in 2050, although much smaller than in the positive scenario. Given the large size of the EU energy systems, small changes in energy security due to PtG as shown by the indicators above, result in significant monetary values. In the alternative scenario and the pessimistic scenario PtG has no benefit for energy security. This is in line with predictions on the deployment of PtG technologies, since not-deployed PtG cannot add to energy security.

The estimates of the value of energy security, which are unavoidably dependent on assumptions, can be used in social cost benefit analysis of PtG, which is the upcoming Deliverable 7.6. The outcomes here show that although PtG is not the main driver for energy security, that is replacement of the import of fossil fuels with locally generated renewable electricity generation, it has in some scenarios clearly a positive value. That value lies outside the investors, potentially leading to underinvestment in this technology.

1 Introduction

Energy mix diversification is a key element of energy security, one of the three main goals of the energy policy in the European Union. The more diverse the energy input of a country or region is, the less prone it is to security of supply disruptions. In the context of the STORE&GO project therefore one of the societal impacts of Power-to-Gas (PtG) that has to be accounted for in a social cost benefit analysis (SCBA) is its effect on energy mix diversity, or in a broader sense, energy security. The SCBA (further described in D7.6) compares the development of the European system with and without PtG and calculates the social costs and benefits under various scenarios. Given the importance and broadness of energy security this deliverable focusses at the effect of PtG on energy security as an input for D7.6.

The central research question is:

> *What is the contribution of Power-to-Gas to energy mix diversity and more broadly to energy security? Can this development be quantified and preferably be valued?*

PtG is defined as transforming 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.

In order to assess the contribution of PtG, energy security indicators and welfare indicators have been calculated for a set of scenarios which previously were elaborated upon in D6.3, all assuming 80 or 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 looks into different concepts and definitions of energy security and energy mix diversification. Section 2 also elaborates in how energy mix diversification and energy security relate to each another and why the scope is widened here.
- Section 3 discusses several energy security indicators, and – based on a few criteria – selects a couple of them for this study.
- Section 4 deals with a number of common assumptions and methods used in both D7.4 and D7.6, that enable the results of this deliverable to be used in D7.6. The most notable are the scenarios, the model (JRC-EU-TIMES), and the discount rate used.
- Section 5 presents the results of application of selected energy security indicators, for a set of scenarios.
- Section 6 discusses the development of several energy security valuation approaches and applies these to a set of scenarios.
- Section 7 concludes and provides recommendations for further research.

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

2 Energy mix diversification and energy security

Energy is key to the functioning of a modern economy and a modern society. Almost all industrial process, economic activities, and personal and social activities are impossible without some form of energy. Furthermore, energy is often an important input in processes, so an increase in an energy price will increase the end price of products resulting from those processes. Energy price changes (for import countries mostly price increases) can therefore distort the economy substantially. This implies that having energy available and at the right prices is a key requirement for modern society. Both availability and affordability issues around energy triggered research on energy security and energy diversity. The more diverse the energy use in a country is with respect to energy sources as well as energy carriers, the less impact a supply disruption or steep price increase of one supplier or one energy carrier. Energy security is broader than just energy diversity, since it for example also includes technical notions (for example stability of the electricity grid) and economic issues (for example, how to deal with scarcity). Here both energy diversity and the broader issue of energy security are discussed.

Energy security is a multi-faceted notion, and is not clearly defined. For instance, [1] mentions 36 definitions of energy security, while [2] distinguish 83 energy security definitions. One reason is that some research started with physical availability while other research was triggered by the price increases of oil in the 1970s. Another reason for the wide variety of definitions is that energy security embraces different time spans as it includes operational security on the short term as well as system planning and investments summarized as long-term energy security.

Furthermore, different definitions have been criticized for the wide variety of interpretations they enable, which amongst others makes quantification difficult.[2] This holds for definitions that include concepts such as welfare and affordability ([3], [4]). For instance, an often mentioned definition provided by [5], interprets energy insecurity as the loss of economic welfare that may occur as a result of a change in the price or availability of energy. And [6] defines energy security as the uninterrupted physical availability on the market of energy products at a price which is affordable for all consumers.

Another reason for this multi-faceted notion is the fact that different scientific disciplines each attach a different meaning to energy security. Political scientist approach energy security as an issue of sovereignty, while engineers and complex system analysts consider energy security as issue related to resilience and robustness respectively [7]. The sovereignty perspective focuses on geopolitical risks which could result in foreign control over vital energy systems such as political instability of suppliers. Economists and system analysts focus on the resilience perspective which looks into all types of risks originating from less predictable factors of any nature, such as political instability, economic crises, disruptive technologies, or extreme weather events. Since these risks cannot be well predicted, it is considered essential to build resilient energy systems to respond to diverse risks. Furthermore, engineers and natural scientists apply the robustness perspective which focuses on technical and natural risks. Examples of technical risks are failure of infrastructure components or generation outages. Natural risks include both calm and cloudy periods limiting the electricity production from wind turbines and solar panels as well as the occurrence of natural disasters such as earthquakes or floodings. This approach applies forecasts and probabilistic estimates for risk evaluation [3].[3]

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[2] Several studies also stress that the meaning of energy security differs from country-to-country and thus is context dependent.

[3] An alternative framework focuses on the four A's of energy security i.e. affordability, availability, accessibility, and acceptability ([10]; [11]). Following [4], it is dismissed here since it lacks solid theoretic foundations and its

All three perspectives are relevant for studies that seek to scrutinize energy security of future energy systems. Sovereignty since shifts in trade affect national interdependencies and energy power balances. Robustness as energy systems become more advanced, dynamic and integrated in the future. Resilience as exposure to complex and uncertain factors will remain.

Until recently, many socio-economic studies focused solely on the sovereignty perspective by looking into the import of primary energy sources and basically aiming to answer two questions. First, is fossil energy supply, notably oil and gas, sufficiently available? And secondly, is the (fossil) energy supply sufficiently diversified?

However, for this study this approach has several shortcomings for four reasons. First, given the goals for largely decarbonizing the energy system by the year 2050, the role of fossil fuels will be less important in the future than today, making an approach that is limited to fossil fuel imports less valuable. This holds the more given the fundamental differences between renewables and fossil fuels as the latter are about tapping stocks while the former is about managing flows from variable production [8].

Besides, as discussed before, apart from geopolitical risks there are also technical and natural risks influencing energy security. It is thus important that the analysis includes not only the first risk category, but all three risk categories whenever possible.

Furthermore, imports are just one of the parts of the energy system value chain and do not directly translate in a societal effect that can be used in a social cost benefit analysis. Since effects usually propagate along the energy system value chain other parts of the chain (e.g. production, network, supply, demand side) may dampen disruptions to e.g. imports, and it is thus crucial to look not only to effects on energy sources but also the impacts on end-users via energy carriers. Moreover, if energy systems are radically transformed given GHG emission reduction targets, new energy security concerns relating to energy carriers such as electricity, hydrogen and biomass production may be more important than the availability of fossil fuels ([8], [4]). Consequently, this study will apply a system approach in order to adequately compare different supply chains (as reflected in different scenarios).

Given the need for an approach that covers multiple perspectives as well as a variety of risks of future energy systems, this deliverable applies the definition of energy security of [9] and [4]. Hence, energy security is interpreted as low vulnerability of vital energy systems. Vital energy systems are systems whose failure may disrupt the functioning and stability of a society. These systems can be differentiated along geographical boundaries i.e. national, regional, or world-wide, and sectoral boundaries i.e. a primary energy source such as natural gas, an energy carrier such as electricity, or an energy end-use sector such as industry. Vulnerabilities of vital energy systems are defined as a combination of its exposure to risks and resilience, i.e. its ability to withstand diverse unforeseen disruptions. Vulnerabilities can be either of physical (disruption of energy flows) or financial (disruptions through energy prices) nature.

Finally, given vulnerabilities of vital energy systems the physical impacts of disruptions on different end user sectors can be translated in welfare effects for society. Given the societal perspective of our social cost-benefit analysis, not the disruption of energy services itself is important but the extent to which society i.e. different user categories face consequences of the disruption. Hence, the way

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use is limited to assessing primary energy sources or fossil fuels. Alternative frameworks are discussed in [1] and [9].

society is organized and reacts to disturbances matters for the effect a disturbance to the energy system has on society. Therefore ultimately energy security is about fulfilling the need of society for energy services [12].[4]

This system can be graphically summarized as in Figure 1.[5] Diversity of energy inputs is valuable if and only if it reduces vulnerability of energy services being disturbed. Imagine a country importing only oil, now it diversifies its imports to half oil and half gas. But if the gas is supplied by the same exporter, does this increased diversity reduce vulnerability? The risk of a supplier also depends on the reputation of that supplier, and its behaviour (if a country only imports gas from one country, it might matter whether the supplier is Norway, Qatar or Russia). Figure 1 is also relatively simple, since geographical distances are not depicted. A supplier far away may be riskier than a nearby supplier because the supply chain might be more easily disturbed with a longer distance, especially in case of land transport. It also matters what is traded internationally, which fuel it concerns and whether this fuel can be readily stored. If only electricity is traded, short term disturbances will be much more important than if better storable energy (like coal, biomass or gas) is traded.

In the analysis of the value of energy security, it is important to remember that the threats to energy security should be identified first. For example, tsunamis were not seen as a major threat to the Japanese energy system before 2011, but they were clearly seen as threat afterwards.

Some of the threats to energy security are unrelated to the energy mix diversity. For example power grid failures are (mostly) unrelated to the energy used to generate electricity. It matters how society uses energy services in performing economic and social functions. Increased use of information and communication technology increases vulnerability of society for disturbances of electricity supply, whereas for instance improvements in batteries will lower the vulnerability. Again, if energy systems are disturbed, societal responses matter a lot for the impact. For example, [15] studied how changes in behaviour could be used to reduce electricity use in the case of sudden shortages. [16] studied rationing of supply shortages for the Netherlands. They found that efficient rationing can reduce social costs by 42 to 93 percent compared to random rationing.

Energy mix diversification is thus part of the wider concept of energy security. It is hard to study it in isolation, at the same time studying energy security completely is impossible given the wide variety of effects, threats and links between energy system and economy. The addition of PtG, or more specifically PtM, as technology option could result in a more sovereign, robust and resilient energy system thus limiting the economic effects of disturbances on society. This assumption will be tested in the following chapters.

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[4] Note that this approach also nicely connects to [13] where the end-use demand in the JRC-EU-TIMES model is not defined as power, gas, oil demand but instead as the services that are satisfied with these commodities (e.g. number of houses, space to be heated, materials, travelling distance).
[5] For more stylized diagrams see [14] and [8].

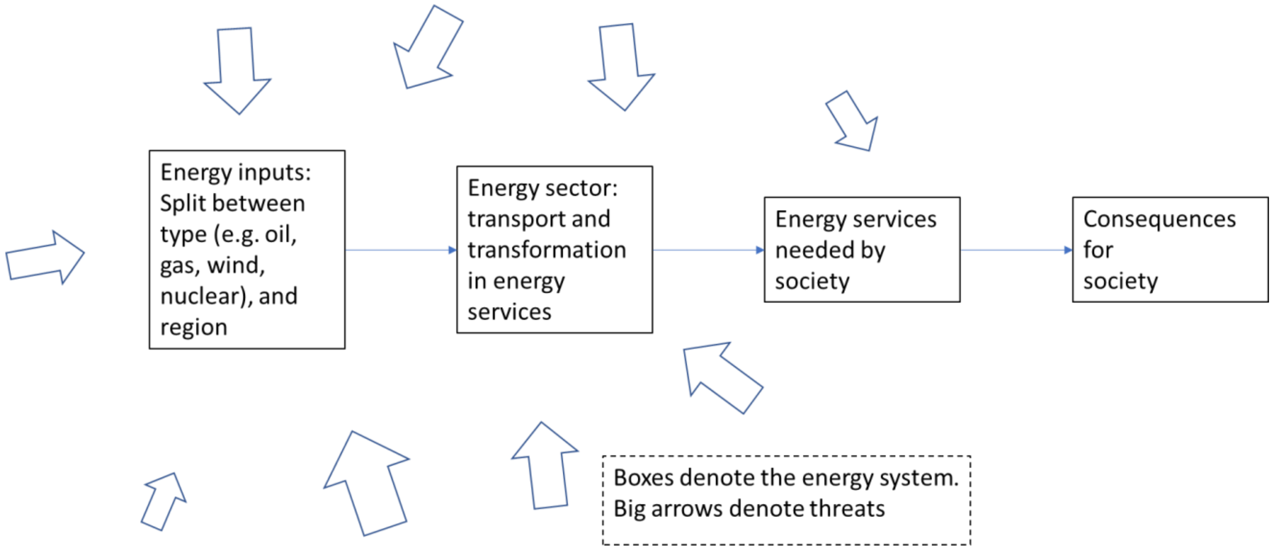


Figure 1: Energy system and threats to the system

3 Review and selection of energy security indicators

In order to test whether vital energy systems with and without PtM are vulnerable to sovereignty, resilience and robustness concerns and thus could fail and disrupt the functioning and stability of a society, it is important to measure energy security with indicators. Given the many energy security indicators that exists, their selection is the subject of this Chapter. Section 3.1 therefore reviews the criteria used for selecting energy security indicators. Section 3.2 describes these indicators, followed by section 3.3, which assesses and selects the appropriate indicators. The indicators are not quantified in this chapter, but in Chapter 5.

3.1 Criteria for selection of energy security indicators

For the purpose of this study, it is important to measure energy security in different energy systems, especially regarding the role of PtM. Different security of energy services dimensions are often scored or ranked by indicators. Generally, an indicator is defined as a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions of, for instance, a country or technology in a given area [17]. They can serve as tools [18]:

- to identify trends regarding the phenomenon captured by the indicator concerned across countries and over time;
- for benchmarking and monitoring performance; or
- to set policy priorities.

Basically, this can be done in two ways: either by applying a range of different indicators to cover trends in separate elements of the value chain (imports, production, network, demand side etc.) or by combining different indicators in a composite indicator. The latter comes down to compiling individual indicators into a single index on the basis of an underlying model [18]. Although these indicators may provide better insights in the net effects of an event as well as the relative importance of different elements in the value chain, they are often less transparent for policy makers.
Nevertheless, both single and composite energy security indicators are relevant for this study.

Concerning the type of indicators, deployment of quantitative indicators is clearly preferred for three distinct reasons. First, quantifying effects can be seen as a manner to make effects of technologies as concrete as possible. The interactions between the deployment of different technology options (e.g. in case a low potential for biomass and carbon capture and storage (CCS) is assumed in a scenario, demand for power-to-methane may be high), cannot adequately be taken into account in a more qualitative type of analysis.

Second, given the different interpretations of energy security or security of energy services as witnessed by the large number of dimensions and indicators mentioned in the literature, from the outset it is unclear which dimensions are more important than others. A quantitative analysis of a range of possible scenarios provides policy makers insights in which energy security elements are most important as well as the contribution of PtM to these elements.

Third, for a social cost benefit analysis availability of quantitative, monetized data for preferably all analysed effects is one of the preconditions to achieve a balanced outcome. It enables analysts to make effects comparable and to prevent double counting.

Therefore, our energy security assessment focuses on quantitative indicators. For more extensive methodological reviews of energy security which include also qualitative dimensions, see e.g. [8].

Given the choice for quantitative indicators, the question arises which indicators are useful to deploy? We deem it not fruitful to make an extensive list of (nearly) all energy security indicators in the world and subsequently to select a limited set of them for quantification. Such overviews have already been made by [19] and [2].[6] Moreover, a single set of metrics which is suitable for assessing energy security for all purposes in all situations does not exist [4]. For instance, part of the indicators of [19] is focused on developing countries with incomplete electricity networks and non-motorized transport. Furthermore, many indicators are not useful in the context of our study since they are focused on threats to primary energy sources and energy carriers which play a major role in current energy systems, while future energy systems could be significantly different. Or, they focus on other energy security vulnerabilities and dimensions than we identified before in Chapter 2.

Rather than going a long way by listing many indicators and afterwards reducing them to a meaningful set, we took into account the fact that energy security is context dependent at the start of our indicator selection procedure by defining a set of criteria for indicators (inspired by [4]):

- The indicator should be instrumental in comparing different scenarios of future energy systems over time in order to test PtM against other low carbon technologies. Therefore, the set of indicators should, where possible, account for the roles of energy carriers and provide information on the effects on end-user sectors.
- The indicators should provide useful information on the three distinguished energy security dimensions i.e. sovereignty, robustness, and resilience.
- The indicator can be calculated from JRC-EU-TIMES model output or scenario data. The JRC-EU-TIMES model contains an extensive energy system representation on the European scale. Given system optimization, the model shows how the transition to a low carbon system could develop until the year 2050 with a focus on energy balances, technology choices and associated costs. It covers many technology pathways and has been updated and extended with different PtM and alternative technology options for the STORE&GO project.
- The indicator should provide additional information to that provided by other indicators.

3.2 Review of selected energy system studies with energy security indicators

Indicators are usually embedded in energy security publications with often different aims and scope. In order to allow for a good understanding of the indicators they are discussed in the context of the studies that deployed them. The following prominent and seminal studies were found in the literature:

- EU standards for energy security of supply – Updates on the crisis capability index and the Supply/Demand Index [20], [21]
- Analysis of impacts of climate change policies on energy security [14]
- Global energy assessment [3]
- Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices [4]

[6] [19] distinguish five dimensions of energy security i.e. availability, affordability, technology development, sustainability, and regulation, and break these down in 20 components. Next, 320 simple indicators and 52 complex indicators of very diverse nature are summarized in a table. [2] reviewed 104 studies published from 2001 to June 2014. They analysed the energy security dimensions and issues considered with indicators, type of study (concerning amongst others temporal and spatial dimensions), specific focused areas (i.e. energy supply, economic, environmental and social areas), and index construction (normalization, weighting, type of aggregation). They emphasize that the meaning of energy security is highly context dependent and results from, amongst others, a country's special circumstances, level of economic development, and risk perceptions.

- Identifying the main uncertainty drivers of energy security in a low-carbon world: the case of Europe [24].

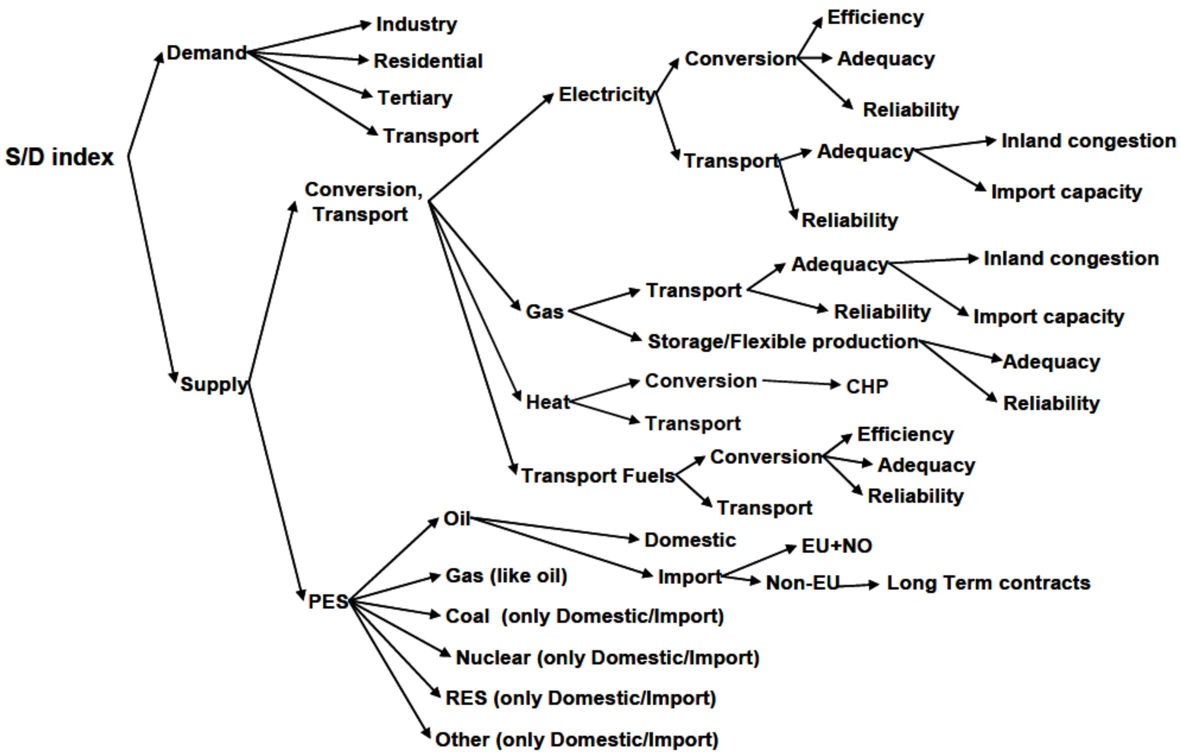
The studies are discussed consecutively in the following sections.

3.2.1 S/D index model (Scheepers et al. 2007)

Context

The S/D (Supply/Demand) index model covers all three parts of the energy system: primary energy supply (PES), energy conversion and transport, and final energy demand. Figure 2 shows the model structure as well as the aspects which are included. For each part of the energy system an indicator is calculated; by combining the three single indicators a composite index can be compiled. This composite indicator is intended to represent the energy demand and supply structure of an EU Member State.

Figure 2: The S/D index model structure



Primary energy supply

Primary energy supply (PES) is subdivided based upon fuels; oil, gas, coal, nuclear, RES, and other. Further distinctions are made based upon;

- Domestic primary energy production versus imports from other EU Member States.
- Imports from the EU (including Norway) versus imports outside of the EU.
- Imports from outside of the EU warranted by long-term contracts versus short-term contracts.

Only with respect to oil and gas, a distinction is made between imports from countries within the EU and outside the EU as well as whether the latter are subject to long-term or short-term contracts.

This branch of the index reflects the sovereignty perspective as effects of geopolitical risks are reflected the score of the PES branch through imports.

Energy conversion and transport

The energy conversion and transport branch is important as the adequacy[7] and reliability of energy conversion and transport infrastructure determines whether final energy demand can be covered by primary energy sources. This branch is thus essential to assess the robustness of energy systems. For this branch, besides gas, the S/D index model distinguishes three secondary energy carriers: electricity, heat and transport fuels. Furthermore, the efficiencies of energy conversion are taken into account, since higher efficiencies will reduce the supply requirements.

Final energy demand

Final energy demand is calculated based upon the energy intensities of the industrial, residential, tertiary, and transport sectors. A higher intensity implies a higher score on the demand branch, indicating a more resilient system.

Calculation of composite indicator

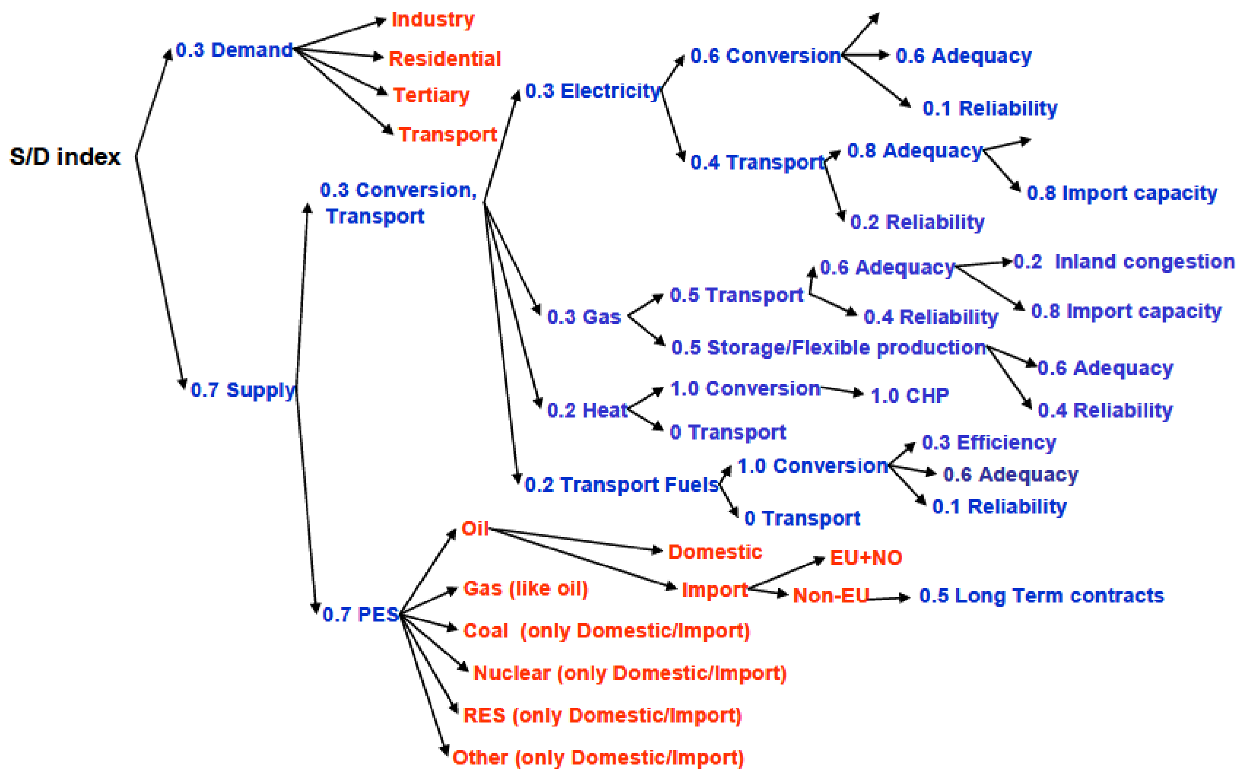
Given the results for the three branches of the energy system, an overall value can be calculated by Member State using four types of inputs:

- Shares of different types of supply and demand
- Values characterising capacity and reliability
- Weights determining the relative contribution of different branches of the model
- Scoring rules determining the index value of each individual aspect contributing to the S/D index

Default values are shown in Figure 3. Objective shares are coloured in red, and subjective weight factors are coloured in blue.

[7] Adequacy is here defined as the extent to which import plus domestic production of an energy carrier exceeds its peak demand.

Figure 3: Weights (defaults) and shares used in the S/D index model



The S/D index has been deployed to compare 27 EU member states on energy security for the years 2005 and 2020 based upon the Trends to 2030 scenario as published by the European Commission in 2006. These scenarios are based upon the PRIMES model.

It has been transposed to a simplified supply and demand index (SSDI) in order to allow for measuring the energy security level of OECD countries over a 40-year period in the past for those countries for which a consistent data set was available [22].

In addition, the index has also been deployed at national level. [21] show recent forward-looking results for Ireland.

3.2.2 Analysis of impacts of climate change policies on energy security (Ecofys et al. 2009)

Context

This study focused on the interaction between achieving a sustainable energy system and improving energy security, and therefore developed a methodology to identify and assess (quantitatively where possible) the impact of (and interactions between) climate policies on energy security. The study aimed to guide policy making by identifying areas, and the extent to which, climate policy can reinforce energy security objectives.

The key link between climate change policies and energy security is through the impact of the climate change policies on the energy system. Climate change policies affect the overall level of consumption of a specific fuel – for example, by fuel switching or demand reduction. In doing so, these policies affect the fuel and technology mix of a country and as such may interact with energy security. Changes at the end of the energy supply chain induced by climate change policies potentially affect the energy security impacts to the EU at all earlier stages of the chain back to international imports.

Due to the effects of fuel switching and demand reduction for primary fuels (either in end-use demand or indirectly through improved conversion efficiencies), climate change effects are found to interact with the majority of energy security issues.

The potential effects of climate change mitigation options on energy security have been analysed for several root causes of energy insecurity:

- Extreme events
- Inadequate market structures
- Resource concentration

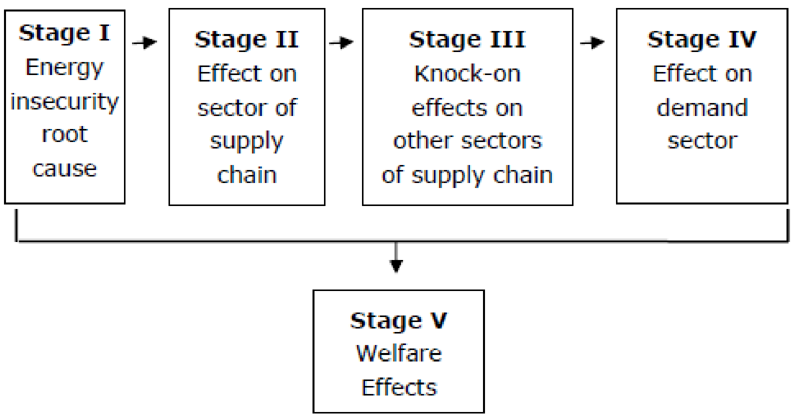
Mitigation options considered include fuel switching to RES for electricity, heat, biogas and transport respectively as well as fuel switching from high to low carbon fuels, amongst others.

Once the interactions between climate change policies and energy security root causes were identified, relevant indicators have been selected based upon an extensive literature review. The review identified two main groups of energy security indicators:

- **Vulnerability-based indicators**: which measure inputs that can be considered a proxy for the potential risk and/or magnitude of an energy security impact, should it actually occur. For example, import dependence provides a proxy for the vulnerability of the energy system to a physical interruption to energy imports rather than a measure of the actual disruption to imports.
- **Outcome-based indicators**: by contrast, these indicators aim to measure the actual outcome of energy insecurity. In an ideal world an outcome-based indicator would measure the actual welfare impact of energy insecurity. However, given the inherent uncertainties in estimating this, an estimate of the level of physical unavailability of energy is normally used. Examples of this type of indicators are discussed in Chapter 6.

Given the complexity of outcome-based approaches, the study focuses on finding the most relevant and applicable vulnerability indicators in order to approximate the effects on social welfare. Hence, they selected and developed a number of composite vulnerability energy system indicators assuming the causal relationships as shown in Figure 4.

Figure 4: Indicator type and link to causal mechanisms of energy security



Source: [14]

Indicators

This results in the following list of indicators (limited to those indicators which subsequently are applied in scenario analysis):

Extreme events

1. Overall short-run availability of primary fuel [ktoe for oil and days for gas]
2. De-rated electricity peak capacity margin [%]

Inadequate market structure

3. Average load factor [%]
4. Cumulative required new capacity [MW]
5. De-rated electricity peak capacity margin [%]
6. Flexibility margin [%]

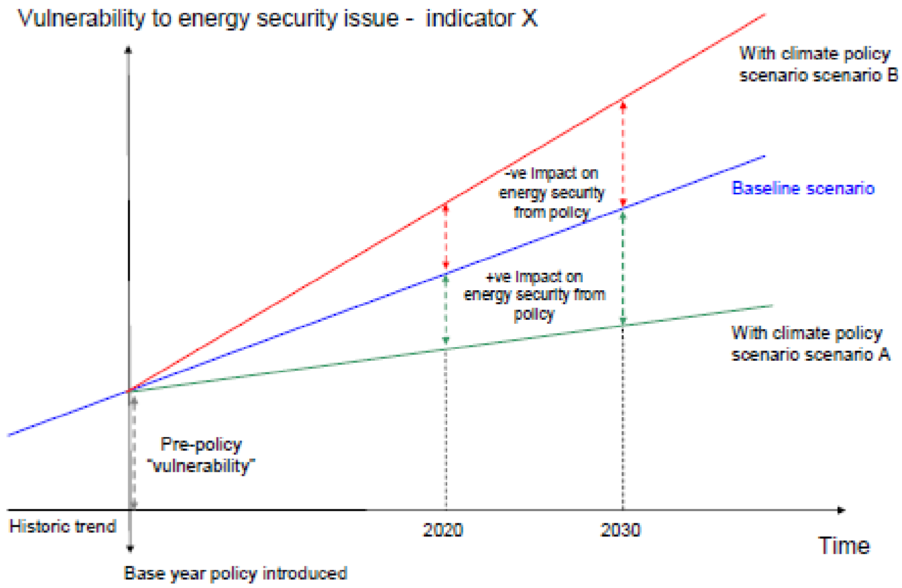
Resource concentration

7. Resource Concentration Price Indicator [no unit]
8. Resource Concentration Physical Unavailability Indicator [no unit]

The resource concentration indicators allow to assess energy systems from the sovereignty perspective, while the other indicators reflect the robustness and resilience perspectives depending on the indicator at hand. Indicators 1 (for gas), 2, 4, 5, and notably 6 account for available flexibility in the system by including variables such as gas storage, capacity credits of generation technologies, or by accounting for loss of plant due to an outage of the largest generation facility or of a critical transmission line. They relate to the resilience perspective since they provide insights in the extent to which unexpected disruptions can be mitigated by energy systems, but also to the robustness perspective since engineering studies are needed for calculating capacity credits and loss of plant probabilities. Besides also indicators 1 and 2 relate to the robustness perspective as far as they provide an indication of the vulnerability of energy systems to extreme natural events rather than intended actions such as strikes and acts of terrorism. Furthermore, indicators 2-6 are related to resilience perspective through the share of final electricity consumption in final energy consumption, thus allowing to capture the overall importance of the energy source in the economy and potential options to mitigate a supply disruption.

Indicators are calculated for a baseline scenario (i.e. without the effect of climate policy) and two alternative climate policy scenarios (called climate package and CCS, respectively). The differences between the evolution of the energy security indicator in each scenario are used to determine whether, and to what extent, the policy has increased or decreased the vulnerability of the EU to previously identified energy security risks (see Figure 5).

Figure 5: Approach to assessing impact of climate policy on energy security



Source: [14]

3.2.3 Global Energy Assessment (GEA), (Cherp et al. 2012)

Context

Study with worldwide perspective aiming at:

- Stabilizing global climate change to 2°C above pre-industrial levels to be achieved in the 21st century
- Enhanced energy security by diversification and resilience of energy supply
- Eliminating household and ambient air pollution, and
- Universal access to modern energy services by 2030.

Indicators

Five energy security indicators are calculated:[8]

1. Import share of primary energy
2. Oil intensity of GDP
3. Oil intensity of the transport sector
4. Shannon-Wiener diversity index (SWDI) for primary energy supply
5. SWDI for primary energy supply, accounting for imported energy (compound SWDI)

The fourth indicator is calculated as follows:

$SWDI = -\sum_i (p_i * \ln(p_i))$

where p_i is the share of primary energy i in total primary energy supply (TPES).

[8] GEA scenario database, see http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=welcome

The fifth indicator is a variant of the fourth indicator as it does not count globally traded fuels as contributing to the overall diversity of primary energy supply. It is calculated by excluding the imported energy from the overall primary energy supply in a nation's or region's diversity index:

Compound SWDI $= -\ \Sigma_i\,(1 - m_i) * (p_i \ln(p_i))$

where p_i is again the share of primary energy resource i in total primary energy supply, and m_i is the share of primary energy resource i that is supplied by net imports.

The first and fifth indicators reflect sovereignty concerns as they measure global energy trade. Indicators 2-5 relate to the resilience concerns as they address the diversity of both primary energy sources and the transport sector as well as the oil intensity of economies. The compound SWDI thus takes into account both sovereignty and resilience concerns.

Scenarios

The Global Energy Assessment (GEA) constructed 40+ scenarios in three steps. Each step entails a different dimension. The first dimension involves the energy demand level. Efficiency scenarios focus on energy efficiency improvements, while supply scenarios are aiming at low-carbon energy supply technologies but at the same time show an increase of energy demand, and mix scenarios resulting in intermediate demand levels since they are a combination of energy efficiency and supply scenarios.

The second dimension are constraints on the following supply-side technologies:

- Limited intermittent solar and wind energies to max 20% of final energy consumption
- Limited bioenergy to max 50% of the estimated global potential
- Nuclear phaseout: no additional nuclear capacity is built after 2020 and all nuclear power is phased out by 2060
- No development of CCS
- No combination of biomass combustion and CCS
- No carbon sinks beyond the baseline scenarios

The third dimension concerns choices around the energy carriers for the transport sector. Either conventional transportation scenarios with transport systems primarily based on liquid fuels or advanced transportation scenarios based on electric and hydrogen vehicles.

Not all combinations of energy demand, supply and transport constraints are possible. Efficiency scenarios impose more limits on the portfolio of energy options than supply and mix scenarios as the former implies variants with combinations of limited intermittent RES and limited bioenergy while the latter do not. Equally, advanced transportation allows for more efficient energy systems than conventional transportation and thus limits the set of feasible energy options. Indicators have been calculated based upon the interpretation of the integrated assessment model MESSAGE of the GEA scenarios.

3.2.4 Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices (Jewell et al. 2014)

This study applies the Global Energy Assessment framework of [3] and thus utilizes the same definitions of energy security and vital energy systems, with vulnerabilities structured according to the well-known three perspectives on energy security: sovereignty, robustness, and resilience. It applies a different set of indicators though, since it is aimed at capturing system transformation impacts on energy security following stabilization of the GHG concentration at 450 ppm CO_2-eq by 2100, which implies 80% GHG emission reduction by 2050. This results in a number of sovereignty and resilience indicators. Robustness indicators are not included as most of them cannot be meaningful estimated in the integrated assessment model MESSAGE, and given space limitations.

Sovereignty indicators

- Global and regional energy trade i.e. trade intensity: affected by supply-side constraints, especially limitations on renewables, and availability of electricity and hydrogen based transport possibilities. The indicator is not affected by the energy demand level since trade volume and overall energy demand alter in the same proportion. RES and nuclear are assumed to be non-tradable and domestic sources i.e. limiting the need for trade.
- Trade in individual fuels such as oil, natural gas, coal, biofuels, synthetic fuels, and hydrogen.
- Geographic concentration of exports of natural gas, coal, bioenergy, and hydrogen.

Resilience indicators

- Energy intensity
- Diversity of energy sources in the total primary energy supply (TPES)
- Diversity of energy sources in electricity generation
- Diversity of energy sources in the transport sector.

Results are obtained for the same 40+ scenarios as deployed by [3].

3.2.5 Identifying the main uncertainty drivers of energy security in a low-carbon world: the case of Europe (Guivarch and Monjon, 2017)

Also this paper applies the framework developed by [3]. It motivates this by stating that “Even if the security of oil supplies remains important, contemporary energy security policies must also address other energy systems.” The paper takes a series of energy security indicators and analyses their dynamics in a low carbon world until 2100. The main drivers of these dynamics have to be sought among low carbon technologies, the evolution of energy efficiency, fossil fuel resources and markets, and economic growth.

It deploys an energy-economy-environment model (Imaclim-R), a multi-region and multi-sector model of the world economy, to create a database of long-term scenarios which accounts for these drivers of future energy systems. Scenarios aim at stabilization of the GHG concentration at 550 ppm CO_2-eq i.e. less than 80% GHG emission reduction by 2050, since a more ambitious emission target would reduce the number of scenarios too much and thus not have allow to entirely explore the variance of results and its determinants.

Criteria for selection of indicators include (i) coverage of the sovereignty, robustness, and resilience perspectives, and (ii) ability to be calculated with the Imaclim-R model.

Indicators applied from the sovereignty perspective are:

- share of imports in TPES,
- regional import dependence of primary fuels, and
- share of imports for generating power.

Indicators from the robustness perspective are:

- production/resource ratio for oil,[9]
- the share of renewable energies in electricity production (excluding biomass and hydro).

From the resilience perspective the indicators are:

- the energy intensity of GDP,
- concentration of oil markets, and
- concentration of primary energy sources used for electricity production.

Explanatory factors for the indicators are determined in two steps. First, the dispersion of each indicator is measured by the relative standard deviation. Subsequently, main explanatory factors for energy security indicators for Europe are identified by applying a multi-factor analysis of variance (ANOVA).

Concerning the determinants of the sovereignty indicators, the analysis reveals that the three indicators share two main drivers namely fossil fuels resources and CCS technologies. The third determinant are the low carbon generation technologies assumptions for the share of import indicators, while it is the assumption on induced energy efficiency for the regional import dependence of primary fuels.

Concerning the determinants of the robustness indicators, the oil production/resource ratio is mainly explained by the assumptions about fossil fuel resources. In case fossil fuels are scarce and expensive the ratio is more worse than in the opposite case. The share of renewable energies in electricity production varies due to assumptions about low carbon power generation technologies; high availability and fast technology learning increase the shares of electricity from intermittent energy sources, which increases the complexity of electricity network management and therefore diminishes the robustness of the energy system.

Concerning the determinants of the resilience indicators,[10] induced energy efficiency mainly explains -as one would expect beforehand- the variation in the energy intensity of GDP. Besides, the availability and learning rates of end-use technologies are another determinant of energy intensity, especially in the short term. In addition, there is a small but constant effect of economic growth on energy intensity. Likewise the share of imports in TPES from the sovereignty perspective, assumptions for low carbon power generation and CCS technologies drive the concentration of primary energy sources used for electricity production. In contrast with the comparable indicator from the sovereignty perspective, the former assumptions are important for the whole time period rather than for the short and medium term only. As regards the latter assumptions, while CCS technologies have a positive impact until 2050 from the sovereignty perspective since they lower the share of imports, from a resilience perspective they have a negative impact until 2050 since they constrain the share of renewable energy and with that the diversification of the generation mix. The third determinant are fossil fuel resources and markets which is most important in the short term. Like the

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[9] Usually, the inverse indicator is applied, but [24] define all indicators such that an increase in their value indicates a worsening of the measured energy security dimension.

[10] Determinants have not been analysed for the concentration of oil markets since this indicator has a very low variation (max 4%).

availability of CCS technologies, a high availability of fossil fuels reduces the cost of generation and limits the share of renewable energy and therefore the diversification of the generation mix.

3.3 Assessment and selection of appropriate energy security indicators

The five studies discussed in the previous sections show a number of similarities and differences. Three studies deploy single indicators, but [20] and [14] apply one or more composite indicators. Furthermore, all studies discuss the indicators in the context of an energy system perspective and have an EU-wide or global perspective. Some studies are mainly based upon EU-wide scenario data from the partial-equilibrium PRIMES model until 2030 ([20], [14]), while others are based upon the (regional) outcomes of global integrated assessment models with a climate module such as MESSAGE until 2050 or beyond ([3], [4], [24]).

The relative importance of various risks (geopolitical, technological, natural, and economic) as reflected in energy security dimensions (sovereignty, robustness, and resilience) differs from study to study. Some studies focus mainly on the sovereignty and resilience perspectives ([3], [4]), others discuss also the robustness perspective ([20], [14], [24]). Note that [24] do not discuss implications for end-use sectors and thus have a more limited resilience perspective. Instead, this is the only study that explicitly includes a quantitative analysis of the main drivers of the indicator scores. This can be explained by the worldwide geographical scope of the former studies with [3] for example discussing energy security for 130 countries, which limits the possibilities to model the energy infrastructure with sufficient geographical detail and therefore to account for the robustness of energy systems.

Studies differ also in the attention paid to *present* energy security concerns (mainly related to primary energy supply and roles of ‘fossil fuels’ in energy systems, e.g. [3]) versus *future* energy security concerns. In case of the latter, given GHG emission reduction targets, more attention is being paid to managing flows of variable electricity production i.e. electrification as well as the roles of energy carriers such as hydrogen and synthetic fuels ([4], [24]). However, [24] do not include the future roles of hydrogen and synthetic fuels in their analysis. Different perspectives towards current and future energy security concerns are also reflected in the time horizon of the analysis; [20] and [14] do not look beyond 2030, while the other studies look beyond 2030 towards 2050 and 2100.

The above discussion of the literature and their context has some consequences for our selection of appropriate energy security indicators;

- JRC-EU-TIMES is an EU-wide integrated assessment model, providing EU-wide scenario data, which is advantageous (see Chapter 4 for discussion);
- Integrated assessment models including the JRC-EU-TIMES model provide limited detail about energy infrastructures (more detailed analysis of the grids including the effect of PtG for example can be found in D6.4 [25]). This limits possibilities to cover the robustness dimension of energy security. Therefore, the indicators that can be shown, might underestimated the relevance of PtG for future energy system;
- Likewise, imports from hydrogen and synthetic fuels from outside Europe are not modelled, limiting possibilities to address future energy security concerns.

Given these limitations, the following suitable indicators remained;

1. Imported energy from outside Europe relative to the total primary energy supply (TPES)

2. Imported gas from outside Europe as percentage of all consumed gas
3. Costs of imported gas from outside Europe
4. Diversity of primary energy sources calculated by deploying the SWDI
5. Diversity of electricity generation calculated by transferring electricity generated into associated primary energy inputs and subsequently estimating its diversity
6. Energy intensity as the amount of energy used as fraction of GDP or value added for different sectors (agriculture, commercial, industry, residential, and transport sectors)
7. The presence of spare capacities for electricity generation i.e. installed capacity divided by critical load i.e. peak load.[11]

Indicators 1-3 are related to the sovereignty perspective, while indicators 4-6 reflect the resilience perspective and indicator 7 the robustness perspective. Hence, we largely follow [4] in the selection of indicators but add an indicator to address also the robustness perspective.

[11] This indicator proved not to be very valuable. With hindsight other robustness indicators should be selected for calculation like overall short-run availability of gas and the flexibility margin. Unfortunately, this requires additional scenario data while JRC-EU-TIMES model runs have already been finished.

4 Research context

This section discusses consecutively the applied scenarios, model, and discount rate, which determine the context of both the calculation of energy security indicators and estimations of the societal value of energy security.

4.1 Scenarios

In JRC-EU-TIMES scenarios have been executed as a parametric variation. In [13] 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 what 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).

For the CBA (D7.6) the situation with and without PtG will be evaluated for various scenarios. The 'situation with PtG' and the 'situation without PtG' will only differ for scenarios where PtG technologies are applied. Therefore the scenarios in D6.3 where no PtG is applied although the technology is available are both relevant and non-relevant. On the one hand, 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. On the other hand, for the current analysis they are not interesting, since they do not see PtG deployed the benefits for energy security will be zero.

Therefore the following scenarios 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 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 favor 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* with PtM. This is a scenario with a different set of constraints that are also likely, but that do not favor 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 favorable 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 gCO2/ton*nm).

Note that the naming of the scenarios is in line with Blanco (2018), and that the optimistic and pessimistic is more about whether or not PtG will be applied than that this does represent opinions on good or bad development. For more information on these scenarios see Blanco (2018).

4.2 Model used: JRC-EU-TIMES[12]

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, minimizes system costs given GHG emission reduction targets and other constraints related to potentials of biomass and other technologies, level 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 five sectors (agriculture, commercial, industry, residential, and transport sectors) 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). For reducing calculation time, it uses hierarchical clustering into representative hours of a year (24 time slices for the power sector and 12 for others). It uses a simple network structure with each member state (MS) being one zone. 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 tariffs, emission trading systems and energy security, among others. The model allows to obtain 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. Due to the capacity expansion component and scope further than power (commercial, residential, industry and transport), the compromise is in temporal (12 time slices for a year and 24 slices per year for the power sector) and spatial (one node per country) resolution. 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 analyze 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 and versus the costs for the complete energy system of other flexibility

[12] This section strongly borrows from [13], which is also the key reference for more details on the model. Further details can also be found in [30].

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 deliverable 6.3 [13].[13]

Since the drafting of [13] 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. This is because the current regulation states that interconnection capacity should be 15% of the installed generation capacity of a Member State. This leads to very large interconnection capacities in the future that are not necessary (since it is largely based on capacity that has a low capacity factor). The effect of this correction is limited.

Costs and benefits included in this analysis

The aim of this report is to shed light on the value of energy security, as input to deliverable 7.6. The scenarios as generated by JRC-EU-TIMES are based on minimizing all direct costs of the energy sector. These direct costs are a direct input into the social cost benefit analysis (D7.6). They are therefore not reported here to avoid double reporting and the risk of including the same costs twice in the social cost benefit analysis. Other costs relevant for the social cost benefit analysis outside energy security and the costs of the energy system will be studied separately in D7.6.

Strengths and weakness of JRC-EU-TIMES[14] for studying energy security

Not all dimensions of energy security can be realistically simulated with JRC-EU-TIMES, for several reasons. First of all, since the model simulates long term developments, it minimizes the costs of the energy sector with one year representing a decade. Energy security can also be affected by short run shocks (short-lived perturbations), like an oil price shock, in one of the constraints. However, given an optimization period of about 10 years these short run shocks are hard to analyse with the model.

Secondly, grids are represented as one zone per country. Therefore energy security from the grids, or transformed through the grid, is less well represented.

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 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, with individual suppliers not being distinguished. Thus if one oil supplier would be replaced by two oil suppliers each supplying half, this would not show up in the model. Hence the model misses a source of diversity.

[13] Originally three ECN models (OPERA, COMPETES and ECN-TIAM) would have been used. With all three these models requiring substantial extension, for example to include a European dimension in OPERA which was a technology rich model, but only with data for the Netherlands). D6.3 ([13]) showed that the JRC-EU-TIMES model is suited for the analysis necessary for this deliverable and D7.6, 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.

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

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.

4.3 Discount rate

One of the key financial parameters with a large impact on the social cost benefit analysis 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). This discounting results in a Present Value (PV) of the calculated future values.

The standard application of JRC-EU-TIMES uses a private discount rate (varying between 9 and 18% for the investor). However since the aim of the current exercise is to determine the value of energy mix diversification (i.e. energy security) for the social cost benefit analysis, the question is what the proper discount rate would be. Basically, the 4 percent social discount rate use in D7.6 is used here as well, as will be explained in the paragraph below.

Determining the discount rate requires a choice between a private and a social discount rate, and determining the level. Below, the main arguments are summarized, for more detail please refer to D7.6.

The aim of the full CBA analysis (D7.6) 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 (PtG) technologies versus the situation that these technologies are not developed. This analysis aims to provide policy makers with a compass to steer and adjust their PtG policies. This requires an analysis of the possible options (see [28]) to select the best option by determining which option is more favourable 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).” [28] 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 costs 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.

The social discount rate differs between countries, this is partly the effect of economies being differently, and partly it is the result of different methods being used to calculate the discount rate. Discount rates can be either calculated based upon the Capital Asset Pricing Model (CAPM) or by applying Ramsey pricing. Since this deliverable and the JRC-EU-TIMES model cover Europe as a whole it seems reasonable to select a discount rate in line with this territory. This study therefore applies the EU discount rate, which is more or less in line with the UK, French and Dutch values as well, and which is consistent with the EU being the funder of this project as well. That is, we use the unweighted average of the social discount rate for cohesion and other EU member states, that is a discount rate of 4% for entire Europe. The model simulations for this deliverable with JRC-EU-TIMES use 4 percent, which differs from the simulations used in D6.3.

5 Results for selected energy security indicators based upon the JRC-EU-TIMES model

Indicator values are calculated for the selected scenarios[15] for each of the three energy security perspectives by using outputs of the JRC-EU-TIMES model i.e.:

- The sovereignty perspective focussing on geopolitical risks relating to fuel supply (Section 5.1);
- The resilience perspective concerning the mitigation of all types of risks originating from less predictable factors of any nature including disruptive technologies that impact the diversity of energy supply options and final energy demand of end-user sectors such as transport (Section 5.2);
- The robustness perspective regarding technical and natural risks i.e. failures of generation components and calm and cloudy periods with low electricity production from wind and solar would benefit from redundant generation capacity (Section 5.3).

5.1 Sovereignty perspective

The following indicators are selected to provide insights in the sovereignty perspective:

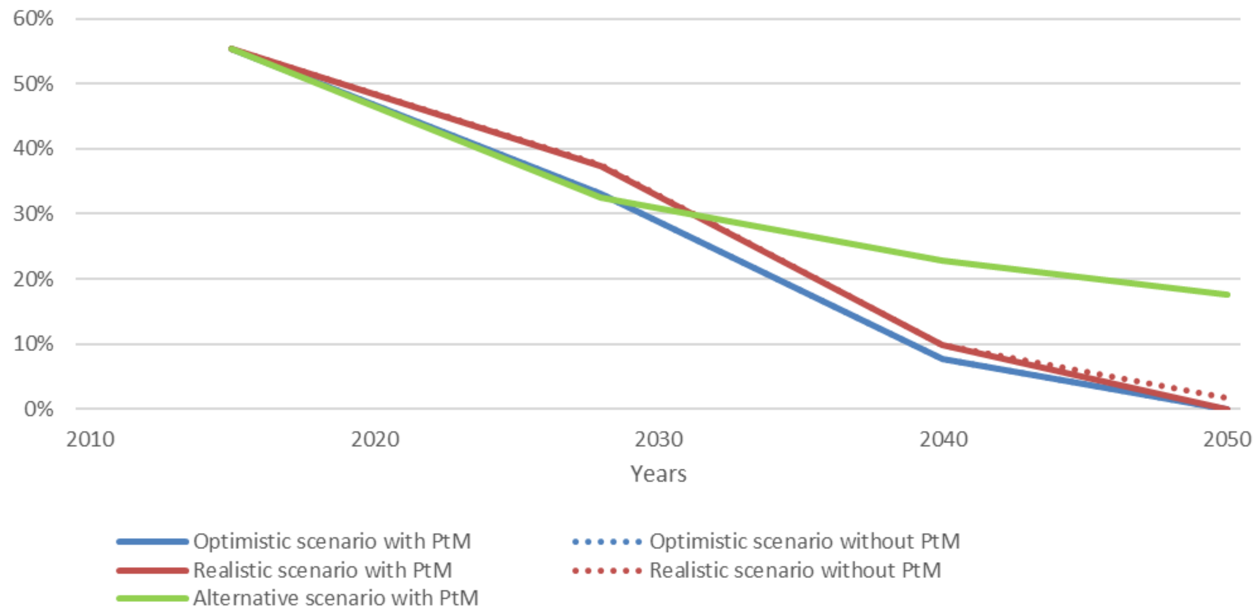
- Imported energy from outside Europe relative to the total primary energy supply (TPES)
- Imported gas as percentage of all consumed gas
- Costs of imported gas

Imported energy from outside Europe relative to TPES

While in 2015 the net imported energy (biomass, coal, gas, LNG, oil, and a small part of electricity from outside Europe) amounted to 55% of TPES, it diminishes to (almost) 0% in 2050 for both the optimistic and realistic scenarios, with and without the deployment of PtM (see Figure 6). The geopolitical risks thus reduce quite significantly in these scenarios. An exception is the alternative scenario with PtM, which shows a decrease of net imported energy as fraction of TPES towards 17% in 2050. This results from the remaining imports of LNG (ca 5,400 PJ) and to a lesser extent coal (1,100 PJ) as well as the import of bio energy (ca 2,800 PJ). The LNG and coal imports originates from the availability of CCS as technology option that is not considered as feasible option in the other scenarios, while the import of bio energy derives from the assumed high biomass potential. This result cannot be compared with the alternative scenario variant without PtM, as data for this variant have not been made available, but since this scenario has limited PtM it is unlikely that the imported energy will change in the case without PtM. The overall picture could change though if scenarios are included that import hydrogen or synthetic fuels from places outside Europe (e.g. from the MENA region) with higher availability of variable renewable energy sources, which would lead to a trade-off between lower cost and sovereignty.

[15] Except for the pessimistic scenario since this scenario does not deploy PtM and hence PtM is not reflected in the energy security indicators.

Figure 6: Imported energy as fraction of total primary energy consumption



Imported gas as percentage of all consumed gas

As shown in Figure 7, for gas the direction of the development towards 2050 is comparable as for all energy sources, although the imported gas as % of all consumed gas (i.e. extracted gas, methanation, and imported gas) is not reduced to zero in the realistic scenario. The figure shows some small differences between cases with and without PtM, with the largest differences in the scenario with the largest PtM deployment in the case with PtM, i.e. the optimistic scenario.

The limited differences in 2050 hide substantial underlying differences in the optimistic scenario though, see Figure 8. The natural gas production including methanation is about 7,500 PJ and 4,500 PJ in 2050 in the optimistic scenario variants with and without PtM respectively, with natural gas production i.e. extraction being 1,500 PJ and 4,500 PJ respectively. Methanation thus is about 6,000 PJ in the PtM scenario. Differences in gas import are negligible for this scenario. In the realistic scenario underlying differences in the variants with and without PtM are much smaller; the 850 PJ methanation in the PtM scenario is partially replaced by 180 PJ additional gas import and 350 PJ additional natural gas extraction. The remainder is cushioned by lower gas consumption. The alternative scenario shows a decreasing amount of methanation from 2030 to 2050; this results from the coupling of biogas with PtM to increase methane yield at the expense of hydrogen consumption (see Table 22 of [13]). This option is deployed to a higher extent in 2030 than in 2050, since in earlier years gas demand is larger and upgrading biogas is useful to “green” the gas grid, while in later years it is better to use that biogas for industry (heat and power) rather than upgrade it (since gas demand is lower).

Figure 7: Imported gas as percentage of all gas

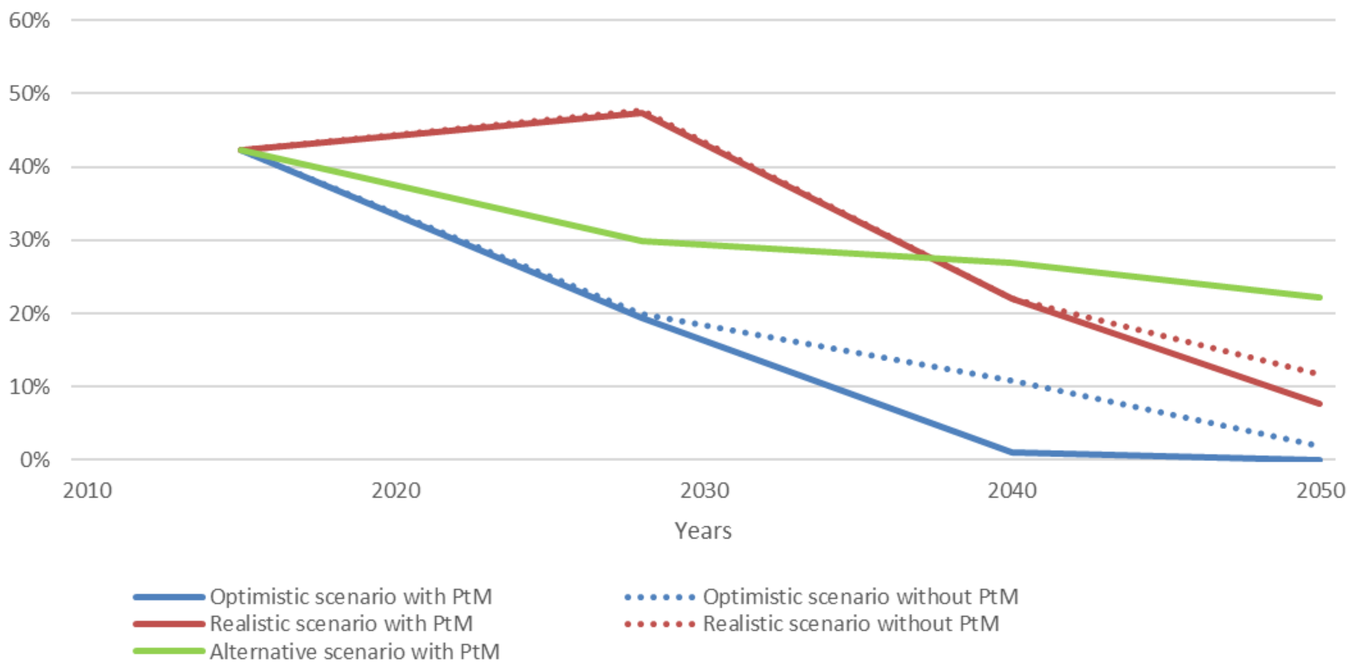
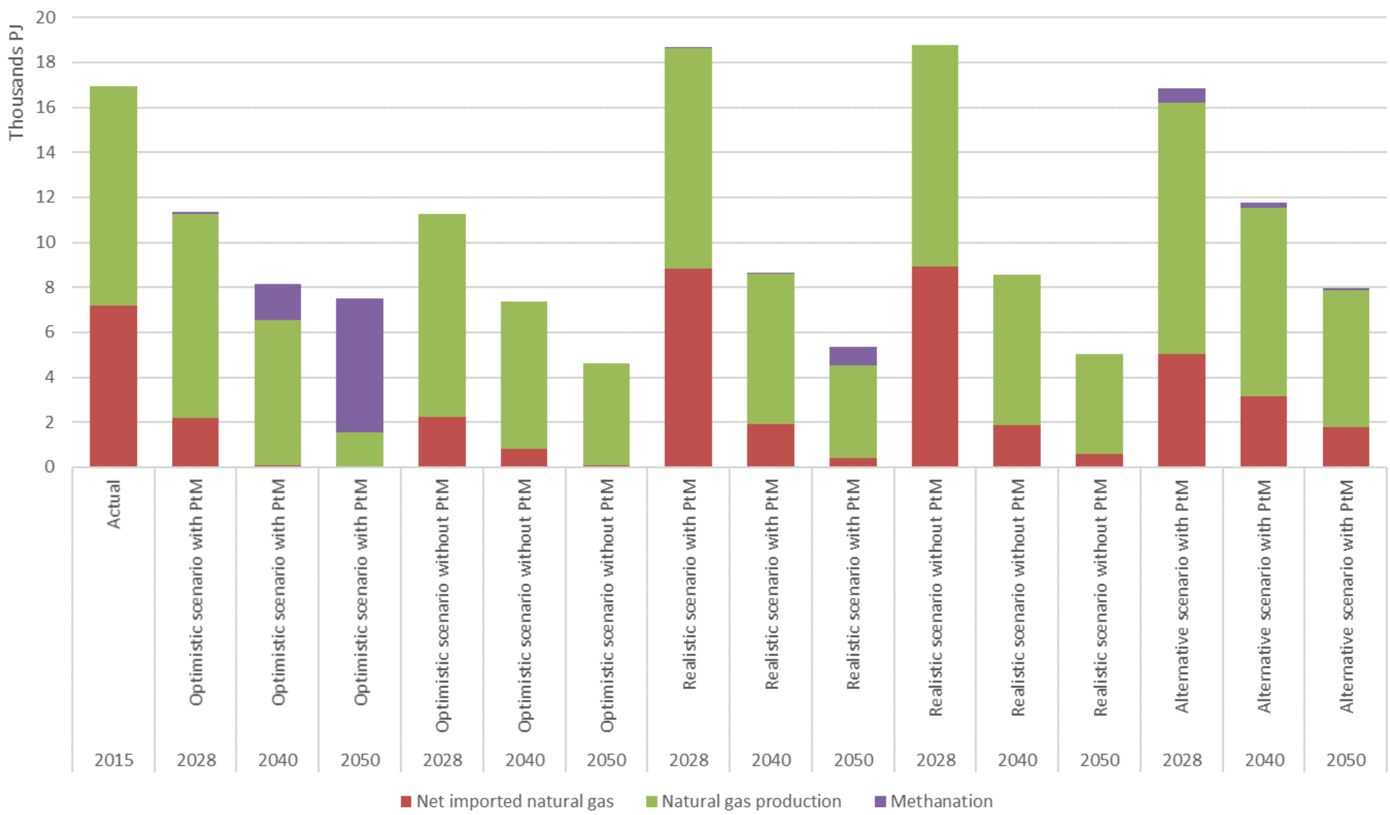


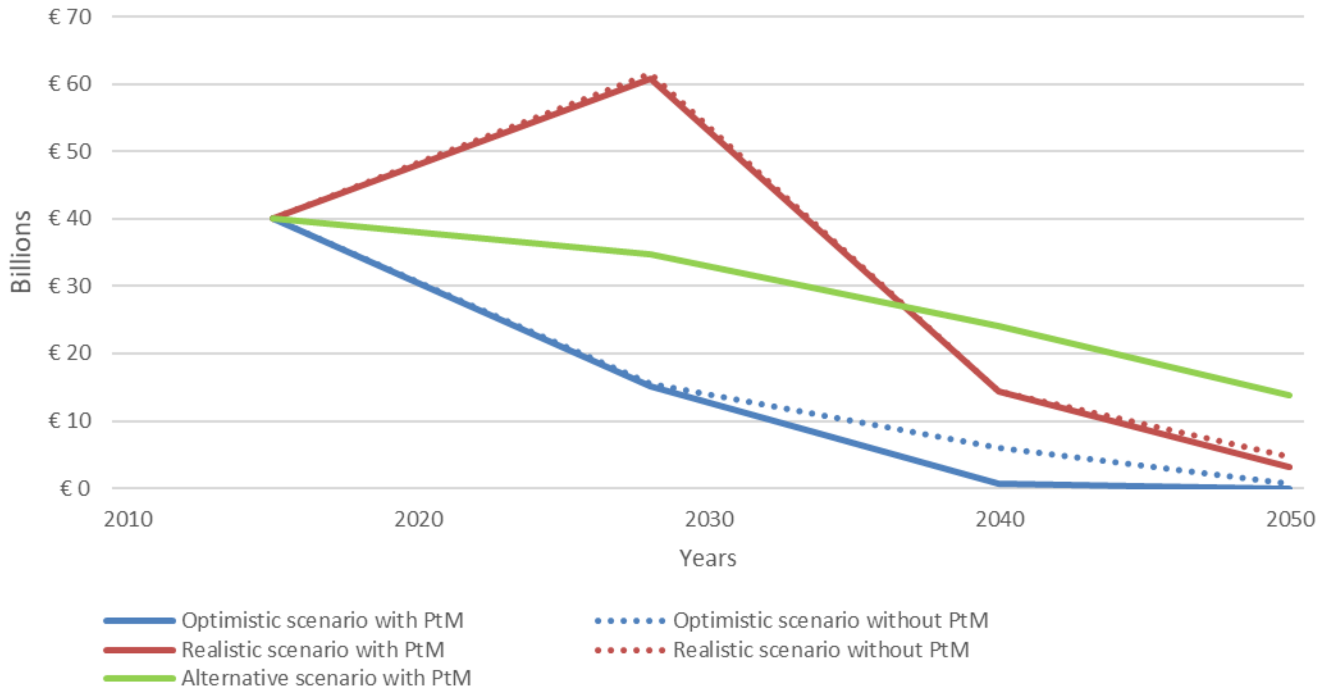
Figure 8: Composition of gross EU gas consumption



Costs of imported gas

Despite a 50% increase of the gas price until 2050,[16] Figure 9 shows that this indicator exhibits a comparable decline over time for all three scenarios as the fraction of imported gas as percentage of total gas. For the year 2015, the cost of imported energy amounts to € 40 billion per year, while in 2050 this cost is reduced to a bandwidth of € 0 to 14 billion per year, with the lower value being the optimistic scenario with PtM and the higher value the alternative scenario. In the optimistic scenario, PtM reduces yearly costs of imported gas with € 5.5 billion in 2040 and € 0.7 billion in 2050. In the realistic scenario, reduced yearly cost of imported gas amount to € 1.4 billion in 2050.

Figure 9: Costs of imported gas



5.2 Resilience perspective

The following indicators provide insights in the resilience perspective:

- Diversity of primary energy sources
- Diversity of electricity generation
- Energy intensity.

Diversity of primary energy sources

The Shannon-Wiener diversity index (SWDI) is deployed to measure the diversity of energy options within an energy system. This index is calculated with the following formula: $SWDI = \sum_i p_i \ln p_i$, where p_i is the share of the primary energy source *i* in the total primary energy supply (TPES).

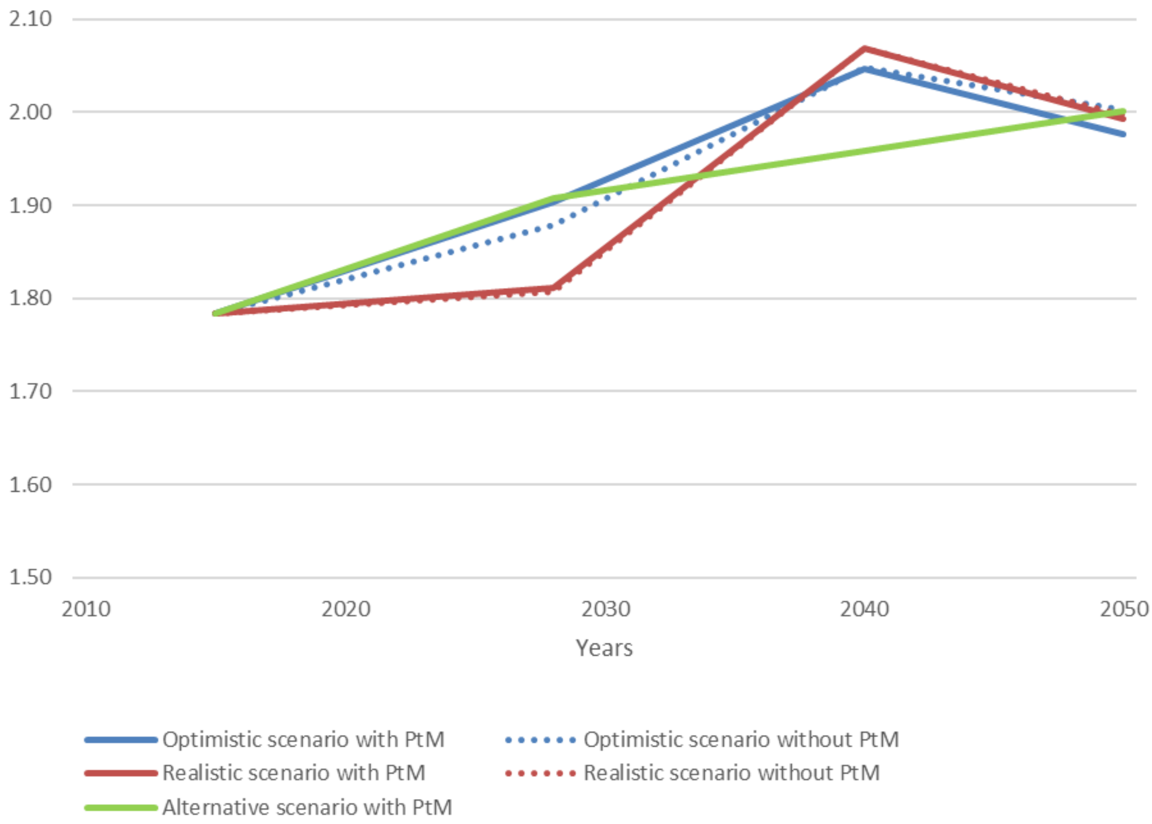
[16] Gas prices in 2015, 2030, 2040 and 2050 amount to 6.6, 8.7, 9.6, and 9.9 $/MBtu respectively. These prices are taken from Table 18 of [13].

The SWDI reflecting the diversity of TPES increases from 1.78 in the year 2015 (calculated with data from [27]) to about 2.00 in the optimistic, realistic and alternative scenarios with and without PtM.[17]

As shown in Figure 10, differences between the three scenarios are larger in the trajectory towards 2050 than in the year 2050 itself. These differences exhibit the radical transformation of the energy system with substitution of fossil fuels by renewables; in the optimistic and realistic scenarios, solid fuels such as coal disappear almost completely from the TPES, while the roles of especially solar-PV and wind increase dramatically. In the year 2050 fossil fuels have been replaced to such extent by low-carbon energy sources that in the optimistic and realistic scenarios the primary energy sources are more concentrated than in 2040. The alternative scenario shows a steady increase of diversity. Compared to the optimistic and realistic scenarios, biogas and biomass play a more prominent role in the alternative scenario, while the growth of wind and solar is more moderate as is the decline of gas, oil and solid fuels.

Although some differences are visible in the optimistic scenario between the variants with and without PtM around 2030, these do not change the picture significantly.

Figure 10: Diversity of total primary energy supply



[17] For calculating the SWDI, RES technologies are not merged to one category but considered separately i.e. biogas, biomass, geothermal, hydro including run of river, solar CSP, solar PV, tidal & wave (&ocean), wind, and other RES.

Diversity of electricity generation
Another variant of the SWDI indicator measuring the diversity of electricity generation is calculated as well. In this case the SWDI is calculated as the sum of the shares of the primary energy source *i* in electricity generation, each share being multiplied by its logarithmic value. To this aim, conversion efficiencies are assumed for combustible fuels (all fossils as well as biomass) as well as for nuclear, geothermal, and solar thermal electricity in order to calculate the associated primary energy use (the so-called 'substitution method'). For other renewable energy one unit of secondary energy counts as one unit of primary energy ('direct equivalent method').[18]

In contrast with the development of the diversity of primary energy sources, the diversity of PES deployed for electricity generation is somewhat lower. Figure 11 shows that the diversity index remains more or less constant at its 2015 value of about 1.75 towards 2050 for all scenarios, except for the alternative scenario which shows a slight increase due to the remaining importance of nuclear generation and the increasing deployment of biogas.[19]

As shown in Figure 12 on the pathways towards 2050 combustible fuels, especially coal and oil, and to a lesser extent gas, are replaced by wind, solar, and tidal & wave in the optimistic and realistic scenarios. In the alternative scenario, combustible fuels in electricity generation are replaced by a portfolio with higher relative shares for amongst others nuclear, wind and biogas and lower relative shares for solar and tidal & wave.

The differences between scenarios with and without PtM are nil. In the optimistic scenario with PtM consumption is about 1,700 PJ higher which is filled by electricity generated by natural gas power plants as well as some additional electricity produced from offshore wind and tidal & wave. Apparently, the higher availability of gas drives a higher electricity production by natural gas fired power plants, while energy systems with methanation require more energy than alternative energy systems without methanation.

For calculating the SWDI, RES technologies are not merged
to one category but considered separately i.e. biogas, biomass, geothermal, hydro including run of river, solar CSP, solar PV, tidal & wave (&ocean), wind, and other RES.
chnologies. The same holds for the allocation of own consumption towards solar PV and solar CSP.

Figure 11: Diversity of electricity generation

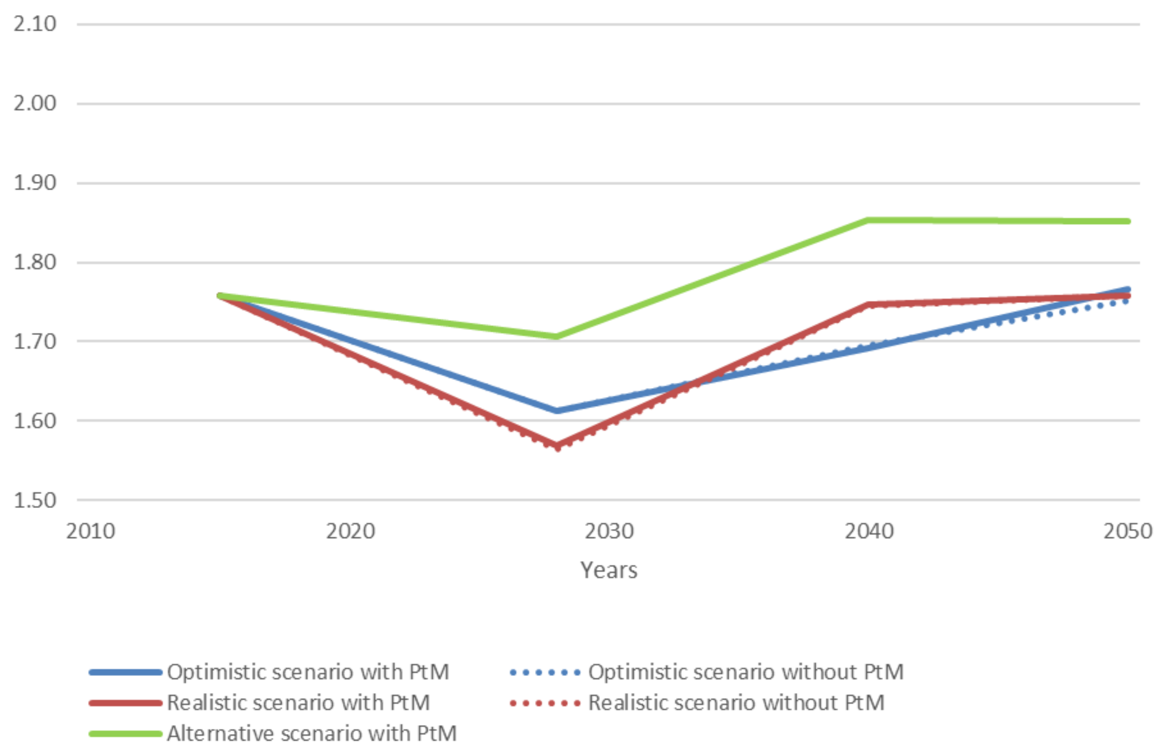
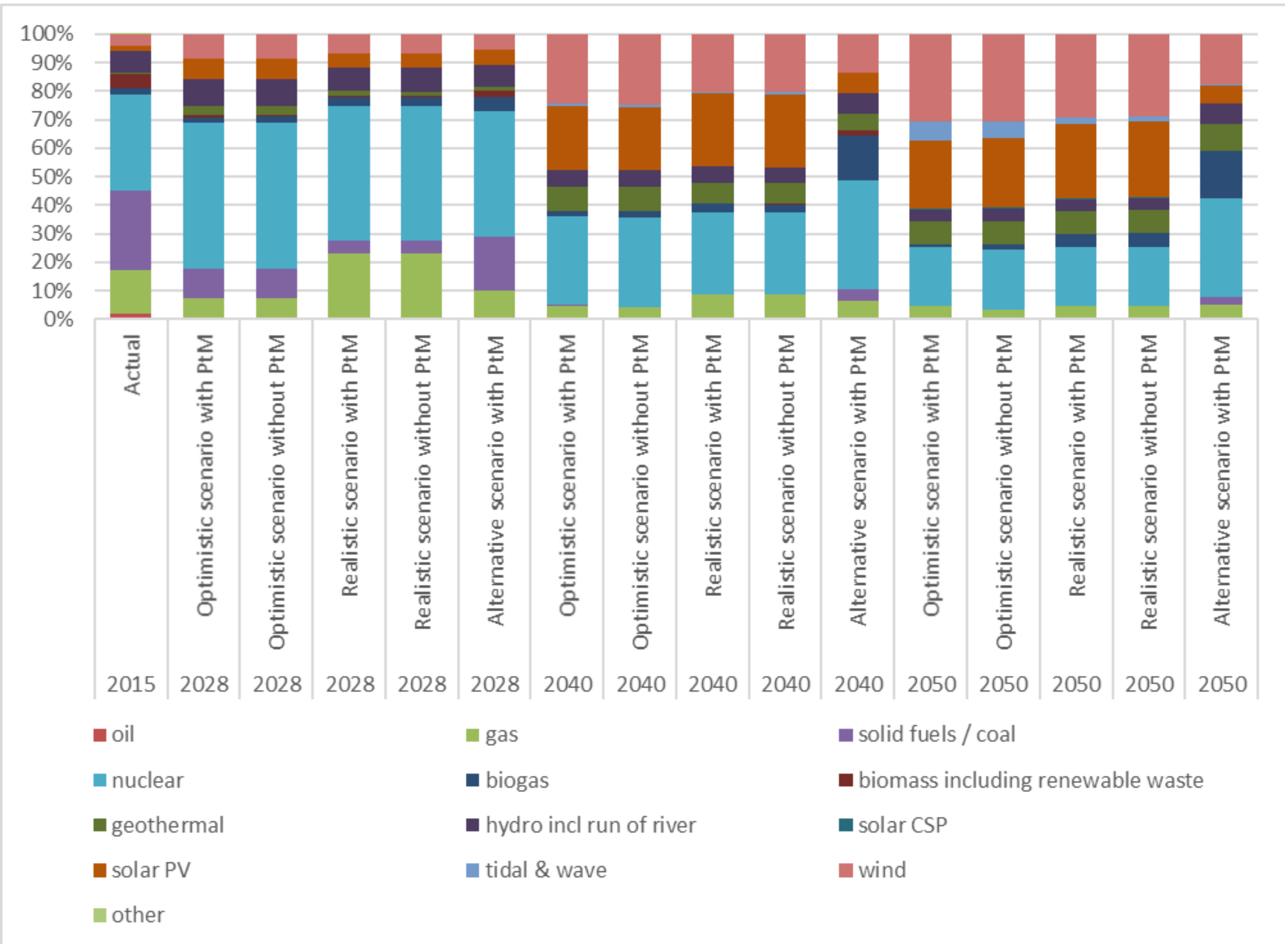


Figure 12: Share of primary energy sources in electricity generation

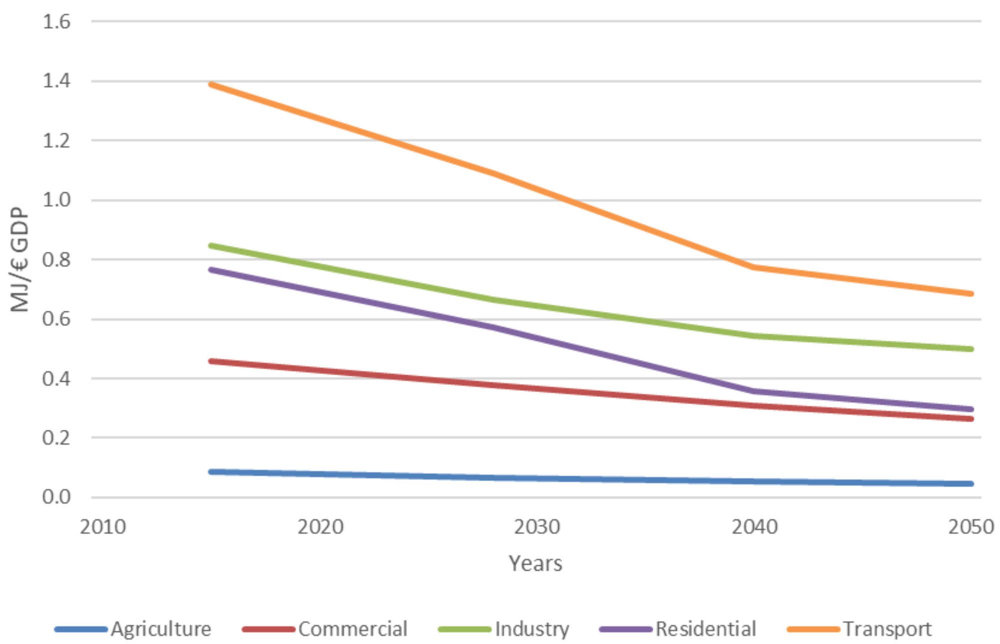


Energy intensity

Energy intensity is the amount of energy used as fraction of GDP, this indicator is calculated for five sectors: the agriculture, commercial, industrial, residential, and transport sectors respectively. Figure 13 shows the indicator values for each sector over time for the optimistic scenario. It is thus projected that the energy intensity reduces with more than 40% per sector, the residential sector shows even a reduction of more than 60%. It should be noted that in absolute terms the commercial and agriculture sectors show a higher amount of energy used in 2050 compared to 2015, but in the indicator values this is outweighed by the increase of GDP.[20] All other sectors show a lower level of final energy demand, the highest reduction is seen in the transport sector.

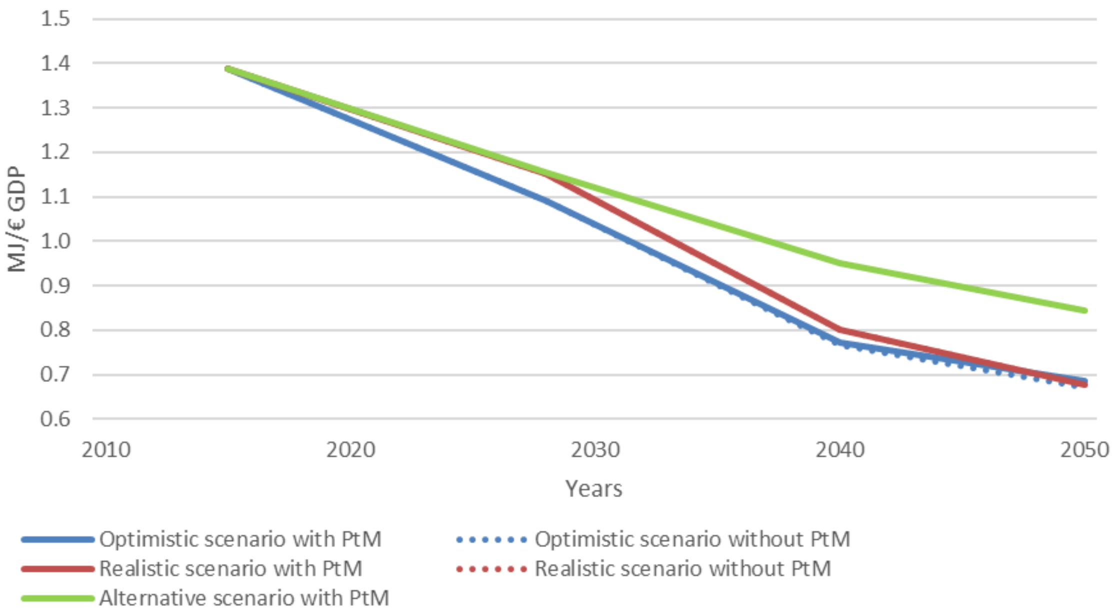
Differences between the optimistic scenario and the realistic and alternative scenarios are negligible though, except for the agriculture, industrial, and transport sectors of the alternative scenario. Figure 14 shows the energy intensity of the transport sector for the three scenarios. Furthermore, it can be seen that differences in energy intensities between scenario variants with and without PtM are insignificant for the transport sector, this result holds also for the other sectors.

Figure 13: Development of sectorial energy intensity for the Optimistic scenario



[20] The GDP is taken from [26].

Figure 14: Energy intensity of the transport sector



Since the energy intensity is a measure for the vulnerability of (parts of) an energy system for energy price fluctuations due to potential economic and physical shocks, the vulnerability is drastically reduced. Or, in other words, the resilience of the energy system is expected to increase drastically. This holds especially for the depicted transport sector, which is the sector with the largest absolute decline of energy intensity over time.

5.3 Robustness perspective

In contrast with the other perspectives, only the presence of spare capacities for electricity generation illustrates the robustness perspective. The spare capacity for electricity generation is defined as installed generation capacity divided by critical load.

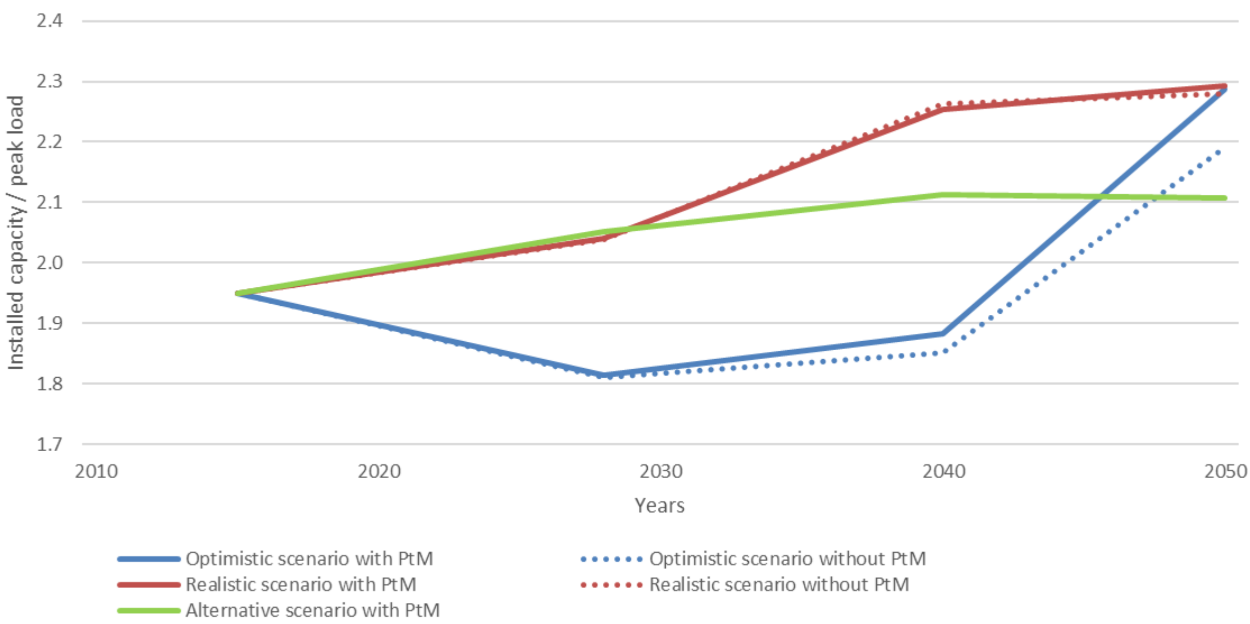
It is foreseen that installed generation capacity will grow faster than peak load, given the increase of variable renewables that are weather dependent and in the absence of significant deployment of demand response and storage additional generation capacity is required as a back-up. In the optimistic and realistic scenarios, the installed generation capacity grows with more than a factor five while peak load increases with more than a factor four in the period 2015-2050.[21] However, this is unlikely to be completely an improvement of energy security since much of the new capacity will have relatively low capacity factor. In the alternative scenario both increase only with a factor two. Furthermore, Figure 15 shows that spare capacities of the three scenarios as well as the with and without PtM variants fall within the same range.

However, with the large amounts of weather dependent renewables expected and less conventional fossil fuel generation, critical situations for the electricity system may occur at different times than at

[21] 2015 values are taken from [29], while 2050 values are JRC EU TIMES model outputs.

peak demand. As such this indicator provides only partial insights in the robustness of possible future electricity systems.

Figure 15: Development of spare capacity for electricity generation



5.4 Conclusions

The main findings for the indicators of the three energy security perspectives can be summarized as follows.

For the *sovereignty perspective* given the 95% GHG emission reduction scenarios the indicators show an improvement in the European energy security from 2015 towards 2050. The imported energy from outside Europe relative to the total primary energy supply (TPES) declines from about 55% in 2015 to 0% for both the optimistic and realistic scenarios, with and without the deployment of PtM. The alternative scenario shows a smaller decrease to about 17% in 2050 given the availability of CCS as technology option and available high biomass potential. The former allows for imports of LNG and to a lesser extent coal, while the latter drives the import of bio energy. The overall picture could change though if scenarios are included that import hydrogen or synthetic fuels from places outside Europe (e.g. from the MENA region) with higher availability of variable renewable energy sources, which would lead to a trade-off between lower cost and sovereignty.

The imported gas as percentage of all consumed gas and the costs of imported gas fall substantially as well in all scenarios, the least in the alternative scenario. Although methanation is about 6,000 PJ in the optimistic scenario with PtM in 2050 this does not change the picture significantly. In the alternative scenario where biogas is coupled with PtM to increase the methane yield the gas consumption and cost of imported gas in 2050 remain higher, not the least because of the availability of CCS.

It should be noted though that the overall improvement in sovereignty could change if scenarios are included that import energy from outside Europe in the form of hydrogen or synthetic fuels from places with higher availability of variable renewable energy sources due to e.g. more solar irradiance or higher wind speeds, which would lead to a trade-off between lower cost and sovereignty.

For the *resilience perspective* the energy security indicators show a slightly diverging perspective. The diversity of primary energy sources increases first and becomes more concentrated again with the replacement of fossil fuels by low carbon energy sources. The diversity of electricity generation first decreases and then increases again to end at current levels. This can be explained by the shares of geothermal, solar PV and wind in the generation mix, which only reach substantial levels by 2040 and beyond. Energy intensity will fall for all scenarios, indicating higher resilience of energy consumption sectors including the transport sector for energy price fluctuations.

For the *robustness perspective* one indicator could be quantified, that is the spare capacity of electricity generation. Another fundamental indicator of robustness is the ability of electricity networks to deal with the intermittent nature of renewable energy sources, and to balance and stabilize the electricity grids. However, this second indicator could not be investigated due to model constraints. The aforementioned indicator, the spare capacity of electricity generation, increases until 2050. However it is unlikely that this is completely an improvement of robustness, since much of the new capacity will have a relatively low capacity factor. Besides, the indicator does not take into account the possibilities for generation reserve sharing across countries as well as the limitations for generation to meet demand due to grid capacity constraints within countries. Future research may apply more advanced indicators for the robustness of energy systems e.g. an flexibility margin indicator that provides insights in the extent to which the available electricity system flexibility exceeds the demand for flexibility in energy systems with high shares of variable renewables, including the role of gas storage. Such an indicator should ideally be granular enough to take into account major congestions that would impede that generation meets demand. The latter would require more granular model outputs than were available for this study. A complementary study with more detailed analysis of the grids including the effect of PtG can be found in D6.4 [25].

Overall, all indicators studied in detail, for the sovereignty, resilience and robustness perspective, show an improvement of energy security towards 2050. For all these indicators the impact of PtG is limited, if distinct at all. Although it should be noted that no indicator covers all (or nearly all) aspects of energy security. The indicators that can be shown, might underestimate the relevance of PtG for future energy system. Nevertheless, the energy security indicators do provide little insight in its monetary value, therefore in the following chapter other approaches into the total societal impact of PtG are scrutinized.

6 Estimations of the value of energy security

6.1 Introduction

This chapter estimates the welfare effects of society being less vulnerable to supply side shocks of energy. Three different methods are identified in the literature, and all three are applied to estimate an energy security benefit of Power-to-Gas. None of these methods has originally been designed to estimate the energy security benefit of PtG, so the application here is unavoidably crude, however better methods so far do not exist.

One of the reasons that energy mix diversification and energy security is so hard to value is that it is a non-market good, that is, there is no market where energy security is directly traded. So no market price nor a market quantity can be used as reference to value energy security. Therefore, indirectly, non-market methods need to be used. Several techniques to value non-market goods have been developed (especially in environmental economics concerned with many non-market effects) like contingent valuation method (CVM), travel cost method, conjoint method, hedonic price method (see for example [33], [32]). Despite all efforts put in these methods, a lot of debate surrounds these methods (see for example [34], pp 47-48).

There are not that many examples of monetarization of the energy mix diversification or the energy security impact. It often requires many assumptions, where a change in an assumption might lead to substantially different outcomes. As [8] state “Cost-benefit analysis… is one option for prioritising on monetary grounds, but it may only be used when the analyst has firm knowledge of the characteristics of the security threat (e.g. magnitude and probability), the outcome of the impact (e.g. severity) and options for a prevention policy.’ In practise this is very complicated, so the number of CBA’s is very limited, and only a few valuations exists. Sometimes a solution for the lack of knowledge on probability of supply threats, is to calculate the breakeven frequency a specific threat should have to make the expected benefits of a measure to outweigh the costs (see for example [31]).

The following three methods to value energy mix diversification and energy security are identified as relevant for this deliverable:

- Sensitivity to price increases: the oil import premium method [35]
- Value of lost load and expected energy unserved
- Willingness to Pay for Security of Supply [45]

Applying each method to value energy security in 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. Therefore the outcomes should be interpreted with care.

The next three sections (6.2-6.4) describe a method and how it is applied in the context of this study. Each method is in first instance applied for one scenario. The final section of this chapter (6.5) presents the results for all methods and all four scenarios and infers some general lessons given similarities and differences across methods and scenarios.

6.2 Sensitivity to price increases: the oil import premium method (Leiby)

In this method 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) is estimated. 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.[22] In this method both the energy intensity (especially of the vulnerable fuel) and the prices changes are relevant.

The key reference in this method is [35] who estimated the welfare effect of a change (increase) of the oil price. The focus in this analysis is on the oil price, because that is the most imported fuel for most Western countries and which price increases are substantial and correlate with the prices of other fuels (even more so in the period Leiby studied than nowadays).

[35] estimates the welfare effects of the Macroeconomic Disruption/Adjustment Costs of an oil supply shock and the following macroeconomic adjustments following that shock. He estimated these macroeconomic costs to be $ 4.59 per barrel (BBL). He followed four steps:

(1) determine the likelihood of oil supply disruption
(2) estimate impact of oil supply disruption on world oil price
(3) estimate impact on US economy (import costs & macroeconomic losses)
(4) estimate how these costs change with imports

For these calculations a range of inputs have been used. First, projected world oil market conditions consisting of world oil price, world oil consumption, oil production (for US and non-US respectively), oil consumption (for US and non-US respectively), US oil imports, and US GDP. Secondly, disruption probabilities. Thirdly, price, income and GDP elasticities.

The estimate is only done for oil (the main imported fossil fuel) and expressed in $ of 2007. Given the uncertainties in many in the input parameters of his calculation, Leiby suggests a wide range for the macroeconomic costs: ($2.77 – $13.11).

Note that Leiby also estimated the extra economic cost due to a higher import price. This additional flow of money out of the country is not included in our calculations of the value of energy security for two reasons. First, the costs of imports are already included in JRC-EU-TIMES, and second given the increase of variable RES the price uncertainty we are interested in is now much more a domestic uncertainty than an external uncertainty. Hence, imports are much less interesting.

The welfare premium of [35] has for example also been used by [36], see pp. 55-56. [37] use this estimate to value the effect of an additional interconnector on the domestic gas fired electricity production and the import of gas needed for that. The reduction in import is estimated and valued using the Leiby estimate which is corrected for inflation and converted to TWh natural gas using the energy content of oil and gas.

In a study comparative to Leiby, [38] noticed that the price sensitivity of the oil price has become more price elastic and that the US GDP is less sensitive to oil price shock than in earlier periods. Notwithstanding these changes in the economy, Brown has an estimate which is rather similar to Leiby's: $\$_{2015}$ 4,83 per barrel.[23]

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[22] [8] note that due to an unexpected and exogenously caused price shock, the economy may move out of equilibrium if it is not able to respond rapidly enough. This causes consumer countries to experience three different types of economic loss: i) loss of the potential to produce, ii) macroeconomic adjustment losses, and iii) excess wealth transfer to producer countries.

[23] See [38] consumption of imported oil in PVL-C model, Table 9.

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 (for example during dark doldrums, discussed in Section 6.3) and reduces demand when intermittent renewables are abundant.

Table 6-1 below summarizes the method and main input in the calculation for the optimistic scenario and for 2050. In the final section of this Chapter the other results for the other scenarios and 2040 are presented and discussed as well. In each estimate we use a low, midpoint and a high estimate to include uncertainty about key variables.

The table starts with the welfare effect ($/barrel) as estimated by Leiby. In the three rows below this line the oil price, oil import and total US oil demand of Leiby are shown respectively. Using oil import per day and damage per barrel, the damage per year is calculated, next this is corrected for inflation. Using population figures, the damage per person is calculated, which is about €56 per person per year. The next four lines depict some key styled facts for Europe. The damage for Europe of oil price fluctuations in 2013 is calculated as the ratio of European GDP in 2013 over US GDP in 2013 times the US damage in 2013$. The 2050 energy security value is the 2013 value increased with the GDP growth between 2013 and 2050. This is used to calculate the energy security value per person. In the final step the final consumption and the conversion of H_2 to CH_4 are used to calculate the contribution of PtG to energy security. The larger is the conversion of H_2 to CH_4 compared to final electricity use the larger is the contribution to energy security. This gives a midpoint estimate of the energy security benefit of PtG in the optimistic scenario of €18.2 billion annually (and a range of €11.3 – €51.0 billion annually). Per person the value is €34.9 (with a range of €21.6 to €97.7 annually). The results for 2040 and for the other scenarios are discussed in Section 6.5.

Table 6-1: Security benefits of PtG, based on [35]. Optimistic scenario 2050

	Low	Midpoint	High
Welfare effect (2007$/barrel)[24]	2.77	4.59	13.11
Oil price ($/barrel)	43.61	50.99	64.54
Oil import (MMBD/year))	13	13	12
US oil demand (MMBD/year)	23	22	22
Damage (million 2007$/year)	13,006	21,044	58,833
Damage (million 2013$/year; inflation 10%)	14,307	23,148	64,717
US population (million, 2007)	301	301	301
Damage per US citizen ($2013)	48	77	215
Damage per person (€2013)[25]	35	56	158
US GDP ($2007)[26]	14,874	14,874	14,874
US GDP 2007 (€2013)	12,009	12,009	12,009
European GDP 2007 (billion €2013)[27]	12,895	12,895	12,895
European GDP 2050 (billion €2013)	22,526	22,526	22,526
European population (million, 2007)	500	500	500
European population (million, 2050)	522	522	522
Security of supply 2013 (billion €/year)	15.4	24.9	69.5
Security of supply 2050 (billion €/year)	26.8	43.4	121.4
Security of supply, per person, 2013 (€/pp)	31	50	139
Security of supply, per person, 2050 (€/pp)	51	83	233
Final consumption of electricity 2050 (PJ)[28]	17,901	17,901	17,901
Conversion H_2 to CH_4 2050 (PJ)	7,521	7,521	7,521
Conversion H_2 to CH_4 divided by electricity consumption	42%	42%	42%
Security of supply value of PtG (billion €/year)	11.3	18.2	51.0
Security of supply value of PtG per person (€/pp, 2050)	21.6	34.9	97.7

Note: The outcomes for the other scenarios are presented in Section 6.5.

6.3 Value of lost load and expected energy unserved

The second approach for valuing the supply security value of power to gas is to study 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 (i.e. the probability weighted average level of energy demand for a specific source/fuel, which would not be met due to demand exceeding supply) over a given period. 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

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[24] Source [35], p. 6 & p. 53.
[25] Using a Purchasing Power Parity of 0,734. https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm
[26] [39], Table 1.3.
[27] [26]
[28] JRC-EU-TIMES

demand options and the probability distributions applied to them (see [40] for a more detailed overview).[29] 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.

The future energy system will be much more than the current system based on electricity. This affects supply security in two ways. First, it increases the number of elements in the electric system, which will increase the probability of a failure. However, this is foreseen and will likely be taken into account when expanding and reinforcing the current grid. So it is unlikely that this will lead to more supply interruptions. Also this will mostly be the same for the situation with and the situation without PtG.

Second, especially when based on variable renewable energy production (solar and wind energy) further electrification increases the possibility of a dark doldrums (also known under the German term “Dunkelflaute” a combination of 'Dunkelheit' and 'Windflaute' meaning a period when it is both dark and without wind leading to substantially reduced solar and wind energy production) reducing the possibility of renewable electricity generation substantially, while demand will be relatively high. 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 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 [41])[30]. 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.

Table 6-2 starts with the expected days per year when power is insufficient. This assumes in the midpoint estimate a two weeks shortage period once every five years and a four week shortage period once every 10 years. Given the uncertainty of this estimate, a wide bandwidth is used: the low estimate is 50 percent lower, while the high estimate is double the midpoint estimate. This is a crude probabilistic calculation, however, long runs statistics on weather in combination with large scale renewable energy production still are being developed and often not looking at a very large scale deployment of intermittent technologies (for example by looking at the period until 2030). The next line specifies the power reduction of wind and solar in such a period. The total electricity and the electricity supply of wind and solar are given next. Combining the power reduction percentage and the share of wind and solar supply gives the absolute reduction in total power production.

The next line gives the European GDP in 2050. Using the stylized fact of [42] found for the Netherlands in 2003, indicating 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.

The shortage in supply does not translate one to one to a shortage on the market, because demand for electricity is likely to react, either via special programs (Demand Side Response programs) or via price increases following the reduction in supply. Furthermore part of the shortage might be solved via extra imports from outside Europe. This gives a remaining shortage (25 percent; 36% *(100%-25%–5%)) in the midpoint estimate.

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[29] This method is also used by for example [43].

[30] See also for example http://euanmearns.com/wind-blowing-nowhere/, https://energytransition.org/2017/07/germanys-worse-case-scenario-in-the-power-sector/

Crucial is that the outages will not be a complete surprise. The damage per day is lowered (in the midpoint estimate) with 50 percent to reflect that people and companies can anticipate the interruptions. [44] uses the term Value of Lack of Adequacy (VoLA), instead of VOLL for the damage of an announced supply interruption. They find that the reduction of VOLL if announced (so their VoLA) is just less than 50% for households and about 25% for commercial sectors (industry and services). See also [16] for an illustration of the large impact the manner in which the interruptions are modelled has on the social damage.

Combining the days, the damage per day, the remaining shortage and the reduction in the VOLL because it is not unexpected, gives the damage of dark doldrums (Dunkelflautes) in billion € year.

Finally an assumption is necessary on how much PtG might help in reducing the damage of such supply shortages (the low, midpoint and high estimate all assume that PtG technology reduces the damage with 50%). This gives a midpoint estimate of the energy security benefit of PtG in the optimistic scenario of €43.3 billion annually (and a range of €12.8 - €78.8 billion annually). Per person the value is €82.9 (with a range of €24.4 to €151.1 annually). The results for 2040 and for the other scenarios are discussed in Section 6.5.

Given that this table is the estimate of the optimistic scenario (of JRC-EU-TIMES), the ratio of PtG technology, compared to optimistic scenario, is 100% by definition. In the other scenarios and for 2040 this line is used to scale back the benefit PtG has in solving this supply shortage in proportion to the installed capacity.

Table 6-2: Security benefits of PtG, case with rationing of demand, optimistic scenario 2050

	Low	**Midpoint**	**High**
Days per year	2.8	5.6	11.2
Reduction in of power production by solar and wind	25%	50%	75%
Total electricity supply (PJ)	42,848	42,848	42,848
of which wind and solar	30,668	30,668	30,668
Reduction in power supply	18%	36%	54%
European GDP, 2050 (billion €)	22,526	22,526	22,526
Value of leisure time, 2050 (billion €)	22,526	22,526	22,526
Total value/year (billion €)	45,052	45,052	45,052
Total value/day (billion €)	123	123	123
Shortage in production covered with DSR	40%	25%	10%
Shortage in production covered by extra imports?	5%	5%	5%
Remaining shortage	10%	25%	46%
Reduction of VoLL because it is not unexpected	75%	50%	25%
Damage (billion €)	25.5	86.6	157.7
Damage per person	48.9	165.9	302.1
PtG reduces the damage with	50%	50%	50%
Ratio of PtG technology, compared to optimistic scenario	100%	100%	100%
Security of supply benefits of PtG: (billions €)	12.8	43.3	78.8
Security of supply benefits of PtG: per person (€/pp)	24.4	82.9	151.1

Note: DSR= Demand side response. VoLL = value of lost load. The outcomes for the other scenarios are presented in Section 6.5.

Table 6-3 applies the other method. It starts by calculating the daily electricity demand, followed by the electricity shortage and duration of Table 6-2. Now the solution for the supply shortage is not to ration demand, but to generate electricity with peaking power plants, which are used only during dark doldrums, using synthetic natural gas. Assuming long run marginal costs of € 1000 per MWh[31] gives a security of supply contribution of PtG in the optimistic scenario of € 27.3 billion annually (and a range of € 6.8 – € 81.9 billion annually). Per person the value is € 52.3 (with a range of € 13.1 to € 157.0 annually). The results for 2040 and for the other scenarios are discussed in Section 6.5.

Table 6-3: Energy security benefits of PtG, case with back-up power, optimistic scenario 2050

	Low	Midpoint	High
Electricity demand, 2050 (PJ)	17,901	17,901	17,901
Electricity per day, 2050 (PJ)	49,0	49,0	49,0
1 PJ= … MWh	277,778	277,778	277,778
Electricity demand per day (MWh)	13,623,299	13,623,299	13,623,299
Electricity shortage (see previous table)	18%	36%	54%
Number of days/year (see previous table)	2.8	5.6	11.2
Price per MWh	1,000	1,000	1,000
Ratio of PtG technology, compared to optimistic scenario	100%	100%	100%
Costs per year (billion €)	6.8	27.3	81.9
Costs per person (€/pp)	13.1	52.3	157.0

Note: The outcomes for the other scenarios are presented in Section 6.5.

6.4 Willingness to Pay for Security of Supply (Bollen et al. 2008)

[45] estimated the value of security of supply based on the revealed willingness to pay of society as a whole. They looked at a number of cases, most information he used 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 did so while analysing integrated approaches that resolve problems relating to global climate change, local air pollution and security of supply at the same time. To this aim, an integrated assessment of energy-economy-environment interactions is carried out with the MERGE model [45]. 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. 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.

As energy insecurity leads to a decrease of welfare, a penalty function is designed to represent what percentage of GDP ('private consumption loss') a country is willing to pay in order to lower the risks

[31] For the costs of peaking plants in 2050 we made the following key assumptions: 0.45 kg CO_2 emissions per kWh at 1,073 €/ton (based on [13], p. 48), gives CO_2 permit costs close to 500 €/MWh. Taking the current market price of 60 €/MWh as proxy for the short run marginal costs of personnel and fuel, and adding 20 percent on top of that to correct for part-loaded operation which reduces operational efficiency results in overall marginal costs of 72 €/MWh. The capital costs of an open cycle gas turbine are estimated at 700,000 €/MW [46]. Given the strongly reduced market for gas fired power plants towards 2050, and stricter environmental standards a markup was applied. Assuming a 30 year payback time, constant payment for the sum of repayment and interest ('annuity'), and 4% discount rate, gives an annual capital costs of about 52,000 €/MWh. Assuming the peak plant operates on average 5,6 days per year, capital costs are just under 400 €/MWh. Summing up the three costs components results in the rounded number of 1000 €/MWh.

from lack of SoS for either oil or gas. It basically makes a trade-off between costs associated with mitigation options and benefits obtained from improving security of supply. The function indicates that the welfare loss can increase when a) import ratios increase, when b) the share of oil or gas in total primary energy supply increases, and when c) the energy intensity of the economy is high. In all of these three cases, supply disruptions will lead to higher welfare losses. Since each of the factors affects the level of impact of the other factors a multiplicative structure is proposed. For instance, if the energy intensity of an economy is high, a high consumption ratio is more critical for security of supply than in case energy intensity is low. Furthermore, it is assumed that the penalty or damage function is convex since the marginal increase of import dependency will be most critical for the welfare loss if e.g. import dependency is already high rather than low.

The implied costs due to a lack of security of supply need to be estimated for the calibration of the penalty function. Using the portfolio management approach the willingness to pay for security of supply can be calibrated on historical cases such as for instance investments in domestic resources (coal), investments in low-risk foreign resources (uranium), and investments in fundamental alternatives (Fischer-Tropsch). [45] chooses investments in nuclear generation, using foreign uranium reserves, in France during the 1970's as exemplary for the willingness to pay until 2100. France's willingness-to-pay to become largely protected from risky foreign fuels for power generation is estimated to be about 0.5% of total consumption. This seems the result of dividing France's capital investments of about 100 billion euro for 60 nuclear power plants by the GDP of France during the investment period.

Bollen found that for the examples they looked at the willingness-to-pay for large national projects, dedicated to ensure energy supply security, typically amounts to a couple per mille up to, at the most, 1% of private consumption ([45], p. 31). They used, based on the example of the nuclear program in France, 0.5% as central value for the willingness-to-pay, and to take a sufficiently large range of values for the corresponding sensitivity analysis, 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; [45], p. 9).

This approach has been used as part of an integrated assessment that includes also evaluation of global climate change and local air pollution in scenario studies that quantify the effect of environmental policies on the demand for oil and gas.

While looking at Europe in 2050, import ratios are hardly interesting anymore, since much more energy is generated within Europe than currently the case. However, society remains sensitive to changes, for example in case of a dark doldrum (Dunkelflaute) (see Section 6.3). PtG may help to increase security of supply by adding more storage possibilities to the system. Therefore it does not make sense to replicate their willingness to pay formula, here the key stylized facts are used as a first approximation.

The approach of [45] has some drawbacks. First, the MERGE model assumes competitive markets, where price changes are a consequence of supply and demand. Hence it only considers energy security welfare impacts from physical unavailability of energy and cannot assess the impact of uncompetitive or highly volatile prices (see also [14]). Nearly all disruptions result in price volatility rather than in physical unavailability. Price risks are therefore of greater importance for oil, gas, and other fuels. Second, the calibration of the WTP function on unique historic cases may be highly questionable as this may result in highly case-specific and country-specific estimates and is unlikely to reflect future cases under different circumstances. Given the GHG emission reduction targets fossil fuels are less relevant towards 2050, and an energy system portfolio based upon renewables rather than fossil fuels would be a more appropriate reference case.

Finally, note that the French nuclear power plant plan was not their only action to improve or secure their energy security. Hence these figures are likely to be an underestimation of the true willingness to pay for energy security. Similarly PtG will not be the only security of supply action taken towards 2050 and thus not all willingness to pay value should be attributed to PtG.

Table 6-4 applies the Bollen approach to estimate the security of supply value of PtG. It starts with the willingness to pay range of [45] followed by the GDP estimates for 2050, and the private consumption ratio. From this a willingness to pay for security of supply is calculated. The next line gives the assumption of the contribution of PtG to security of supply. This contribution ranges from 10 to 50 percent. The following line gives the ratio of PtG technology, compared to optimistic scenario. Given that this table is the estimate of the optimistic scenario, the Ratio of PtG technology, compared to optimistic scenario, is 100 % by definition. In the other scenario's and for 2040 this line is used to scale back the benefit PtG has in solving this supply shortage in proportion to the installed capacity.

From this the security of supply contribution of PtG in the optimistic scenario is calculated at €22.5 billion annually (and a range of € 1.8 - € 90.1 billion annually). Per person the value is €43.2 (with a range of €3.5 to €172.6 annually). The results for 2040 and for the other scenarios are discussed in Section 6.5.

Table 6-4: Security of supply based on Willingness to Pay, Bollen approach, optimistic scenario 2050

	Low	**Midpoint**	**High**
Willingness to pay as % of private consumption	0.10%	0.50%	1.00%
GDP 2050 (billion €)	22,526	22,526	22,526
Private consumption as % of GDP	80%	80%	80%
Private consumption (billion €)	18,021	18,021	18,021
Willingness to pay (billion €)	18	90	180
Willingness to pay (€/pp)	35	173	345
Contribution of PtG to Security of Supply	10%	25%	50%
Ratio of PtG technology, compared to optimistic scenario	100%	100%	100%
Security of Supply benefit of PtG (billion €)	1.8	22.5	90.1
Security of Supply benefit of PtG per person (€/pp)	3.5	43.2	172.6

Note: The outcomes for the other scenarios are presented in Section 6.5.

6.5 Conclusion

In this section, the first two tables 6-5 and 6-6 present the energy security benefits for all four estimation methods, all scenarios and for the years 2040 and 2050. Like in sections 6.2–6.4 for each estimate a low, midpoint and a high estimate is presented based on the different assumptions as discussed in these sections. Table 6-5 presents the estimates of the total value of energy security for the four methods discussed in the preceding sections and for all scenarios discussed. Table 6-6 shows the value of supply security of PtG per person.

The first four rows of each table show the results for the optimistic scenario, with in the last three columns the results for 2050 as presented in this chapter (low, midpoint and high estimate respectively). 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 4.1.

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 estimation 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 tenth of the value in the optimistic scenario in 2050 or zero. Also 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.

Each estimation approach 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, without doing so arriving at a value of the energy security value for PtG would be impossible. The fact that the outcomes of the four different estimations are more or less in line with each other gives confidence in the methods applied. Still, the outcomes can serve as an indication, whereas future research and additional insights are necessary to increase precision.

Table 6-5: Security benefits of PtG, billion euro

method	scenario	2040 low	2040 mid-point	2040 high	2050 low	2050 mid-point	2050 high
Leiby	optimistic	2,5	4,1	11,5	11,3	18,2	51,0
Rationing of demand	optimistic	2,8	9,5	17,2	12,8	43,3	78,8
Back-up power	optimistic	1,5	6,1	18,2	6,8	27,3	81,9
Bollen	optimistic	0,1	0,3	0,5	1,8	22,5	90,1
average	**optimistic**	**1,7**	**5,0**	**11,8**	**8,2**	**27,8**	**75,5**
Leiby	realistic	0,0	0,0	0,0	1,5	2,5	6,9
Rationing of demand	realistic	0,0	0,0	0,0	1,9	3,5	11,2
Back-up power	realistic	0,0	0,0	0,0	1,0	2,2	11,8
Bollen	realistic	0,0	0,0	0,0	0,2	3,1	12,4
average	**realistic**	**0,0**	**0,0**	**0,0**	**1,2**	**2,8**	**10,6**
Leiby	alternative	0,0	0,0	0,0	0,1	0,2	0,4
Rationing of demand	alternative	0,0	0,0	0,0	0,1	0,2	0,4
Back-up power	alternative	0,0	0,0	0,0	0,0	0,1	0,4
Bollen	alternative	0,0	0,0	0,0	0,0	0,2	0,8
average	**alternative**	**0,0**	**0,0**	**0,0**	**0,1**	**0,2**	**0,5**
Leiby	pessimistic	0,0	0,0	0,0	0,0	0,0	0,0
Rationing of demand	pessimistic	0,0	0,0	0,0	0,0	0,0	0,0
Back-up power	pessimistic	0,0	0,0	0,0	0,0	0,0	0,0
Bollen	pessimistic	0,0	0,0	0,0	0,0	0,0	0,0
average	**pessimistic**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

Table 6-6: Security benefits of PtG, per person (euro pp)

method	scenario	2040 low	2040 mid-point	2040 high	2050 low	2050 mid-point	2050 high
Leiby	optimistic	5	8	22	22	35	98
Rationing of demand	optimistic	5	18	33	24	83	151
Back-up power	optimistic	3	12	35	13	52	157
Bollen	optimistic	0	0	1	3	43	173
average	**optimistic**	**3**	**10**	**23**	**16**	**53**	**145**
Leiby	realistic	0	0	0	3	5	13
Rationing of demand	realistic	0	0	0	4	7	22
Back-up power	realistic	0	0	0	2	4	23
Bollen	realistic	0	0	0	0	6	24
average	**realistic**	**0**	**0**	**0**	**2**	**5**	**20**
Leiby	alternative	0	0	0	0	0	1
Rationing of demand	alternative	0	0	0	0	0	1
Back-up power	alternative	0	0	0	0	0	1
Bollen	alternative	0	0	0	0	0	1
average	**alternative**	**0**	**0**	**0**	**0**	**0**	**1**
Leiby	pessimistic	0	0	0	0	0	0
Rationing of demand	pessimistic	0	0	0	0	0	0
Back-up power	pessimistic	0	0	0	0	0	0
Bollen	pessimistic	0	0	0	0	0	0
average	**pessimistic**	**0**	**0**	**0**	**0**	**0**	**0**

7 Conclusions and recommendations

Energy security is a broad and diverse concept. Various ways to look at the issue matter, and as a result there are many different indicators on energy security. There are only a few valuation studies on energy security. This deliverable presents the results of several indicators and all relevant valuation approaches on PtG, using the JRC-EU-TIMES for four different EU energy system scenarios. All scenarios studied target at 95 percent CO_2 emission reduction in 2050.

The indicators are all related to the sovereignty, resilience and robustness dimensions of energy systems. For these indicators the main findings for all scenarios are that:

- Overall, all indicators studied in detail show an improvement of energy security towards 2050. For all these indicators the impact of PtG is limited, although it should be noted that no indicator covers all (or nearly all) aspects of energy security. The indicators that can be shown, might underestimate the relevance of PtG for future energy system. Nevertheless, the total societal impact of PtG can be significant, as shown in the validation estimations below.

- For the *sovereignty perspective* given the 95% GHG emission reduction scenarios the indicators show an improvement in the European energy security from 2015 towards 2050. The imported energy from outside Europe relative to the total primary energy supply (TPES) falls, the imported gas as percentage of all consumed gas and the costs of imported gas decline substantially as well. This picture could change if scenarios are included that import in the form of hydrogen or synthetic fuels from places outside Europe (e.g. from the MENA region) with higher availability of variable renewable energy sources, which would lead to a trade-off between lower cost and sovereignty.

- For the *resilience perspective* the energy security indicators show a slightly diverging perspective. The diversity of primary energy sources increases towards 2030, showing an improvement of energy security, while it becomes more concentrated afterwards. Electricity generation shows the opposite pattern. The diversity of electricity generation decreases towards 2030 and then increases again towards 2050 at current levels. Energy intensity (energy used as fraction of GDP) will fall for all scenarios, indicating higher resilience of energy consumption sectors including the transport sector for energy price fluctuations.

- For the *robustness perspective* one indicator could be quantified, that is the spare capacity of electricity generation. Another fundamental indicator of robustness is the ability of electricity networks to deal with the intermittent nature of renewable energy sources, and to balance and stabilize the electricity grids. However, this second indicator could not be investigated due to model constraints. The aforementioned indicator, the spare capacity of electricity generation, increases until 2050. However it is unlikely that this is completely an improvement of energy security, since much of the new capacity will have a relatively low capacity factor. Besides, the indicator does not take into account the possibilities for generation reserve sharing across countries as well as the limitations for generation to meet demand due to grid capacity constraints within countries. Future research may apply more advanced indicators for this perspective e.g. a flexibility margin indicator that provides insights in the extent to which the available electricity system flexibility exceeds the demand for flexibility in energy systems with high shares of variable renewables, including the role of gas storage. Such an indicator should ideally be granular enough to take into account major congestions that would impede that generation meets demand. The latter would require more granular model outputs than were available for this study. A complementary study with more detailed analysis of the grids including the effect of PtG can be found in D6.4 [25].

- No indicator covers all (or nearly all) aspects of energy security. The indicators that can be shown, might underestimated the relevance of PtG for future energy system. Most indicators are expressed in physical units, if an indicator is monetary this is not the same as a welfare effect.

Most indicators are expressed in physical units, if an indicator is monetary this is not the same as a welfare effect that can be inserted in a cost-benefit analysis. For these reasons, we complemented our study with estimations of the societal value of PtG for energy security, with the valuations being expressed in euros to enable comparison with other costs and benefits in a social cost benefit analysis. The few existing valuation studies of energy security were scrutinized on their merits and for the first time (as far as we know) applied to analyse the contribution of PtG to the energy security of low-carbon energy systems. The following conclusions can be drawn:

- Three methods are elaborated and applied to estimate the societal value of energy security for the European Union: the first method is based on oil price fluctuations and their impact on the economy, the second method is based either on the costs of avoiding outages in periods of very low wind and solar energy production during several weeks or on the costs of outages if no action is taken to avoid outages in periods of very low wind and solar energy production during several weeks, and the third method is based on the willingness to pay for security of supply. Although these methods differ substantially, the outcomes are more or less in line with each other.

- In the positive scenario the societal value of PtG is already substantial in 2040 and increases towards 2050. In the so-called realistic scenario, PtG has a positive energy security benefit in 2050, although much smaller than in the positive scenario. Given the large size of the EU energy systems, small changes in energy security due to PtG as shown by the indicators above, result in significant monetary values. In the alternative scenario and the pessimistic scenario PtG has no benefit for energy security. This is in line with predictions on the deployment of PtG technologies, since not-deployed PtG cannot add to energy security.

These estimates of the value of energy security, which are unavoidably dependent on assumptions, can be used in cost benefit analysis of PtG, which is the upcoming Deliverable 7.6. The outcomes here show that although PtG is not the main driver for energy security, that is replacement of the import of fossil fuels with locally generated renewable electricity generation, it has in some scenarios clearly a positive value. That value lies outside the investors, potentially leading to underinvestment in this technology.

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