Assessing Security of Energy Services in Dutch Energy Transition Scenarios

Adriaan van der Welle
Francesco Dalla Longa
Bert Daniëls
Jeroen de Joode
Arjan Plomp
Ad Seebregts

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Contact information

Contact person for this study at ECN is Adriaan van der Welle (tel. 088 515 4496, vanderwelle@ecn.nl). The ECN internal project number is 5.0965.

Contact person at Delft University of Technology is Aad Correljé (overall project leader).

Abstract

This report compares and assesses several gas and electricity oriented energy transition scenarios for 2030 on a range of security of energy services dimensions, while taking into account effects for system costs and CO_2 emissions. To this aim, both gas and electricity oriented energy systems have been integrally compared on their ability to withstand unforeseen disruptions and to adapt to them. Given the propagation of shocks along the system value chain, it is simulated how price spikes would impact on energy users through dedicated security of energy services indicators. These indicators provide objective and quantitative insights in the resilience, flexibility, redundancy, and diversification dimensions of the energy transition scenarios. Results indicate that scenarios that deploy significantly more gas-based technology options do not score better towards 2030 on security of energy services than electricity oriented scenarios.

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Summary

Security of supply is usually not analysed in context of different energy transition routes, suggesting possibly too optimistic view on 'all-electric' society
The Netherlands can realize the national CO_2 emission reduction targets for 2030 with a variety of different energy transition routes that can be orientated towards the development of an electricity and/or gas-based system. The actual transition trajectory is often assessed from the perspectives of technological development of low carbon technologies, stimulation of development by financial incentives, and public acceptance of their monetary and non-monetary effects. Available transition studies thus generally evaluate on criteria of sustainability (degree of GHG emission reductions) and affordability (cost efficiency).

Security of supply, which is generally defined as the uninterrupted provision of vital energy services (Cherp *et al.* 2012), is usually included only implicitly as a precondition in network infrastructure and system development. Furthermore, whereas the import dependency for fossil fuels is often mentioned, a thorough and overall evaluation of actual security of supply properties of different possible future energy systems is often lacking. In the context of electricity versus gas-oriented energy transition scenarios, our presumption is that in an 'all-electric' society possibilities for substitution of energy services may be limited, whereas a future energy system with deployment of both electricity and gas[1] for energy services provision could be more robust for security of supply failures.

The role of gas in energy system scenarios for 2030
As a starting point, four different energy system scenarios have been constructed i.e. a reference, gas moderate, gas extreme, and nearly all-electric scenario for 2030. Each scenario is tested for a range of possible non-ETS emission reduction targets for the Netherlands i.e. 28-43% for 2030 compared to 2005 levels, which results in instantaneous non-ETS emission levels of 96, 89, 82, and 76 Mton respectively. Together with the emission target for diminishing emissions within the ETS (43% compared to 2005), these emission targets reflect the goals for meeting sustainability

[1] Here gas includes both natural gas and alternatives like biogas, SNG and hydrogen.

targets in 2030. With these 2030 targets, the energy system will also be on target for achieving the 2050 GHG goals.

Given these sustainability targets, the integral Dutch energy system model called OPERA has been applied to determine for each scenario a future mix of technologies that achieves these decarbonisation goals at the lowest costs for society, thus accounting for the policy goal affordability. However, the scenarios appear not to be fully comparable on affordability (i.e. energy system costs) given choices made in the scenario construction which affect the degrees of freedom for the model in the deployment of technology options. In the gas moderate and gas extreme scenarios, gas is assumed to play a larger role in the built environment, industry, agriculture, and transport sectors. Compared to the reference scenario, the gas moderate and gas extreme scenarios allow for larger possibilities for consumption of natural gas in built environment, industry (both ETS and non-ETS) and agriculture sectors. Additionally, the gas extreme scenario assumes larger possibilities for consumption of gas in the transport sector, and restrictions to consume electricity in built environment and transport sectors. This favours the greening of gas supply by applying bio-based gas, and the substitution of oil in the transport sector by either natural gas or bio-based gas. In contrast with the gas extreme scenario, the nearly all-electric scenario allows for more electrification at the demand side rather than the supply side of the energy system. The role of electricity is enlarged by stimulation of electricity consumption in built environment, industry, agriculture, and transport sectors. It also includes restrictions on the maximum deployment of natural gas in various sectors. These stimulations and restrictions allow for a larger role of options that substitute electricity for fuels such as electric cars and plug-in hybrids, and resistance heating. Besides, electricity can be used as an auxiliary source for harvesting renewable energy, for instance by application of resistance heating in industrial boilers at moment that RES-E is abundant, and instantaneous electricity prices are low.

Level of security of energy services within scenarios with and without disruptions
Both gas and electricity oriented energy systems have been integrally compared on their ability to withstand unforeseen disruptions and to adapt to them. Three disruptions have been analysed; two fossil price shocks (gas and coal prices respectively) and a physical disruption due to geopolitical tensions and a military dispute between Ukraine and Russia. The propagation of the physical disruption within energy transition scenarios is discussed in a more qualitative way, while the effects of the fossil price shocks are quantitatively analysed. To this aim, based upon a literature review seven composite security indicators have been deployed. These indicators allow for assessing impacts of unforeseen disruptions on consumers given the resilience, flexibility, and redundancy within gas and electricity-oriented energy systems (import, production, supply and network) respectively to mitigate these impacts. Additionally, indicators to assess impacts of disruptions on resource concentration in energy supply with concomitant effects on consumers have been calculated.

The seven selected indicators are:
1. Electricity peak capacity margin.
2. Gas peak supply margin.
3. Flexibility margin.
4. Energy intensity.

5. Costs of imported fuels.
6. Import dependency.
7. Energy security market concentration.

Indicators have been calculated for both gas and coal price disruptions. The gas price disruption shows often insignificant results compared to the situation without disruption. This mainly reflects the fact that the role of coal is prominent in the generation mix in the situation without disruption, and a higher gas price will logically not lead to a larger role for gas. Moreover, the analysis is mainly focused on the demand-side of the energy system where possibilities to substitute gas for other fuels are fairly limited in the operational time frame. Therefore, Table 1 summarizes the results for the seven indicators, for the situation without disruption as well as for the situation with coal price disruption. The results reflect averages for the different CO_2 emission target levels analysed.

Table 1: Summary of indicator results for situations without disruption and with coal price disruption

	No disruption				Coal price disruption			
Scenario → Indicator↓	Reference	Gas moderate	Gas extreme	Nearly all-electric	Reference	Gas moderate	Gas extreme	Nearly all-electric
Electricity peak capacity margin	+	+	+	+	=	=	↓	↑
Gas peak supply margin	+	+	+	+	=	↓	↑	↓
Flexibility margin	+	+	+/-	+	=	↑	=	=
Energy intensity	+/-	+/-	+/-	+	=	↓	↑	↓
Cost of imported fuels	+	+	+	-	↑	↑	↑	↑↑
Import dependency - Gas	+/-	+/-	-	+	=	=	↑	=
Import dependency - Oil	+/-	+/-	+/-	+/-	=	↓	↑	↓
Import dependency - Coal	+/-	+/-	+	-	=	↓	=	↓
Import dependency - Biomass	+/-	+/-	+/-	+/-	=	=	=	=
Energy security market concentration	-	-	-	-	=	=	=	=

Legend: + positive, =/- neutral, - negative. All effects of coal price disruption relative to situation without disruption; ↑↑ large relative increase of indicator, ↑ relative increase, = no significant change, ↓ relative decrease.

Implications of the evaluation of security of energy services for energy policy, taking into account sustainability and affordability aspects

Orientation of energy transition scenarios towards gas or electricity has limited impacts on security of energy services

The analysis suggests that orientation towards either gas or electricity in energy transition scenarios for 2030 has often fairly limited impacts on security of energy services. Overall, differences between indicator scores for different scenarios, with and without shocks, are often insignificant or small. Scenarios that deploy a higher amount of gas-based options do generally not score better on either system resilience, flexibility, and redundancy indicators or resource concentration indicators. The only exception is the lower import dependency from coal in gas oriented scenarios. Therefore the hypothesis that a future energy system with deployment of both electricity and gas for energy services provision would be more robust to mitigate random security of supply failures than an energy system that is mainly based on electricity, cannot be confirmed. Indeed, the gas moderate and gas extreme scenarios do not score significantly better than the reference and nearly all-electric scenarios.

.. while gas oriented scenarios may reduce overall system costs but may increase marginal CO_2 emission costs

When comparing energy transition scenarios on overall system costs (as indicator of affordability) and CO_2 emission costs, it can be seen that the overall system costs of the gas extreme scenario are generally lower than in the other scenarios, while the marginal costs of CO_2 emission reduction are considerably higher in the gas extreme scenario. This can be explained by the fact that in case of less stringent emission reduction targets the gas extreme scenario deploys to a lower extent technology options that simultaneously reduce CO_2 emissions, increasing the marginal costs of further CO_2 emission reductions, but to the advantage of lower overall system costs. However, it should be kept in mind that this comparison is somewhat blurred by different degrees of freedom of both the gas extreme and nearly all-electric scenarios.

Results should be interpreted with care due to different assumptions made for scenario construction and calculation of SoS indicators

More generally, results should be interpreted with care due to the inherent uncertainties regarding several assumptions in the scenario construction and modelling as well as the SoS indicators. Results are partially explained by OPERA modelling constraints on quality of supply, realization of technology potentials, minimum and maximum shares of gas and electricity consumption in various sectors, and the availability and prices of fuels and CO_2. A critical assumption is the larger availability of biomass for the gas extreme scenario. It remains to be seen whether the biomass supply can be increased substantially, given potential negative consequences for food supply. Adequate containment of this risk by biomass certification is required to allow for such substantial increases of biomass supply. If this requirement is not met, it would be increasingly difficult to achieve stricter emission reduction targets with the gas extreme scenario. Furthermore, although uncertainties around assumptions for SoS indicators are substantially reduced by deploying seven different SoS indicators and by performing part of the analysis in a qualitative way, still some uncertainties remain due to complexities in modelling of regulatory (N-1) conditions to secure gas supply during disturbances.

Security of energy services in gas oriented scenarios can be improved by diminishing the dependency of gas on electricity

For structurally improving security of energy services it is advised to take measures to diminish the dependency of the provision of gas-based services (like heating and cooking) on the availability of electricity since gas-based services currently can often not be provided without the latter. One could foresee that gas-based devices are equipped with devices (e.g. a battery) to function independently from electricity. Likewise, by decoupling electricity demand (partly) from supply through implementation of flexibility enhancing technology options such as storage and demand response, security of electricity-based services can be improved.

A longer term perspective is advised to explore the development of security of energy services

Finally, it is advised to take a longer term perspective in future security of energy services' analyses. Given the fact that 2030 is relatively nearby, and therefore affected by current policies and policies foreseen for both 2020 and 2030, degrees of freedom are limited and therefore the differences between scenarios, the optimal mix of technology options, and its resulting security of supply level. Towards 2050, the scenario space would increase dramatically, and therefore also the likely divergence of security of supply aspects of gas versus electricity based scenarios. Consequently, in future research it would be useful to explore the development of security of energy services towards the 2050 horizon.

1

Introduction

1.1 What future role for gas?

Security of supply is usually not analysed in context of different energy transition routes, suggesting possibly too optimistic view on 'all-electric' society
The drive for a more sustainable energy future is visible everywhere in society. An important driver are the European policy targets with concomitant targets at national level. In addition to the long term target for GHG emission reduction in 2050 (with 80% relative to 1990), recently the discussion about an intermediate target for 2030 has started. The European Commission proposes to reduce CO_2 emissions in 2030 with 40% compared to 1990 (EC, 2014a). The emission target is splitted in targets for diminishing emissions within the ETS (43% compared to 2005) and the non-ETS (30% compared to 2005 levels) respectively. The non-ETS goal will be translated in a binding targets for each Member State (effort sharing).

The Netherlands can realize the national targets with a variety of different energy transition routes that can be orientated towards the development of an electricity and/or gas-based system. The actual transition trajectory is often assessed from the perspectives of technological development of low carbon technologies, stimulation of development by financial incentives, and public acceptance of their monetary and non-monetary effects. Available transition studies thus generally evaluate on criteria of sustainability (degree of GHG reductions) and affordability (costs).

Security of supply, which is generally defined as the uninterrupted provision of vital energy services (Cherp *et al.* 2012), is usually included only implicitly as a precondition in network infrastructure and system development. Furthermore, whereas the import dependency for fossil fuels is often mentioned, a thorough and overall evaluation of actual security of supply properties of different possible future energy systems is often lacking. In the context of electricity versus gas-oriented energy transition scenarios, our hypothesis is that in an 'all-electric' society possibilities for substitution of energy services may be limited, whereas a future energy system with deployment of both electricity and gas[2] for energy services provision could be more robust for security of supply failures. This may be considered an important caveat in thinking about how future energy systems should look like from the perspective of gas as an energy carrier, gas markets and gas infrastructure. We will test this hypothesis in the study at hand.

This study wants to fill that gap by identifying impacts of a diverse set of scenarios with a varying role for gas as opposed to electricity, on sustainability, affordability, and security of supply

The starting point of this study is a variety of scenarios; not only an (nearly) all-electric future, but also scenarios that deploy more gas-based technologies. The scenarios are analysed with a model of the integral Dutch energy system called OPERA. This model is regularly applied to answer questions of policy makers on the contributions of policies to achieve targets for renewables, energy efficiency, and GHG emission reductions. The model allows to determine a future mix of technologies that achieves decarbonisation goals at the lowest cost for society. Optional additional constraints shape the role for gas as opposed to electricity. It allows for an integral comparison between energy systems with different shares of electricity and gas, dealing with all system parts i.e. import, production, supply and network.

Since the model does not address all aspects of security of supply, we conduct a separate security of supply assessment afterwards, while taking into account model outputs such as gas generating capacity, maximum intermittent supply change, primary and final energy consumption, and peak gas demand.

Assessing security of energy services instead of security of supply requires systematic comparison over the whole value chain

Given the project title, this study focuses on the downstream part of the energy system value chain. This is done by focusing on energy services. From the perspective of different groups of users, not the disruption of energy itself is important but the extent to which these users face consequences of the disruption. This depends on the resilience, flexibility, diversification and redundancy dimensions of the whole energy system (import, production, supply and network). Therefore an integral comparison between energy systems with different shares of electricity and gas is necessary. To that aim, a set of SoS indicators has been selected that, together with an integral energy system model that takes into account main aspects of the flexibility dimension, allows for an innovative security of energy services assessment across the entire value chain.

Moreover, for testing the flexibility, diversification and redundancy dimensions it is simulated how disruptions would affect the SoS indicators. Energy systems, either gas-based or electricity-based, that are best capable of withstanding unforeseen shocks and of adapting (Keppler, 2010) will likely show a higher security of energy services.

Objective and research questions

The main objective of research can thus be summarized as the assessment of the role gas and gas infrastructure can play in achieving security of energy services in energy systems for 2030, given emission targets.

[2] Here gas includes both natural gas and alternatives like biogas, SNG and hydrogen.

It is aimed to fulfill this objective by answering three separate research questions;

1. What is the role of gas in energy system scenarios for 2030?
2. What is the level of security of energy services of end-users within scenarios reflecting different possible future energy supply systems? How do disruptions affect indicators for security of energy services for different scenarios?
3. What are the implications of this evaluation of security of energy services for energy policy, taking into account aspects of sustainability (i.e. level of GHG emissions) and affordability (i.e. cost efficiency)?

Figure 1: below summarizes the relations between the different research questions or building blocks.

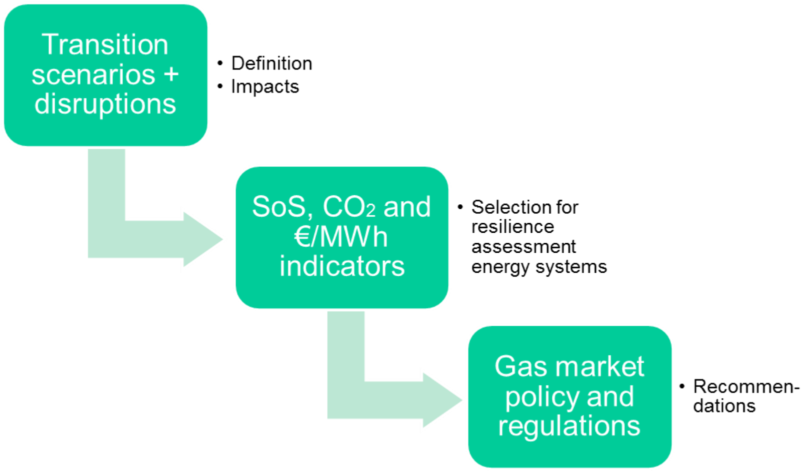


Figure 1: Summary of research approach

1.2 Reading guide

This report is structured as follows. Chapter 2 sets out the methodological approach for assessing the possible role for gas in future energy systems. It is based upon scenario analysis by an optimization model covering the integral Dutch energy system (OPERA) combined with a dedicated SoS analysis using indicators. Chapter 3 then presents the results of the model-based analysis for each of the four electricity and gas-based scenarios , demonstrating the impacts of disruptions on SoS indicators. Finally, Chapter 4 summarises the key overall messages that may be drawn based on the performed analyses and provides policy recommendations.

2

Methodology

This chapter outlines the main components that enable the model-based security of supply analysis in the next chapter. First, the four gas and electricity oriented energy transition scenarios for 2030 are described and choices made in the model-based definition are clarified (Section 2.1). The scenarios are analysed by using an optimization model (OPERA) covering the integral Dutch energy system given decarbonisation targets. Section 2.2 outlines the OPERA model, which provides major inputs for the ensuing security of supply analysis. Section 2.3 describes the selected security of supply indicators as well as the disruptions that are deployed to test the flexibility, resilience, redundancy, and diversification dimensions of the energy scenarios.

2.1 Scenario framework

In order to deal adequately with the uncertainty concerning the development of energy systems in the future, four energy scenarios have been constructed. Some energy scenarios deploy more electricity-based technology options, while others are more based upon gas-based options. Each scenario is evaluated on fulfilment of the three main policy goals; decarbonisation, affordability and security of supply. The first two objectives are addressed by the scenario framework in combination with deployment of the OPERA model, the latter objective, security of supply (SoS) is analysed separately afterwards. The SoS analysis is further discussed in Section 2.3.

Concerning decarbonisation, the top-down greenhouse gas emissions reduction targets for 2050 will drive the energy transition. As this transition will not occur overnight, the European Commission has translated the target for 2050 in an intermediate milestone for 2030. They proposed to reduce CO2 emissions in 2030 with 40% compared to 1990 (EC, 2014a). The emission target is splitted in targets for diminishing emission within the ETS (43% compared to 2005) and the non-ETS (30% compared to 2005 levels) respectively. The emission cap only varies for the non-ETS sectors. This is a reflection of the varying ways with which the overall European target for the non-ETS sector can be translated into binding targets for the individual member states (effort sharing).

Political agreement over this translation has still to take place. Dependent on the allocation of the burden over member states, the most recent estimate at the time of writing (October 2014) is that the non-ETS emission reduction target for the Netherlands will vary between 28-43% (compared to 2005 levels) (Daniels *et al.* 2014). The percentage of 28% corresponds with the most cost-effective situation for Europa as a whole, while a percentage of 48% corresponds with burden sharing in which costs are distributed across member states according to the ability to pay.[3] Non-ETS emission reduction targets of 28-43% results in instantaneous non-ETS emission levels of 89-76 Mton. Therefore, we report all scenarios for four different non-ETS emission reduction targets within this range. For the ETS sectors, an overall European target of 43% reduction applies. According to the EC impact assessments (EC, 2014b; EC, 2014c), this would result in a CO_2-price of 40€/tonne CO_2-equivalent.[4] All scenario's apply this CO_2-price, which explains the small differences between the supply sectors.

Available emission reduction options for the non-ETS sectors

The OPERA calculations include various emission reduction targets for the non-ETS emissions. The model may apply various emissions options as specified in the database. The overall 2030 CO_2 emission reduction has to be realized by contributions from several sectors; residential and services, power, industry, and transport sectors. For the different sectors a range of technology options is available to cope with increasing emission constraints on the non-ETS emissions. This paragraph provides a short description on the nature of energy demand by sector and the possibilities to reduce non-ETS emissions. Technologies that exclusively reduce emissions in the ETS-sector are not included, e.g. solar PV, wind power, CCS.

Energy demand in the *built environment* and the *non-ETS industry sectors* is mostly determined by demand of heat for space heating, hot water and cooking, and electricity demand for lighting and appliances. Currently, most of the heat is provided by natural gas oriented systems.

Technological directions for reducing non-ETS emissions include:

- Insulation to reduce heat demand (wall and roof insulation, double glazing).
- More efficient heating systems.
- Greening the natural gas by e.g. biobased gas.
- Seasonal heat storage.
- Renewable heating systems such as heat pumps and geothermal energy.
- Heat networks.

There may be various hybrid configurations imaginable, such as hybrid heat pumps with a back-up boiler for peak demand.

Energy demand in the *agriculture sector* is mostly determined by heat demand for space heating and electricity demand for assimilation lighting in the greenhouse horticulture. For the fuel demand by mobile equipment refer to the text about the transport sector. Currently, most of the heat is provided for by natural gas oriented systems, with an important role for CHPs equipped with gas engines. These also provide

[3] The outcome of a recent European agreement (October 2014) appears to point towards a target approaching 40% for the Netherlands, and is based on both criteria.

[4] Other emissions including CH_4 and N_2O are converted to CO_2-equivalents.

electricity for the assimilation lighting. Technological directions for reducing non-ETS emissions include:

- Insulation and other measures to reduce heat demand.
- Deep geothermal energy.
- Greening the natural gas by e.g. biobased gas.
- Seasonal heat storage in aquifers, often combined with heat pumps.

Energy demand in the *transport sector*, including mobile equipment in agriculture, construction and industry is almost exclusively determined by demand for traction energy. Oil is by far the dominant energy carrier. Examples of technological directions for reducing non-ETS emissions include:

- Demand reduction (more efficient cars, including hybrids).
- Substitution of oil based fuel by bio fuel.
- Substitution of oil based fuel by natural gas or green gas.
- Electrification (plug-in hybrids or all electric cars).
- Hydrogen based cars.

Affordability is taken into account by deployment of a dedicated optimization model called OPERA (Option Portfolio for Emissions Reduction Assessment). OPERA enables to put together a technology option package at minimum system costs. The option package meets a target for one or more kinds of emissions, while adhering to preconditions (constraints) specified by the user. More information about the OPERA model can be found in Section 2.3.

Shaping the scenarios

The four scenarios differ with regard to their tendency to implement gas based as opposed to electricity based solutions for achieving the emissions reduction target. A more or less neutral scenario is accompanied by two scenarios with a stronger tendency towards gas, and on scenario with a stronger tendency towards electricity based solutions. The respective tendencies have manly been shaped by generic constraints on sectoral gas and electricity consumption, rather than specific constraints on individual technologies. In this way, the model has a greater freedom in choosing specific technologies in response to various emission constraints, and the results reflect a cost-optimal technology mix given these generic constraints.

1. Reference scenario
2. Gas moderate scenario
3. Gas extreme scenario
4. Nearly all-electric scenario

The reference scenario is based on the NEV (Hekkenberg and Verdonk, 2014), and does not include additional restrictions that force the system towards either gas of electricity in end-use appliances. To a varying degree, the other scenarios apply additional constraints that force the system towards more gas or electricity. In addition, scenarios 3 and 4 apply more optimistic assumptions for the availability of resources or technologies that allow for a higher share of either gas or electricity. Finally, since restrictions on the deployment of gas as opposed to electricity options differ per scenario, the cost of emission reduction will also vary per scenario.

The four scenarios are roughly defined as follows:

1. Reference scenario
- Based on Witboek scenario (Daniels *et al.* 2014)
- Least cost while accounting for GHG emission reduction target by 2030.

2. Gas moderate scenario
- Deployment of gas in end-user sectors is forced on the 2030 level according to the NEV scenario with determined policy (NEV-V), Hekkenberg & Verdonk (2014)
- Higher lower limits for natural gas consumption in built environment, industry (both ETS and non-ETS), and agriculture sectors. No change in possibilities to consume natural gas in transport sector compared to reference scenario.
- All constraints concerning the realisation of technical potential apply.

3. Gas extreme scenario
- Possibilities for consumption of natural gas in built environment, industry (both ETS and non-ETS) and agriculture sectors are comparable to the gas moderate scenario. Wider possibilities to consume gas in the transport sector because of more optimistic stance about the limitation of the existence of unburnt gas in the exhaust (methane slip) of (bio)gas fuelled engines towards 2030.
- Possibilities to consume electricity in built environment and transport sectors are somewhat limited compared to other scenarios.
- Constraints on minimal deployment of natural gas apply, remaining constraints are relaxed.
- Greater availability of biomass, to allow for a larger role for bio based gas.

4. Nearly all-electric scenario
- Options for biogas consumption in the built environment as well as the industrial sector (ETS), and consumption of biofuels in the transport sector are restricted. Consumption of biofuels in transport sector is restricted due to issues around sustainability of biomass.
- At the same time, electricity consumption is stimulated in built environment, industrial (ETS-sector), agriculture and transport sectors.
- Upper limits for natural gas consumption in built environment, industry (both ETS and non-ETS), agriculture, and transport sectors. Less possibilities to consume gas in the transport sector because of more pessimistic opinion about the limitation of the existence of unburnt gas in the exhaust (methane slip) of (bio)gas fuelled engines towards 2030.
- Constraints on maximum deployment of natural gas apply, remaining constraints are relaxed to allow for higher application of electric solutions.

The various constraints as chosen are primary a way of shaping a smaller or larger role for gas and electricity, and do not reflect any concrete policy choices. In reality of course, actual developments would reflect such factors as policy instruments, political preferences and availability of resources. However, the nature of these is not a subject of the study: here the constraints merely serve the purpose of creating varying shares of natural gas and electricity based options.

Application of technologies within the four scenarios

As described, the scenarios encompass varying constraints forcing the energy system towards either gas based solutions or electricity based solutions when faced with emission caps. The constraints themselves are general in character rather than technology-specific, leaving it up to the model which mix of reduction options to apply when faced with a particular emission cap.

For each scenario, four variants with different emissions caps have been included. The tighter the emission cap, the more the model is forced to apply additional emission reduction technologies and the more the bias towards gas or electricity becomes visible in the technology mix. As a consequence, the differences between the scenarios are gradual instead of absolute, and the differences become more outspoken in case of tighter emission caps (Figure 2:).

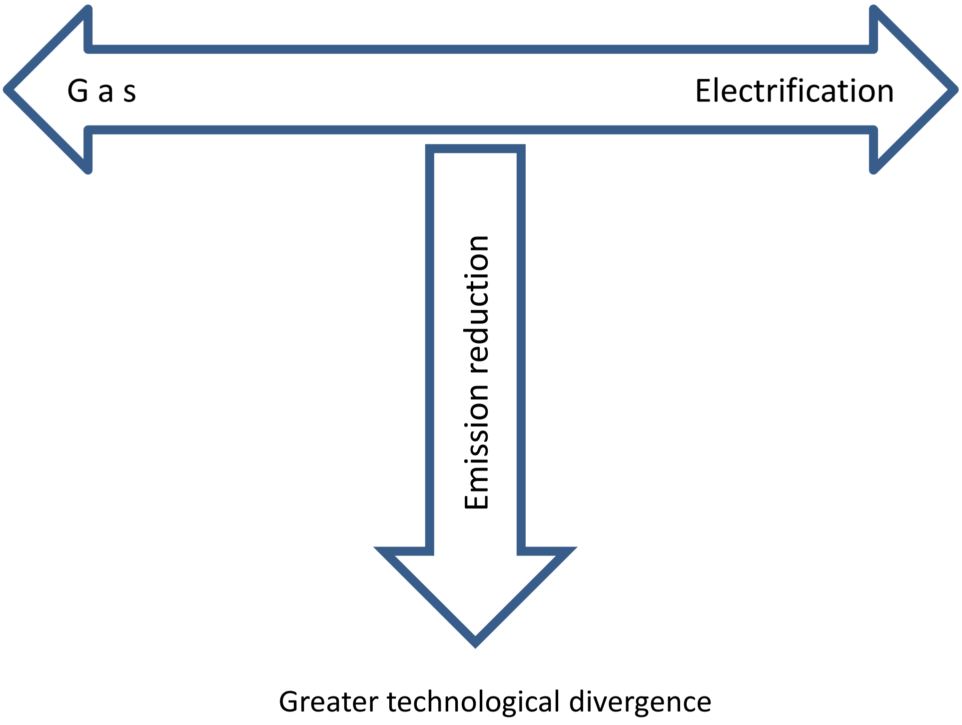


Figure 2: Main dimensions of scenarios

There are various technological solutions towards lower emissions which do not touch upon direction towards gas versus electricity based system, such as reduction of other greenhouse gases, and end use savings. This section focuses on the options which touch upon the effects on gas and electricity application.

Gas based emissions reduction

The most important gas based emission reduction option is greening of the gas supply, by applying bio-based gas. Emissions of biobased fuels do not count for the emissions cap, as the carbon is short-cyclic[5]. In addition, there may be a potential for substituting oil in the transport sector by natural gas or bio-based gas. This results in emission

[5] This means that it has recently been withdrawn from the earth's atmosphere, as opposed to emissions of fossil fuels.

reductions because of the lower emission factor of gas as compared to oil. The latter is a fairly low-cost option that may be cost-effective even in case of low emissions reduction, but its emissions reduction is debatable[6]. The application of biobased gas becomes more important when emission caps become tighter.

Electricity based emissions reduction
Options that enlarge the role of electricity in end-use appliances include both options that substitute fuels by electricity, and options that use electricity as an auxiliary energy source for harvesting renewable energy. Examples of the latter include electric heat pumps, geothermal energy and seasonal storage of heat and cold. Options that merely substitute electricity for fuels include electric cars and plug-in hybrids, and resistance heating. The latter may also be applied as an auxiliary heat source in industrial boilers at moments that renewable electricity from wind and solar is abundant, and momentaneous electricity prices are low. As with the gas based options, the rate of application becomes higher when emission constraints becomes tighter. Contrary to the gas based options, the changes affect the demand side rather than the supply side of the energy system.

Common scenario assumptions
Like the P2G project (De Joode *et al.* 2014) and the Dutch national energy outlook of ECN & PBL (Hekkenberg & Verdonk, 2014), IEA scenarios are the basis for the description of the international context and developments regarding fuel prices and cost development for categories of technologies in each of the scenarios. For the CO_2 price, the assumption of Daniels *et al.* (2014) is utilized, which is based on the European impact assessments on European climate and energy targets (EC, 2014b; EC, 2014c). Table 2 below shows the fuel and CO_2 price assumptions.

Table 2: Fuel and CO_2 price assumptions for 2030 (real prices 2013)

Oil ($ per barrel)	143
Gas (€ct per m^3)	32
Coal (€ per ton)	94
CO_2 (€ per ton)	40

Sources: fuel prices: Hekkenberg & Verdonk (2014), CO_2 price: Daniels *et al.* (2014).

Similarly, the scenarios are connected to the OPERA factsheets which contain information regarding the national context i.e. national technology potentials, infrastructure costs, demand and supply profiles, and Dutch Policy related inputs amongst others. For each of the technology options that result in reduction of non-ETS emissions, it is assumed that the technical potential can be developed for approximately 50% by deployment of policy instruments. Amongst others, the deployment of certain technical options may be restricted by physical restrictions (no room in buildings for heat pumps) or lack of political feasibility.

[6] The methane leakage in internal combustions engines is as yet an unsolved problem. In addition, flexifuel internal combustion engines (ICEs) capable of using both gas and oil based fuels, have a lower efficiency than gas only engines. A disadvantage of the latter is that they can't revert to oil when gas is not available, such as in other countries.

2.2 Model-based analysis using OPERA

2.2.1 Introduction

This part of the report gives a concise description of the OPERA-model, which has been applied for the system analysis.[7]

OPERA (Option Portfolio for Emissions Reduction Assessment) is an integrated optimisation model, and the successor of the *'Optie Document'*.[8] It is a bottom-up technology model that determines which configuration and operation of the energy system combined with other sources of emissions (e.g. non CO2 greenhouse gases) meets all requirements, whether market-driven or policy imposed, at minimum energy system costs. In most applications, these requirements include one or multiple emission caps. In addition to energy related emissions and technologies, the model is capable to include emissions and technologies that are not energy-related as well.

For the choice of technologies (technology options), it draws upon an elaborate database containing technology factsheets, as well as data on energy and resource prices, demand for energy services, emission factors of energy carriers, emission constraints and resource availability.

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

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

The reference scenario is represented by a technology portfolio based on the technology specific output of the National Energy Outlook Modelling System (NEO-MS).[9] Final demand is based om the energy balances of the Netherlands as reported in MONIT (www.monitweb.nl). These energy balances distinguish between energetic energy use (with energy in- and output of CHP separately reported), non-energetic use (feedstock in e.g. petro-chemical industry) and other conversions (e.g. cokes ovens or

[7] This section is largely based upon De Joode *et al.* (2014).

[8] We considered the utilization of different models for scenario analysis which have been internally developed and applied before. The OPERA model seems most suited for this analysis; it allows for system optimization, model-based selection of options given inputs, and contains both conventional and innovative options.

[9] In Dutch called Nationale EnergieVerkenning RekenSysteem (NEV-RS).

refineries). Energy service levels are also derived from the baseline, whether as energy demand (electricity and/or heat) or a projected activity level expressed in physical units (e.g. iron and steel, ammonia, ethylene, passenger road transport, freight road transport).

In this study, the OPERA model calculates four different target levels for non-ETS emissions in 2030: 96, 89, 82, and 76 Mton. These instantaneous emission levels of 76-96 Mton correspond with the range of cumulative emission reduction targets for the non-ETS sector (43%-28%), relative to 2005, that are currently (October 2014) deemed as most realistic. With a cumulative target of 28% or 33% no or hardly any additional measures are necessary to comply with the emission targets compared to the reference scenario.

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

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

2.2.2 Energy system representation

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

The energy supply sectors covered are:

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

The model assumes that the demand has to be covered by supply and that both generation and network capacities are sufficient to cover peak demand. This holds not only for the total system, but also on sectoral level; e.g. the capacity of boilers in a sector has to be sufficient to cover the peak of heat demand. Moreover, there is an availability margin which indicates the availability of every technology option at times of peak demand, this margin is at the conservative side. Hence, quality and security of supply are partly taken into account in the model.

Energy technology representation

The model database contains conventional technologies describing the actual energy system on supply and demand sides, as well as existing and future alternatives. Generally, tighter emissions constraint favour the more expensive low emission alternatives over the conventional - lower costs but higher emissions reference technologies. More specific limiting constraints, such as additional technology or energy limitations (e.g. limits on nuclear expansion or CCS or biomass availability) will limit the role of the directly affected technologies and technologies linked to these, while favouring the position of other technologies that fulfil the same functions. Constraints imposing minimal values (e.g. target to meet a certain amount of wind or solar energy) force implementation of the affected technology while placing competitors at a disadvantage. There are various ways in which technologies influence each other: technologies may compete with each other, but they may also favour each other. For example, a lot of intermittent renewable energy may favour the position of storage and peak load technologies, and a lot of electricity supply is likely to favour the position of technologies that convert electricity to other energy carriers and vice versa.

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

Table 3 provides a list of the different elements in the modelled energy system chains.

Table 3: Broad overview of technology options included in the energy value chain as modelled by OPERA

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

2.2.3 Representation of infrastructure

Given the diversity of levels of demand (households consume electricity at low voltage levels, while industry consumes at medium or high voltage levels), it is important to take into account that energy, electricity, gas and heat, is not directly consumed at the suppliers site. To transport energy from the suppliers to the end-users, a network capable of transmitting the required energy at every moment of demand is required.

In order to account for network capacity requirements and flows, a stylised representation of the different grids is included in the model (See Figure 3 below). The electric network is differentiated in three voltage levels (high, medium, low) with on each levels the appropriate supply options as well as the demand and consumers (based on statistic data on level of consumption a “fixed” share of different voltage levels is currently assumed, later this will be made flexible). In order to be able to convey energy at different levels, also electric transformers are included. They can ensure the flow of electricity between the voltage levels, in both directions. Often the capacity of the transformers rather than the grid capacity itself limits the electricity flows. Investments in transformers will take place if the required peak demand on a certain voltage level exceeds the existing capacity.

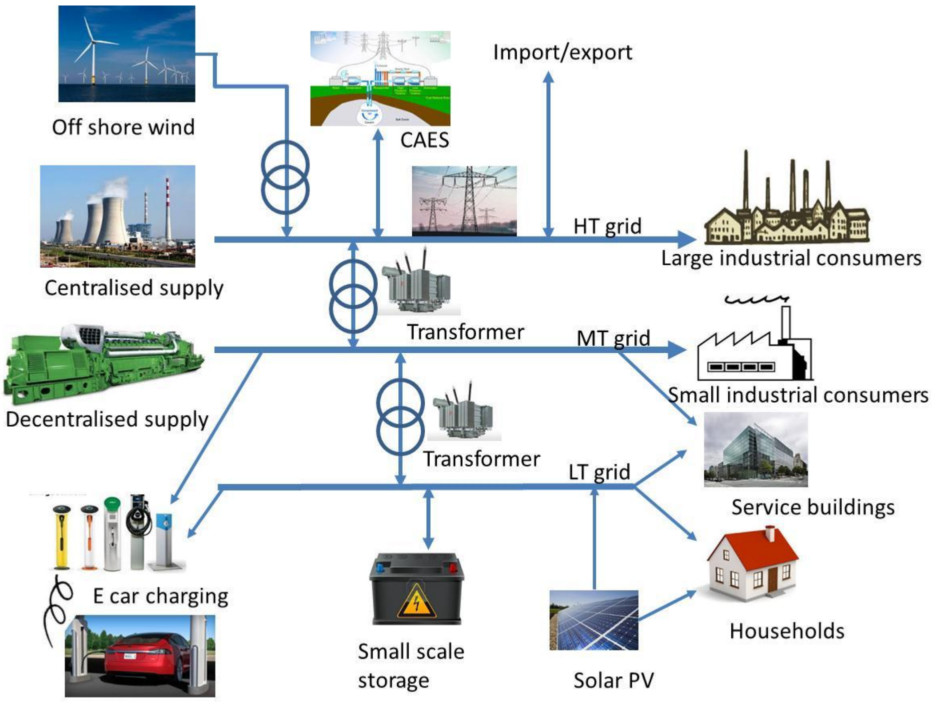


Figure 3: Schematic illustration of the electric supply, infrastructure and demand

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

The gas grid has various pressure levels, analogous to the electricity voltage levels: a high pressure with most production facilities feeding in, a medium pressure grid and a distribution network that serves most end users. Between the pressure grids, connectors are modelled which reduce pressure from high to low. In contrast with electricity no pressurising from a lower to a higher pressure is envisaged as this go against quality assurance of the gas on the different levels (e.g odorisation and dilution with N2 to maintain low caloric quality for most end users vis-a-vis high caloric gas consumption by a growing number of industrial end users). As increases in demand are met by increasing transported volumes, no expansion technologies are provided here, just a specific consumption related to the transported amount of gas.

2.2.4 Representation of time units and relevant demand and supply profiles

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

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

2.3 Security of supply analysis

As said before, the security of supply aspect is often missing in scenario studies. We try to fill this gap by a dedicated security of supply analysis. Recognizing that from the perspective of different groups of users, not the disruption of energy services itself is important but the extent to which these users face consequences of the disruption, we focus on security of energy services (Jansen and Seebregts, 2010). The security of energy services depends on the resilience, flexibility, redundancy, and diversification of the whole energy system i.e. import, production, supply and network, to withstand unforeseen shocks and to adapt to them (Keppler, 2010). In order to account properly for the contribution of different parts of the value chain to security of energy services, an integral comparison between gas-oriented and electricity-oriented scenarios is necessary.

An integral comparison can be done either in a qualitative or a quantitative way. It seems valuable to perform the analysis at least partially quantitative for two reasons. First, given the large numbers of security of supply or security of energy services dimensions mentioned in the literature, from the outset it is unclear which dimensions are more important than others. Second, the interactions between the deployment of different technology options (e.g. if the generation mix consists of a high share of controllable gas-based generation, storage might be superfluous), cannot be taken into account in a more qualitative analysis. At the same time, some issues are difficult to model, for instance because of the many geopolitical dimensions involved or the complexity of societal choices (e.g. around demand rationing). Thus a combined quantitative and qualitative analysis seems best suited for the purposes of this study.

Different security of energy services dimensions are often scored or ranked by SoS 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 in a given area (Jansen & Van der Welle, 2010). They can serve as tools (OECD, 2008):

- 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.

In the context of this study, security of energy services indicators are applied to obtain objective insights in the resilience, flexibility, redundancy, and diversification dimensions of the modelled energy systems which are closely linked to the energy transition scenarios. This is tested by simulating how disruptions would affect the SoS indicators, and therefore energy users, for each energy transition scenario, given the propagation of shocks along the value chain in gas and electricity oriented energy systems. Section 2.3.1 sets out the selected SoS indicators, while Section 2.3.2 describes the types of disruptions one could think about as well as the selected ones.

2.3.1 SoS indicators

Several studies use different indicators to cover trends in separate elements of the value chain; energy carriers, production, network, supply etc. by looking e.g. to import dependency, diversification of fuels, market concentration, electricity generation adequacy and sectoral development of electricity demand separately. Although this is advantageous from transparency point of view, they often do not provide insight in the net effects of an event or disruption for groups of end-consumers.

As an alternative, a composite indicator can be designed, compiling individual indicators into a single index on the basis of an underlying model (OECD, 2008). Although these indicators are more complex and less transparent, they may provide better insights in the net effects of an event. Furthermore, since they provide information about the relative importance of different elements in the value chain, policy implications might be more easily drawn.

In order to capture the effects of shocks across the value chain, some composite type of indicators will be used for this analysis. We do not deploy composite indicators here to derive a single index, but rather to account for the effects of disruptions on end-consumers given the resilience, flexibility, and redundancy dimensions of the whole energy system (import, production, supply and network). IEA (2007) and Ecofys *et al.* (2009) developed relevant composite indicators which cover the propagation of disruptions through the supply chain i.e. are based upon the causal relationships within the energy system. In addition, we selected indicators that provide insight in the diversification and dependency of fuel imports.

Thus we distinguish two different groups of indicators:[10]

(1) Indicators assessing impacts of unforeseen disruptions on consumers given the resilience, flexibility, and redundancy along the value chain to mitigate these impacts by adapting gas and electricity-based energy systems respectively;
(2) Indicators assessing impacts of disruptions on resource concentration (the opposite of diversification) in primary energy supply and finally on consumers.

For each group, a list of indicators has been reviewed based on an extensive literature search (including Scheepers *et al.* 2007; IEA, 2007; Ecofys *et al.* 2009; Jansen and Van der Welle, 2010; and Cherp *et al.* 2012). Subsequently, specific indicators have been selected based on the criteria usefulness, transparency, and data availability (Jansen and Van der Welle, 2010). Usefulness is here defined as the indicator giving a fair reflection of the level of security of supply risk for the security of supply risk dimensions (resilience, flexibility, redundancy, and diversification) considered. Transparency requires that the indicator scores are readily interpretable in terms of security of supply risk and are instrumental in ranking different scenarios. Data availability requires that information with regard to the indicator is available from public sources and the indicator can be used for both historical analysis and forward looking analysis.

Relevant indicators in the first group are capacity margin, flexibility margin and energy intensity indicators. A major indicator providing insights in the adequacy of energy supply to demand is the capacity margin, like the **peak capacity margin for electricity (EPCM)**. EPCM measures the extent to which energy supply fulfils peak demand with and without shocks given existing flexibility in supply or demand. Furthermore, in order to account for the overall importance of electricity in the delivery of energy services to end-consumers, we multiply the peak capacity margin by the share of electricity in final energy consumption.

$$EPCM\ [\%] = \frac{\sum_{all\ technologies} Capacity - Peak\ Demand}{Peak\ Demand} * \left(1 - \frac{FEC_{electricity}}{FEC_{all}}\right)$$

Where:

- Capacity (MW) = nameplate capacity of electricity plant
- Peak Demand (MW) = peak electricity demand
- FEC (PJ) = final energy consumption

A similar type of indicator has been derived for gas i.e. the **gas peak supply margin (GPSM)**. The importance of gas in the delivery of energy services to end-users is here calculated by the complement of the adjusted share of gas in final energy consumption. This share accounts for the energy carriers electricity and heat, and related transformation efficiencies.

[10] This distinction bears similarities to Keppler (2010) who distinguishes an internal and an external dimension: an internal dimension that is concerned with maintaining domestic infrastructures at adequate capacity levels and good working conditions and an external dimension that aims at ensuring a stable supply of imports. The distinction in the text differs since resilience to changes in climate policy is here not exclusively considered as part of the external dimension.

$$GPSM\ [\%] = \frac{Capacity - Peak\ Demand}{Peak\ Demand} * \left(1 - \frac{DFEC_{gas} + EHC_{gas} \cdot \frac{eff_{gas}}{eff_{all}}}{Total\ FEC}\right)$$

Where:

- Capacity (PJ) = maximum capacity of gas supply options
- Peak Demand (PJ) = peak gas demand
- $DFEC_{gas}$ (PJ) = direct final energy consumption of gas
- EHC_{gas} = electricity and heat generated by gas
- Eff_{gas} =efficiency of heat and power generation from gas (including CHP and district heating)
- Eff_{all} = efficiency of all heat and power generation (including CHP and district heating)
- Total FEC (PJ) = total final energy consumption

A limitation for both indicators is that we do not account for the expected availability of power plant categories at peak demand, which relates to the probability of forced outages and expected output from intermittent renewables. Furthermore, we do not account for the flexibility of demand response, storage, and other substitution possibilities. For these indicators all parameter data is taken from the OPERA model.

A major, partially flow-based indicator is the flexibility margin. **The flexibility margin** measures the flexibility of the system to respond to rapid changes in output (Ecofys *et al.* 2009). The most critical situation for the system would be a maximum increase of demand combined with a maximum decrease of electricity supplied by intermittent renewable energy sources (RES-E) (i.e. a flow), leading to maximum demand for flexibility from controllable plants as well as other sources of flexibility such as demand response and interconnections. The maximum demand for flexibility depends on the geographic area considered, the correlation between different renewable energy types, and the correlation between the maximum increase of demand and the concurrent maximum decrease of electricity supply by intermittent RES-E.

Flexibility is supplied from sources from both the supply and demand side of the electricity system. The degree to which the different sectors can and may respond to sudden changes in fuel prices or availability of fossil fuels varies considerably. The power supply sector generally has much larger possibilities to respond to fuel price changes than the demand sectors.

By nature, the power supply sector has excess power generation capacity. This excess capacity is dictated by the fluctuations in electricity demand and fluctuations in electricity production by intermittent supply, combined with the requirement than at any moment, the supply sector has to be able to meet peak demand. This results in a considerable freedom in the dispatch of power plants throughout most hours of the year. The operational decisions on which power plant to operate at each moment, depend on the merit order of power plants. The merit order is determined by short run marginal costs, with fuel costs and CO_2 emission costs as its main constituents. Furthermore, some power plants dispose of dual firing possibilities, implying they are able to burn either gas or coal, depending on the relative levels of gas, coal, and CO_2

prices. For both reasons, given a sufficiently diverse power supply sector with regard to the primary energy source (coal, nuclear, natural gas, biomass), the power supply sector can respond strongly to short term fluctuations of fuel prices.

By contrast, the demand sector hardly has any possibilities to switch to other energy sources in the short term. In most cases, there is a strong one-to-one relationship between the primary energy source and a specific energy service. Currently, oil is the dominant fuel for transport and chemical feedstock, gas the dominant fuel for heating of building and industrial processes. As a consequence, there is very little room for short-term reduction of the demand for a specific fuel without impairing the delivery of the required energy services. Some technological developments may increase the short-term flexibility to some extent. Examples include heat pumps with back-up boilers (electricity/gas), flexifuel cars (oil/gas), plug in hybrid cars or electric cars with a range extender (oil/electricity).

The supply of flexibility by controllable plants depends on the ramping capability of controllable power plants (which in turn depends on whether they are cold or warm), their availability (the overall demand for energy from power plants differs across the day and therefore their availability to ramp up), and the capacity of these type of plants (related to the geographic area as well as whether or not they are already running part-loaded). Besides flexibility supply by interconnections is included. For interconnections holds that weather systems often influence the weather equally in large geographical areas, implying that intermittent RES-E is likely to decrease in a comparable way, and both countries are in need for flexibility. Therefore an estimate for the flexibility offered by interconnections is used (from De Joode *et al.* 2014), which accounts for this correlation effect. Furthermore, curtailment of RES-E is taken into account as flexibility option, assuming that RES-E is treated as a mature technology by 2030 and therefore can be curtailed for economic reasons. On the other hand, although the model takes into account some demand response since it sometimes chooses for some additional capacity on the demand side to cover the need for flexibility (e.g. industrial boiler capacity and additional capacity for the conversion of electricity into heat for part of the time), it proved to be difficult to estimate the size of the demand response. Consequently, indicator results do not account for the flexibility from demand response.

As a result, given the assumptions above the flexibility margin assesses the difference, if any, between required and (the largest part of) available system flexibility. Finally, we account for the impact on the demand-side by multiplying this difference with the complement of the share of electricity within final energy use. In this way, we correct for the overall importance of electricity within the Dutch economy.

$$Flexibility\ margin[\%] =$$

$$\frac{\left(\sum_{controllable\ technologies} \max ramp\ rate * availability * capacity\right) - \max flexibility\ need}{\max flexibility\ need} * \left(1 - \frac{FEC_{electricity}}{FEC_{all}}\right)$$

Where:

- Max ramp rate (%) = % of nameplate capacity from each dispatchable plant type available in 1 hour
- Availability (%) = the capacity that is available for use at the time that availability is needed
- Capacity (MW) = total nameplate capacity of each dispatchable plant type
- Max flexibility need (MW) = maximum simultaneous change of decrease of intermittent output per hour and increase of demand per hour
- FEC (PJ) = final energy consumption

The maximum ramp rate, availability, and capacity values are based upon assumptions from the Competes market model. The maximum rate of intermittent output change, maximum rate of possible demand change, and final energy consumption values are derived from OPERA model runs for one specific year (assuming 15 time slices).

Another indicator of the first group is energy intensity. **Energy intensity** is often defined as the ratio of energy supply (total primary energy supply i.e. TPES) to GDP or capita. Here we define it as the ratio of final energy consumption to GDP or capita. This allows to measure the extent to which energy savings take place. A decline of the ratio means an increase of energy efficiency (Scheepers *et al.* 2007).

The second group consists of indicators assessing the impacts of disruptions on resource concentration. They are mainly related to the geopolitical risks related to the imports of fossil fuels, which countries such as the Netherlands experience in the form of price and physical risks. Selected indicators include costs of imported fuels, import dependency, and energy security market concentration.

Costs of imported fuels can be expressed as proportion of GDP (also known as ratio of net fuel import bill to GDP) to show the importance of fuel import costs in the overall economy (Jansen and Van der Welle, 2010; Cherp *et al.* 2012).

Import dependency is the extent to which a country depends on physical imports of fossil fuels as fraction of total consumption (possibly accounting for diversity of import routes) (a.o. Cherp *et al.* 2012).

Energy security market concentration (ESMC):[11] In order to minimize the exposure to resource concentration price risks in fossil fuel markets the ESMC can be determined. It starts off by calculating the percentage share of each supplier i in the international market for fuel f defined by its net export potential (IEA, 2007). The higher the square of the index, the larger the departure of a situation with full competition and the risk of exploitation of market power, implying a higher ESMC. It is possible to correct the ESMC for political instability of fuel supplying countries. Political risk ratings are based upon scores for both political stability and regulatory quality from the World Bank (2013). Political risk ratings have been scaled linearly towards 1-3, with 1 being the lowest risk level (representing zero political risk) and 3 the highest risk level. An overall indicator for a country can be obtained by dividing the corrected ESMC of each fuel by the share

[11] Other diversity indices can be developed using the Shannon-Wiener index. An example is Jansen *et al.* (2004).

of primary energy supply of that fuel in the country specific total primary energy supply and summing up all fuel specific scores (Ecofys *et al.* 2009).[12]

2.3.2 Disruptions

For assessing the vulnerability and resilience of end-users for effects of security of supply incidents in the energy value chain, definition of such incidents or unforeseen disruptions is necessary. Without disruptions, the operational flexibility of power system actors to react to shocks which originate from the supply or demand side cannot be tested.

Shocks can entail both short and long term energy security issues resulting from disruptions. Short term energy issues include exposure of the power system actors to changing prices and quantities of global oil, gas and coal markets. Both the exposure to imported fuels (including biofuels) as well as exposure to (potential) restrictions to the availability of energy carriers are important in this context. Long term issues relate to domestic availability of oil, gas and coal, aging infrastructure, and generation adequacy (partly Cherp and Jewell, 2011) and sufficient investments in options related to national fuel supply as well as generation and energy infrastructure (including e.g. storage and demand response) to withstand these issues. The focus of this study is on short term energy issues, that is why electricity and gas generation capacities are assumed to be fixed, and the operational flexibility of the power system is the only source of responses to events.

Keppler (2010) provides an useful typology of different shocks and discerns three types:

- Long or medium term physical interruptions of energy supplies (political decisions such as embargoes, geopolitical tensions, internal problems of supplier country or region, restrictions of supplies due to long-term exercise of monopoly power by a cartel (OPEC) etc.)
- Short term physical interruptions due to isolated and non-predictable events (political and military reasons, commercial disputes, sabotage etc.)
- Short term price spikes in the price of energy (sudden exercise of monopoly power by a single entity or a cartel (OPEC quota revisions), speculative bubbles and herd behavior, and new information concerning the reserves position of a major supplier.

Long or medium term physical interruptions are often related to the long lifetimes of network assets and the substantial lead and construction time needed for replacement of these assets. An example is the situation in Germany where the nuclear phase out has large consequences for system operation for several years, and the situation in Belgium where the unavailability of nuclear power plants has consequences for several months during the winter period. Instead, short-term physical interruptions and price spikes last for shorter periods, typically for days or months. Both long or medium term and short term shocks are discussed in (scientific) literature studies of CPB (2004) and Eckle *et al.* (2011).

[12] The country's own share of the market affects the price risk of insecurity for consumers as well. If a country is a large net exporter and sets prices above competitive levels, it depends on redistribution policies how consumers are affected. If there is limited redistribution associated with export revenues, consumers face the same price risks as consumers in other countries, while when there exists significant redistribution these consumers face less price risks than consumers of other countries. Following Ecorys *et al.* (2009) we assume that all countries face the same price risk associated with resource concentration.

CPB (2004) distinguishes SoS incidents for different energy carriers and intermediate outputs: oil, gas and electricity. For electricity, a distinction is made between electricity markets and electricity networks; only for electricity markets quantitative shocks are defined. The following shocks are analysed in the CPB report:

For oil:
- Significant supply disruption due to political unrest in the Middle East region, short-lived but large increase in oil prices. Disruption of 10 million barrels a day over period of 6 months (1/3 of strategic stock)
- Cartel behavior of a group of major oil producers causes long lasting restraint of production. Reduction in global supply of oil by 4 million barrels a day over a period of one year results in price increase of $5 per barrel (based upon Considine, 2002).

For natural gas:
- Severely cold winter in Europe leads to extremely high demand for natural gas. Two cases can be imagined; a) gas price 200% of normal winter price for period of 4 months; b) physical shortage of gas of a specific area in the Western part of the Randstad area for a period of 24 hours with average gas system start-up time of 3 days. A specific area in the Western Randstad area was selected since this area is at 'the end of the pipeline' from Groningen and therefore will face the impact of interruptions the earliest. The gas system start-up time of 3 days accounts for the fact that residential customers often have to be manually reconnected after a physical gas interruption.
- Market power gas exporting countries increases average European gas price by 50% to the expected price level for a full year. Cost increase of 1.3 eurocent per kWh.

For electricity market:
- Short-living extreme surge in demand or unexpected shock in availability of capacity, leading to either price spikes or black outs. Assumption that availability of all fossil-fueled power generation decreases from 75% to 65% leads to either price spike or 24-hour black-out for the Randstad area.
- Execution of market power by producers causes longer lasting increase of average level of power price. This results into a 50% rise of average electricity price level over a period of one year.

Besides, Eckle *et al.* (2011) distinguish three shocks;
- An increase in the price of oil and gas by a factor of three in 2015
- A nuclear accident in 2015 with a moratorium on new nuclear plants after 2015 and progressive phase-out of existing plants, decreasing the availability of nuclear power plant capacity to zero
- No deployment of CCS due to barriers to safe and cost effective deployment, increasing CO_2 emissions and chances of not meeting CO_2 emission targets.

From the potential shock identified above, some shocks are less relevant for this study for various reasons; a market power shock translates also in a fossil price shock and is thus not distinctive while disruptions due to a nuclear accident or no CCS are unlikely to have a major impact. For the nuclear accident holds that its impact is limited due to the low penetration of nuclear energy, while the effect of a restriction on the deployment of CCS is reduced by the fact that CCS in non-ETS sectors is not necessary to meet the 2030 emission targets. Consequently, we selected two types of shocks for our analysis; a fossil price shock (both gas and coal), and a physical disruption due to geopolitical tensions and military dispute between Ukraine and Russia (the latter as a variant of a physical gas shortage due to a severely cold winter). Since it is problematic to determine the likelihood of each disruption, impacts are calculated under the 'what-if' approach. The impact of disruptions is estimated by comparing impacts of indicators with disruptions to indicator results without disruptions (for the SoS indicators we refer to Section 2.3.1).

An important choice when deploying the selected shocks is whether these shocks have to be implemented in the OPERA model as scenario variants or whether effects of shocks have to be assessed by using post-processing. This clearly depends on the particular shock to be evaluated. For both the fossil price shocks it seems most appropriate to model them as scenario variant since the model then can automatically decide which flexibility options are most optimal to deploy to mitigate the shock or diminish its propagation along the value chain. In order to prevent that the model anticipates the shock due to perfect foresight, model runs are performed in two steps; first a run that covers the time frame before the shock; second a run that covers the time period after the shock in which only operational decisions are possible to cope with each shock.

For the physical shock, an exogenous approach with postprocessing is most appropriate since effects of these type of shocks depend on multiple societal choices such as the sequence of curtailment of different types of energy users (e.g. which sectors or functions are seen as most vital or vulnerable, which sectors do have the highest value of lost load), and regulatory conditions to secure gas supply during disturbances (e.g. following the N-1 principle, in case of the failure of the single largest gas failure during a day of exceptional high gas demand, supply should be able to satisfy total gas demand). Incorporating these societal choices and regulatory conditions exactly as restrictions in the model is deemed too complex. Hence, the postprocessing method is favoured in this case.

3

Results modelling analysis and SoS analysis

This chapter presents the results from the model-based analysis with OPERA and the concomitant security of supply analysis. Section 3.1 summarizes the modelling results for each of the four electricity and gas-based scenarios. Section 3.2 demonstrates the impacts of disruptions on each of the SoS indicators for each scenario, compared to the situation without disruptions. Conclusions on the SoS impacts, while also accounting for the impacts of scenarios on sustainability and affordability, are provided in Chapter 4.

3.1 Summary of modelling results

This section provides a summary of the modelling results. Figures 4-7 provide insight in the mix of primary energy sources in each of the four scenarios both for the highest and lowest non-ETS emission targets (96 Mton and 76 Mton respectively) considered. Both intermediate emission targets (89 Mton and 82 Mton) are not shown here, since differences between emission levels are relatively minor. The figures represent the net consumption of energy carriers. Since the net trade balance for electricity, heat, biogas, and hydrogen shows a net contribution of zero, these energy carriers are not represented in the figure. Generally, the results do not indicate a large difference between both non-ETS emission targets considered for each scenario. This can be explained by the fact that non-ETS emission targets primarily constrain the demand sectors, while the supply sector is under the ETS and therefore not significantly affected. However, the differences in the mix between the reference scenario and the gas extreme and nearly all-electric scenarios are significant. In the gas extreme scenario the share of gas increases with about 6% entirely at the expense of coal. Instead, in the nearly all-electric scenario the relative share of coal increases with broadly 8-10% (lowest share in scenario with 76 Mton CO_2 target, highest share in case of 96 Mton target), reducing gas with 5-8% as well as biomass and oil both with about 1%.

Furthermore, the share of oil is remarkable high. This relates to the fact that a large share of oil is used as feedstock for the production of petro-chemicals and plastics. Since the carbon is stored in the product this results only in a modest share in the GHG emissions.

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

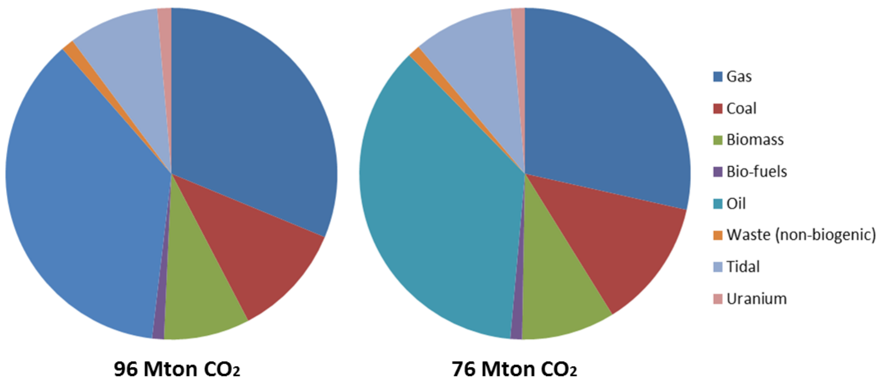


Figure 5: Mix of primary energy sources in the gas moderate scenario

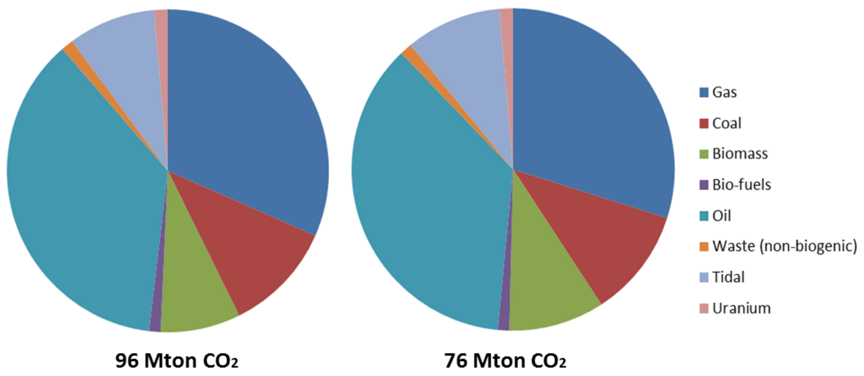


Figure 6: Mix of primary energy sources in the gas extreme scenario

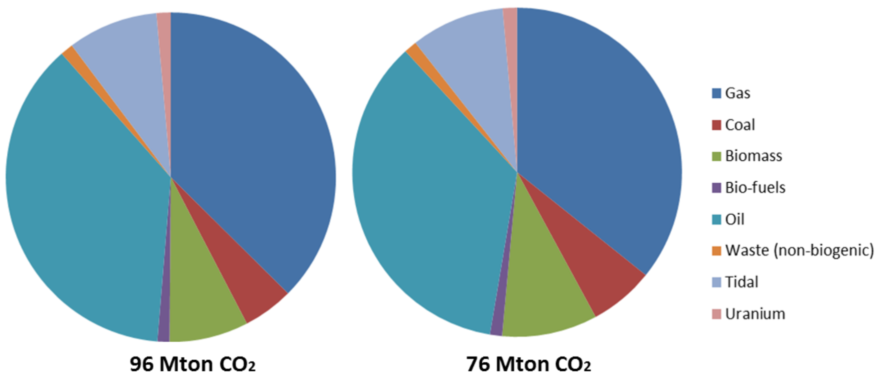
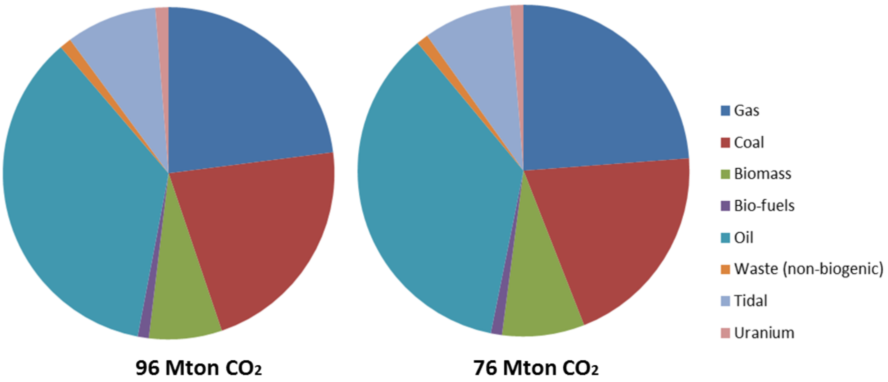


Figure 7: Mix of primary energy sources in the nearly all-electric scenario



Wind and solar PV capacities, their curtailment, overall system costs and CO_2 shadow prices of the four scenarios are shown for all four CO_2 emission targets, rather than for just the highest and lowest ones, in Table 4:

- As expected the result is that the lower the CO_2 emission level, the higher the CO_2 shadow prices and the total system costs.
- The gas extreme scenario generally shows the lowest total system costs but the highest CO_2 shadow prices, while the opposite holds for the nearly all-electric scenario. This can be explained by the additional constraints and degree of freedoms of both scenarios in order to realize higher shares of gas and electricity respectively. The additional constraints in the nearly all-electric scenario on maximum gas consumption and minimum electricity consumption increase the total system costs but reduce CO_2 emissions, implying that the CO_2 shadow prices diminishes. The marginal costs of CO_2 emission reduction are thus lower for the nearly all-electric scenario compared to the gas extreme scenario. Instead, in the gas extreme scenario the constraints on minimum gas consumption and maximum electricity consumption decrease the total system costs but increase CO_2 emissions costs and therefore CO_2 shadow prices.
- Given the different degrees of freedom for the model, it should be noted that the scenarios are not fully comparable on system costs. The nearly all-electric scenario as well as gas scenarios in some respects do have higher degrees of freedom than the reference scenario.
- The penetration of wind and solar PV is not significantly different between the four scenarios. Scenarios score also comparable on curtailment of wind and solar PV.

Table 4: Selected OPERA outputs

	Emission level	96	96	96	96	89	89	89	89	82	82	82	82	76	76	76	76
	Scenario	Refe-rence	Gas Mode-rate	Gas Extreme	Nearly all-electric	Refe-rence	Gas Mode-rate	Gas Extreme	Nearly all-electric	Refe-rence	Gas Mode-rate	Gas Extreme	Nearly all-electric	Refe-rence	Gas Mode-rate	Gas Extreme	Nearly all-electric
Indicator	Unit																
CO2 shadow price	[€/ton]	-	-	40	-	13,4	25,2	85,9	-	64,7	75,4	577,6	40	312,6	667,3	3443,8	171,4
Total system costs	[M€/yr]	69755	69287	68381	74711	69758	69302	68753	74711	70048	69618	70113	74810	71059	71649	79337	75303
Penetration Wind	[GWe]	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3	11,3
Penetration Wind	[TWh/yr]	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1	41,1
Penetration Solar PV	[GWe]	15,2	15,2	16,0	15,6	15,2	15,2	16,1	15,6	15,2	15,2	16,1	15,6	15,2	15,2	15,8	15,2
Penetration Solar PV	[TWh/yr]	12,6	12,6	12,9	12,6	12,6	12,6	12,9	12,6	12,6	12,6	12,9	12,6	12,6	12,6	12,6	12,6
Curtailment Wind	[TWh/yr]	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,2	0,0	0,0	0,0	0,3	0,0
Curtailment Wind	[%]	0,1	0,1	0,7	0,1	0,1	0,1	0,6	0,1	0,1	0,1	0,5	0,1	0,1	0,1	0,6	0,1
Curtailment Solar PV	[TWh/yr]	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Curtailment Solar PV	[%]	0,4	0,4	1,0	0,4	0,4	0,4	0,9	0,4	0,4	0,4	0,9	0,4	0,4	0,4	0,7	0,4

3.2 Impacts of disruptions on SoS indicators

For identifying impacts of disruptions, notably price spikes, on SoS indicators, as seen before one has to compare the indicator results with disruptions to the indicator results without disruptions. Therefore, first the results for the SoS indicators without occurrence of disruptions are shown and discussed (Section 3.2.1). Afterwards the changes in the SoS indicators following a gas price disruption (Section 3.2.2) and a coal price disruption (Section 3.2.3) respectively are elaborated upon. Gas and coal disruptions have been simulated by doubling the gas and coal price respectively. Assumed absolute price levels of these fuels before and after disruptions are shown in Table 5.

Table 5: Gas and coal prices before and after disruptions

Energy carrier	Before disruption	After disruption
Gas (€ct per m^3)	32	64
Coal (€ per ton)	94	188

Finally, the impacts of a physical gas supply disruption due to a war in Ukraine are discussed in a more qualitative way (Section 3.2.4).

3.2.1 SoS indicators without disruptions

This section discusses the SoS indicator results for the situation without disruptions, which serves as a 'reference' situation for the assessment of the effects of disruptions in next sessions. Section 2.3 distinguished two groups of indicators; (1) system resilience, flexibility, and redundancy indicators; and (2) resource concentration indicators. Subsequently, each group of indicators is here discussed for the specific situation at hand.

System resilience, flexibility, and redundancy indicators

Capacity margins

Both for electricity and gas oriented scenarios electricity peak capacity margins have been calculated. The peak capacity margin can measure the extent to which available generation capacity is able to fulfil peak electricity demand before and after a disruption. A similar type of indicator has been derived for gas i.e. the peak capacity margin for gas. Both indicators have been defined in more detail in Section 2.3.

The electricity peak capacity margin is fairly comparable between the four scenarios; production capacity exceeds peak demand with a net factor (i.e. corrected for the complement of the share of electricity within final energy use) of about 2.4-2.9. Highest scores are obtained in case of most stringent emission reduction targets since the increase of generation capacity foreseen outweighs the peak demand which is fairly constant (nearly all-electric scenario) or increases at moderate pace (gas moderate scenario).

Some notable differences exist between the scenarios. For emission reduction levels of 96 and 89 Mton, the EPCM is the lowest for the nearly all-electric scenario. This is expected since this scenario deploys most electricity-based production and consumption options. One would also expect that the gas extreme scenario would obtain the highest score due to its high reliance on gas-based options, decreasing the importance of electricity. However, that is not the case since the generation capacity is substantially lower than in the gas moderate and reference scenarios, while the peak electricity demand decreases not very significantly compared to the latter. The decrease of the importance of electricity within Dutch energy supply in the gas extreme scenario does not outweigh this negative effect on the peak capacity margin score. For the emission target levels of 82 and 76 Mton, the gas extreme scenario has the lowest margin since the peak demand for electricity increases faster than the electricity generation capacity.

The peak supply margins for gas are considerably smaller than for electricity. This reflects that the gas system is considered to be more controllable than the electricity sector, allowing for smaller peak supply margins. Furthermore, smaller peak supply margins can be explained by the fact that the role of gas storage, LNG, and linepack is not accounted for in the indicator, while the importance of these alternative sources of supply and storage is more important for gas than for electricity. Similar to the electricity peak capacity margin, highest scores for the gas peak supply margin are obtained under the most stringent emission reduction targets. For the reference, gas moderate, and gas extreme scenarios, peak capacity margins for the emission target level of 76 Mton are about 13-18 percentage points higher compared to the 96 Mton emission target level for two reasons. First, peak gas demand decreases relative to available gas supply. This results from lower gas consumption levels combined with a fairly constant gas supply. Second, the complement of the adjusted share of gas in final energy consumption indicates that the importance of gas within Dutch energy supply declines under stricter emission reduction targets, increasing the gas supply margin. Concerning the differences between scenarios, as expected the gas extreme scenario scores lowest due to its higher reliance on gas based technology options, while the nearly all-electric scenario obtains the highest score.

Flexibility margin
The flexibility margin measures the flexibility of the system to respond to rapid changes in output (Ecofys *et al.* 2009). The need for flexibility in the most critical situation for the system would be equal to the maximum simultaneous increase of demand and decrease of electricity from intermittent renewable energy sources. Available flexibility includes flexibility from controllable plants, interconnections, and RES-E curtailment. Options for storage of heat and electricity are included in the OPERA model, but not utilized in the scenarios. This is an indication that they are not part of a cost-optimal way of dealing with the 2030 emission targets. For a further discussion, we refer to Section 2.3.

The flexibility margin is positive for all scenarios and all emission levels, although considerable differences between scenarios as well as between emission levels exist (the margin ranges from 0% to 165%). The flexibility margin is highest in the nearly all-electric scenario and generally lowest in the gas extreme scenario. In the nearly all-electric scenario the flexibility margin is about 55-80%-points higher than the reference scenario (absolute level of 25-100%), while in case of the gas extreme scenario it is about 10-70%-points lower than the reference scenario. In both cases the exact percentage depends on the selected emission target level. The higher flexibility margin in the nearly all-electric scenario originates from the higher amount of available flexibility due to its generation mix, while the need for flexibility is lower for all emission target levels. The latter may be due to the increase of electricity based heat supply (such as heat pumps), which results in a situation in which heat demand patterns become part of the overall electricity demand. In the case of the gas extreme scenario the opposite situation holds; the amount of available flexibility is lower, while the need for flexibility is higher. The latter may be explained by restrictions on the use of electricity options, resulting in a lower amount of flexibility offered by controllable power plants (available flexibility decreases with 1200-2750 MW in case of emission levels of 96-82 Mton), while especially for the emission level of 76 Mton the gas extreme scenario has a considerable higher need for flexibility (ca. 2500 MW/h) than the other scenarios.

Energy intensity
Energy intensity has been defined as the ratio of final energy consumption to GDP (all sectors, industrial, and tertiary sectors), capita (residential sector) or M-km (transport sector). A decline of the ratio means an increase of energy efficiency (Scheepers *et al.* 2007). According to the ratios, energy intensities are not significantly affected by different scenarios due to low variation of final energy consumption with the scenarios. However, this is mainly due to the large denominators of the ratio (GDP, capita, M-km) which outweigh significant changes in final energy consumption patterns. Final energy consumption diminishes with more stringent emission target levels, especially in gas moderate and nearly all-electric scenarios compared to the reference scenario; in the gas moderate scenario it declines from a difference of about zero for an emission target level of 89 Mton to -30 PJ for an emission target level of 82 Mton. Equally, for the nearly all-electric scenario final energy consumption decreases from 80 PJ more consumption than the reference scenario (emission target level 89 Mton), to no significant difference with the reference scenario (emission target levels of 82 and 76 Mton).

Resource concentration indicators

Cost of imported fuels
Total costs for imports of oil, gas, coal, and biomass amount to about € 566 billion in the reference scenario of which about € 562 billion for oil imports. Absolute differences between scenarios are considerable, cost of imported fuels compared to the reference case range from $€_{2013}$ -34 billion in the gas extreme scenario (76 Mton) to $€_{2013}$ +25 billion in the nearly all-electric scenario (all emission target levels).

When the cost of imported fuels are related to the GDP projected for 2030 the differences are less significant; they range from 0,63% of GDP in the gas extreme scenario (76 Mton) to 0,70% of GDP in the nearly all-electric scenario (all emission target levels). Costs of imported fuels in the reference and gas moderate scenarios are estimated to be about 0,67% of GDP.

Import dependency
Import dependency has been calculated for several fuels; oil, gas, coal and biomass, given the expected primary energy supply, fuel extraction, and fuel import by 2030.

Import dependencies are not significantly affected by stricter emission reduction targets. Instead, differences between the four scenarios do have a major impact on import dependencies. Largest differences are visible for the coal import; in the gas extreme scenario imports are about 6-9% lower than in the reference scenario (with absolute levels of 15-17% depending on the emission target level), while in the nearly all-electric scenario coal import dependencies are about 14-19% higher than the latter. This reflects the fact that both the capacity of electricity-based options and the share of coal-based generation capacity is much higher in the nearly all-electric scenario, while the opposite holds for the gas extreme scenario. Concerning gas, the gas imports in the gas extreme scenario are about 4-8% higher than in the reference (with absolute levels of 8-11% depending on the emission target level), while in the nearly all-electric scenario these are about 4-9% lower. This result is also in line with expectations. Likewise coal imports, differences in gas imports can be explained by differences in amounts of absolute capacity from electricity based options as well as differences in the generation mix. Finally, import dependency of oil is about 5-6% higher in the nearly all-electric scenario compared to the reference scenario (with absolute levels of 43-44% depending on the emission target level), while import dependency of biomass (2-4% in the reference case) is not significantly affected.

Energy security market concentration
Energy security market concentration (ESMC) has been defined before as the percentage share of each supplier i in the international market for fuel f defined by its net export potential (IEA, 2007) and corrected for its political stability. Based on worldwide gas, oil and coal production and domestic consumption figures for regions and main countries in 2030 (IEA, 2014, New Policies scenario), the ESMCs of gas, oil, and coal suppliers have been calculated. For gas it has been assumed that only piped natural gas in adjacent regions to Europe is readily available under price hikes. Besides as a correction for geographic reasons, this can be also considered as a correction for the fact that gas is partially traded under long term bilateral contracts instead of spot markets. For oil, OPEC and non-OPEC countries have been treated similar as currently OPEC is ineffective in containing prices. Shares have been adjusted for political risk rating of fuel supplying countries from the World Bank (2013). Political risk ratings of fuel supplying countries in 2030 are assumed to be equal to 2012, since projections of political risk ratings are not available. An overall indicator for the Netherlands has been obtained by dividing the corrected ESMC of each fuel by the share of primary energy supply of that fuel in the total primary energy supply projected for 2030 and by summing up all fuel specific scores. This results into a total $ESMC_{pol}$ in the range of 2140-2220 depending on the scenario and emission target level selected.[13] Differences between scenarios and emission target levels are thus insignificant. Furthermore, since

[13] If it is assumed that both piped natural gas and LNG are worldwide available, total $ESMC_{pol}$ is in the range of 1350-1620 depending on the scenario and emission target level selected. This changes the conclusions in two ways. First, it implies significant differences between scenarios; in this case the gas extreme scenario shows the lowest value and the nearly all-electric scenario the highest value. Second, $ESMC_{pol}$ indicates that the market for fuel supply is moderately concentrated rather than strongly concentrated.

this range is well above the value of 1800, the market for fuel supply is considered to be strongly concentrated (Jansen & Van der Welle, 2010).

3.2.2 Gas price disruption

This section discusses the effects of a doubling of the gas price on the selected SoS indicators. Like before, we distinguish two groups of indicators and discuss them group by group.

System resilience, flexibility, and redundancy indicators

Capacity margins
The electricity peak capacity margin (EPCM) does not show significant changes. Capacity of electricity-based options, including power plants, is fixed since investments in new capacities cannot be performed in the short-term. Furthermore, peak demand for electricity is not significantly affected. Likewise the EPCM indicator, the gas peak supply margin (GPSM) does not change significantly compared to the situation without gas price disruption.

Flexibility margin
The flexibility margin changes for some scenarios and emission levels significantly compared to the situation without a shock. As we have seen before, these changes result from changes in the need for flexibility, since flexibility supply remains unchanged.

The need for flexibility results from the simultaneous peak of the maximum decrease of intermittent electricity supply and maximum increase of electricity demand in one hour during a year. After the gas price disruption the maximum flexibility need sometimes shows significant changes (i.e. 200-600 MW); in most instances decreases, but also increases in two cases (nearly all-electric scenario for emission level of 96 Mton and gas extreme scenario for emission level of 76 Mton). This means a corresponding decrease of the flexibility margin of respectively 21% and 5%-points. Significant decreases of the maximum flexibility need occur in gas moderate (for emission level of 82 Mton) and nearly all-electric (for emission levels of 89 and 82 Mton) scenarios. In the gas moderate scenario the need for flexibility reduces with -350 MW (indicator +10%-point), while in the nearly all-electric scenario the flexibility need reduces with 200 and 250 MW respectively (indicator +8%-point and +15%-point respectively).

The decrease of the need for flexibility in the nearly all-electric scenario can be explained by the fact that flexible electricity-based technology options (including electric vehicles and electric heat pumps amongst others) are most present since combined scenario and emission constraints force the model to implement these options. Following a gas price disruption, they can be operated over longer periods of time, decreasing the changes between hours, and consequently the maximum simultaneous peak demand for flexibility. In case of the gas extreme scenario subject to an emission level of 96 Mton, the need for flexibility increases. This can be explained by the higher consumption of electricity, which apparently fluctuates more in time following the lower deployment of gas based options after the disruption.

Energy intensity
Energy intensity has been defined as the ratio of final energy consumption to GDP (all sectors, industrial, and tertiary sectors), capita (residential sector) or M-km (transport sector) respectively. A decline of the ratio means an increase of energy efficiency. This indicator is not significantly affected since final energy consumption is only marginally affected by the gas price disruption, while GDP and M-km are fixed.

Resource concentration indicators

Cost of imported fuels
Total costs of oil, gas and coal before and after a gas price disruption have been compared to each other across scenarios. Costs of imported fuels expressed as percentage of GDP do not change significantly. However, absolute cost of imported fuel compared to the situation without disruptions increase significantly due to the doubling of the gas price. This holds especially for the gas moderate and gas extreme scenarios, which deploy the most gas-based options, resulting in increases up to 4.4 billion. In the reference case, cost of imported fuels increase about 1.9 to 2.7 billion euro. Generally, the lower the emission target level, the lower the additional costs of the gas price disruption. As expected, the nearly all-electric scenario is least affected, showing fuel cost increases of € 0.6-0.9 billion.

Import dependency
Import dependency of oil, gas, coal and biomass has been calculated, before and after the gas price disruption. Since the primary energy consumption of oil, gas, coal, and biomass is not significantly affected in one of the scenarios, also import dependency is not significantly affected.

Energy security market concentration
Energy security market concentration (ESMC) has been defined as the percentage share of each supplier i in the international market for fuel f defined by its net export potential (IEA, 2007) and corrected for its political stability. Relevant assumptions and data sources have been outlined in Section 3.2.1. Since the shares of primary energy supply for each fuel f in total primary energy supply do not change significantly after the gas price disruption, ESMC results do not change either. Consequently, total $ESMC_{pol}$ remains in the range of 2140-2220 depending on the scenario and emission target level selected, and differences between scenarios and emission target levels remain insignificant.

3.2.3 Coal price disruption

This section discusses the effects of a doubling of the coal price on the selected SoS indicators. Like before, we distinguish two groups of indicators and discuss them group by group.

System resilience, flexibility, and redundancy indicators

Capacity margins
The electricity peak capacity margin (EPCM) shows that after a coal price disruption available generation capacity still exceeds peak demand by a factor two to three, like before the disruption. However, in contrast with the gas price disruption a coal price disruption leads to significant changes in the indicator results. For the gas extreme scenario, the indicator worsens with 14-67%-points, while for the nearly all-electric scenario the indicator improves with 37-62%-points. The gas moderate scenario shows a mixed picture; for the highest emission target levels it shows an increase of the indicator with about 20%-points while for the lowest emission target levels it shows a decrease up to 34%-points. These results can be explained by changes of peak electricity demand relative to available generation capacity after the disruption as well as changes in the importance of electricity in the overall energy system. Generally, the change of the peak electricity demand compared to fixed generation capacity explains roughly 70%-points of the indicator change, with the remaining 30%-points explained by relatively small changes in the importance of electricity consumption in the overall economy. Peak electricity demand thus increases in the gas extreme scenario and gas moderate scenarios (the latter for the lowest emission target levels only), and decreases in the nearly all-electric scenario and gas moderate scenario (the latter for the highest emission target levels only) after a shock.

After a coal price disruption, primary energy consumption of coal is partially replaced by primary energy consumption of gas due to more running hours for gas-fired power plants. Also peak gas demand increases; in the gas moderate scenario with about 5-7 GW, and in the nearly all-electric scenario up to 4 GW depending on the emission target level. These increases imply a reduction of the gas peak supply margin (GPSM) with about 18-24%-points in case of the gas moderate scenario and 7%-20%-points in case of the nearly all-electric scenario. Instead, in the gas extreme scenario the peak gas demand decreases with about 8-10 GW, although for unknown reasons, increasing the GPSM indicator with 40-50%-points.

Flexibility margin
Changes in the flexibility margin due to the coal price shock are often not very significant, and noteworthy for the nearly all-electric (all emission levels) and gas moderate (82 Mton) scenarios only (range from -18%-point to +22%-point). Limited changes can be seen in both the need for flexibility and the importance of electricity in the overall energy system.

Energy intensity
Energy intensity has been defined as the ratio of final energy consumption to GDP (all sectors, industrial, and tertiary sectors), capita (residential sector) or M-km (transport sector) respectively. Ratios decrease only marginally, indicating a small increase of energy efficiency. Again this is mainly due to the large denominators of the sector-specific indicator calculations; billions of GDP and millions of ton transport kilometres compensate for quite significant changes final energy consumption, ranging from a decrease of 300 PJ in the case of the nearly all-electric scenario to 400 PJ in the case of the gas extreme scenario. The gas moderate scenario is in between with a decrease of final energy consumption of 100 to 200 PJ, with the largest decrease for the most

stringent emission target levels. Overall, scenarios do not show a strong link between the emission target level and the changes in final energy consumption after the coal price disruption.

However, this is mainly due to the large denominators of the ratio (GDP, capita, M-km) which outweigh significant changes in final energy consumption patterns.

Resource concentration indicators

Cost of imported fuels
Fuel import cost are not significantly affected when showed as fraction of GDP. However, like before when fuel import costs are not expressed in GDP, increases in fuel import costs are substantial. Most substantial changes are shown in the nearly all-electric scenario (increase with 2.1 to 2.4 billion euro) due to its larger reliance on electricity, which given the assumptions for fuel and CO2 prices is still produced from a generation mix with a significant share of coal-fired generation. Smallest changes occur in the gas extreme scenario (increase with 0.4 to 0.6 billion euro, due to its focus on gas-fired generation. The reference and gas moderate scenarios are in between. Fuel import costs are lower for scenario variants with lowest emission target levels. Consequently, a coal price shock would increase the cost of imported fuels for the Netherlands, decreasing energy affordability.

Import dependency
Import dependency of coal decreases due to the shock in gas moderate, gas extreme and nearly all-electric scenarios. The decrease is the highest in the nearly all-electric scenario (about 5% compared to situation without shock). Coal is replaced by gas and, more significantly, by oil. Both the gas extreme and nearly all-electric scenario show a limited increase of the import dependency of gas. Somewhat unexpected, oil imports as fraction of primary energy supply increase the most in the gas extreme scenario, while the nearly all-electric scenario shows the largest decrease of import dependency of oil.

Energy security market concentration
Energy security market concentration (ESMC) has been defined as the percentage share of each supplier i in the international market for fuel f defined by its net export potential (IEA, 2007) and corrected for its political stability. Relevant assumptions and data sources have been outlined in Section 3.2.1. Since the shares of primary energy supply for each fuel f in total primary energy supply do not change significantly after the coal price disruption, ESMC results do not change either. Consequently, total $ESMC_{pol}$ remains in the range of 2140-2220 depending on the scenario and emission target level selected, and differences between scenarios and emission target levels remain insignificant.

3.2.4 Gas supply disruption due to war in Ukraine

This shock entails a large physical interruption of the gas supply, through pipelines that take care of imports. As root cause one can think of such a disruption due to a geo-political conflict involving Russia and transit through Ukraine.

It should be noted that such an event is considered extreme since it is unlikely that its propagating effect would influence gas supply in Northwest Europe. Two such events which occurred in the past when Russia stopped its gas supply to Ukraine, affected only the adjacent EU member states in that region. These member states had to shut down some of their gas-fired power plants leading to electricity rationing in some cases. Recently, ENTSOG (2014) concluded that a disruption of transit through Ukraine under peak situations will still strongly impact South-East Europe (but does not impact North-West Europe). Figure 8: below shows the impact for the winter season of 2014-2015 of such an event.

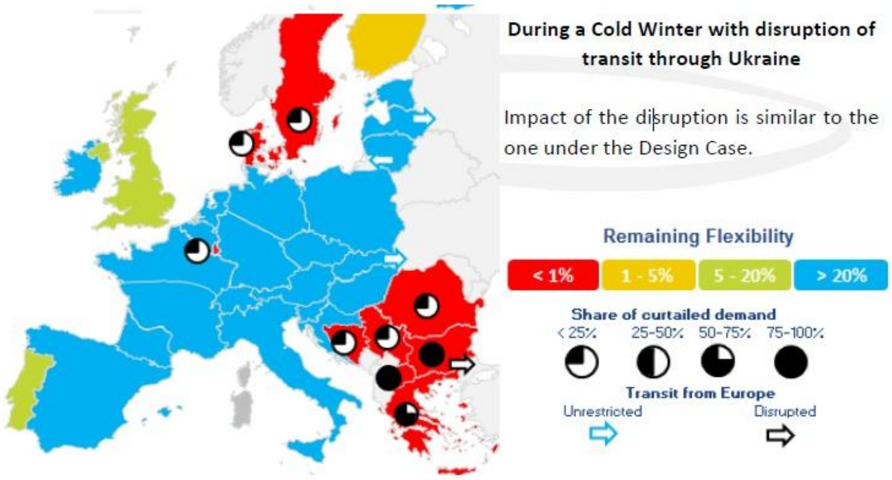


Figure 8: Impact of disruption of transit through Ukraine in winter 2014-2015 (ENTSOG, 2014)

However, in the longer term given the increasing role of imported gas, the Netherlands may be more susceptible to such events if no appropriate measures are taken.[14]

Harsh winter conditions as proxy for a gas supply disruption due to a war in Ukraine
Since earlier gas supply disruptions in Ukraine did not affect the Netherlands significantly, there is a little experience on the effects of such a disruption. We assume a suitable proxy event is a long lasting increase in gas demand during harsh winter conditions. This event also leads to an decrease in (even contracted) gas volumes in case of the hypothetical disruption in supply during winter.

The first line of defense is similar to the current 'designed' resilience against such long lasting harsh winter conditions. In developing and maintaining the gas infrastructure gas infrastructure operator GTS is obliged by Law to provide gas to small gas users (households etc.) up to a temperature of -17 degrees Celsius. During such conditions, the demand for gas will be much higher than usual. Such event is currently the most extreme event considered by Gasunie Transport Services (GTS). In general gas storage facilities and the Maasvlakte LNG peak shaver determine the duration how long such an interruption in supply can be dealt with without impact on the end users.

During winter time usually supply from underground gas storage (UGS) fields is deployed, while during summer they are filled again (see Figure 9: below for one winter

[14] The gas supply situation is also subject to regular monitoring on European level (ENTSOG, 2014) as well as national level (GTS, 2014).

season, note that winter conditions and therefore storage utilization vary from year to year).

A larger role for LNG in the future, with extension of LNG storage facilities in the Netherlands, can contribute to more resilience. If the disruption continues for longer period, more LNG may be shipped to the Netherlands. However, it is unlikely that LNG can make up for the full supply shortage, since other countries in North-West Europe will face similar shortages at the same time.

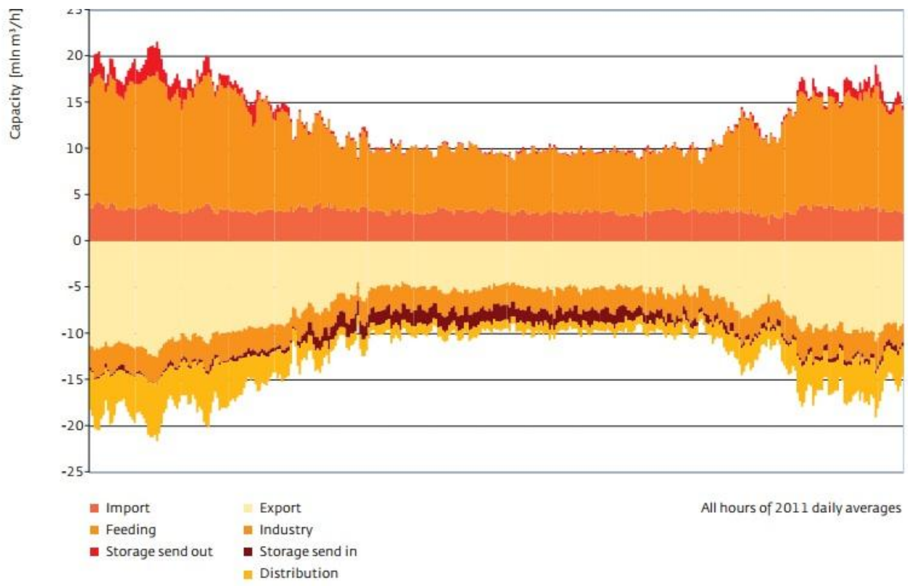


Figure 9: Capacity of storage facilities during one winter season (GTS, 2012)

If gas supply from these alternative sources is not enough, curtailment of gas delivery to end users has to be considered. Gas users could be disconnected depending on its economic impact (value of lost load)[15], health (to prevent that people freeze to cold, hence the obligation to secure gas supply to households even during extreme weather conditions i.e. -17 degrees Celsius), or as being critical to other infrastructure e.g. the electricity system.

In case of a limited gas supply shortage, interruption of gas supply to small users is also less likely or less preferred. Manual reconnection of small users is quite cumbersome due to safety reasons, and can take several days. Therefore, interruption of gas supply to a small amount of large users may be preferred over interruption of a huge amount of smaller users. Also gas power plants, if running, could be effected. If the power system has alternative fuelled capacity which is not yet running, it will be preferred over gas fired capacity. However, also the electricity system could be considered as critical, given the fact that it is considered as a vital infrastructure that is severely negatively impacted by a disruption.

[15] SEO (2003) and CPB (2004) identify the security of supply costs for different branches by determining the value of lost load (VOLL). The VOLL is determined by measuring lost production of firms and lost leisure time, given an assumption for the amount of hours that firms and household function.

All in all, a multitude of considerations plays a role around disconnection of gas users. These considerations make it very difficult, if not impossible, to quantify the effect of a physical gas disruption in detail. Hence, we followed the postprocessing method in this case, as discussed in Section 2.3.2, and refrained from attempts to quantify this disruption and its effects. After all, it can be said that a gas oriented scenario may be more affected by this physical disruption than an electricity oriented scenario, but it remains to be seen whether the difference will be significant.

4

Conclusions and recommendations

This study aimed to contribute to the discussion about the future role of gas in achieving security of energy services for end-users in a sustainable energy system around 2030. Therefore we tested the hypothesis that a future energy system with deployment of both electricity and gas for energy services provision would be more robust to mitigate random security of supply failures than an energy system that is too a high extent based on electricity. To that aim, both gas and electricity oriented energy systems have been integrally compared on different security of energy services aspects on their ability to withstand unforeseen disruptions and to adapt to them.

A combined quantitative and qualitative analysis has been deployed. Amongst others, seven composite security indicators have been selected from the extensive literature and deployed. These indicators allow for assessing impacts of unforeseen disruptions on consumers given the resilience, flexibility, and redundancy within gas and electricity-oriented energy systems (import, production, supply and network) respectively to mitigate these impacts. Additionally, indicators to assess impacts of disruptions on resource concentration in energy supply with concomitant effects on consumers have been calculated.

Table 6 summarizes the results for the seven indicators, for the situation without disruption as well as for the situation with coal price disruption. The situation with gas price disruption is not shown in the table, since differences are found to be insignificant compared to the situation without disruption. Furthermore, for reasons of conciseness average results for all emission target levels are shown rather than results for each emission target level.

The first group of indicators includes the peak capacity margins for electricity as well as gas, flexibility margin, and energy intensity. These indicators provide insight in the system resilience, flexibility, and redundancy aspects of the energy systems.

The **peak capacity margin for electricity** is considerable, capacity exceeds peak demand with a factor 2.4-2.9 in the situation without disruptions. Highest scores are obtained in the case of most stringent emission reduction targets, while lowest scores are shown by the nearly all-electric and gas extreme scenarios for high and low emission target levels respectively. In contrast with the gas price disruption, the coal price disruption leads to significant changes in the electricity peak capacity margin. The coal price disruption leads to a higher peak capacity margin for the nearly all-electric scenario, but to a lower peak capacity margin for the gas extreme scenario, implying the electricity peak capacity margin varies from 1.9 to 3.2. Differences result from changes in the importance of electricity in the energy sector as well as changes in the proportion of peak demand and peak capacity. A limitation is that we do not account for the expected availability of power plant categories at peak demand, which relates to the probability of forced outages and expected output from intermittent renewables.

The **gas peak supply margin** also shows the highest scores in the case of most stringent emission reductions. Stricter emission targets imply a reduction of peak gas demand, increasing the margin between peak supply and peak gas demand. This reflects also the decline of the importance of gas within the Dutch energy system. The margin is highest for the nearly all-electric scenario, and lowest for the gas extreme scenario. Again the gas price disruption does not lead to any significant change of the indicator. Instead, the coal price disruption leads to a reduction of the peak supply margin in gas moderate and nearly all-electric scenarios compared to the situation without shocks, and a relative increase of the margin in the gas extreme scenario.

The **flexibility margin** indicates the possibilities for the system to cope with rapid simultaneous changes in electricity from renewable energy production and demand. Again, highest scores are obtained in the case of more stringent emission target levels. The flexibility margin is highest for the nearly all-electric scenario (with flexibility supply exceeding demand with a factor 1.3), and lowest for the gas extreme scenario. In the latter, relatively less electricity capacity is available in the system, combined with a relatively higher need for flexibility. In case of the coal price disruption, the flexibility margin changes significantly in the nearly all-electric and gas moderate scenarios, in most cases the flexibility margin increases which is probably due to the fact that the OPERA model performs system optimization given some minimum constraints for guaranteeing quality of supply. It may be the case that demand rationing takes place in order to prevent an infeasible model outcome.

Energy intensity is the ratio of final energy consumption to GDP. It provides an indication of changes in energy efficiency; a decline of energy intensity means an energy efficiency improvement. Overall, in line with expectations more stringent emission target levels drive the implementation of measures to improve energy efficiency, as witnessed by the decrease of final energy consumption. Largest improvements are realized by the nearly all-electric scenario, followed by the gas moderate scenario. However, if energy intensities are expressed in GDP, changes appear to be minor. The gas price shock does not affect the energy intensity significantly, while the coal price shock shows considerable changes in final energy consumption; after the shock a considerable decrease of consumption in the nearly all-electric scenario is visible (maximum change of 300 PJ), while consumption in the gas extreme scenario increases significantly (maximum change of 400 PJ).

Table 6: Summary of indicator results for situations without disruption and with coal price disruption

	No disruption				Coal price disruption			
Scenario → Indicator↓	Reference	Gas moderate	Gas extreme	Nearly all-electric	Reference	Gas moderate	Gas extreme	Nearly all-electric
Electricity peak capacity margin	+	+	+	+	=	=	↓	↑
Gas peak supply margin	+	+	+	+	=	↓	↑	↓
Flexibility margin	+	+	+/-	+	=	↑	=	=
Energy intensity	+/-	+/-	+/-	+	=	↓	↑	↓
Cost of imported fuels	+	+	+	-	↑	↑	↑	↑↑
Import dependency - Gas	+/-	+/-	-	+	=	=	↑	=
Import dependency - Oil	+/-	+/-	+/-	+/-	=	↓	↑	↓
Import dependency - Coal	+/-	+/-	+	-	=	↓	=	↓
Import dependency - Biomass	+/-	+/-	+/-	+/-	=	=	=	=
Energy security market concentration	-	-	-	-	=	=	=	=

Legend: + positive, =/- neutral, - negative. All effects of coal price disruption relative to situation without disruption; ↑↑ large relative increase of indicator, ↑ relative increase, = no significant change, ↓ relative decrease.

The second group of indicators consists of resource concentration indicators i.e. cost of imported fuels, import dependency, and energy security market concentration.

Cost of imported fuels i.e. imports of oil, gas, coal, and biomass, are projected to amount to about € 566 billion in the reference scenario of which about € 562 billion for oil imports. Absolute differences between scenarios are considerable, cost of imported fuels compared to the reference case range from $€_{2013}$ -34 billion in the gas extreme scenario (76 Mton) to $€_{2013}$ +25 billion in the nearly all-electric scenario (all emission target levels). After a gas price disruption, increases in fuel import costs are substantial. Most substantial changes are shown in the nearly all-electric scenario (increase with 2.1 to 2.4 billion euro) due to its larger reliance on electricity, which given the assumptions for fuel and CO_2 prices is still produced from a generation mix with a significant share of coal-fired generation. Smallest changes occur in the gas extreme scenario (increase with 0.4 to 0.6 billion euro), due to its focus on gas-fired generation. The reference and gas moderate scenarios are in between. Fuel import costs are lower for scenario variants with lowest emission target levels. Consequently, a coal price shock would increase the cost of imported fuels for the Netherlands, decreasing energy affordability.

Import dependency of oil, gas, coal and biomass is not significantly affected by stricter emission reduction targets. Instead, differences between gas and electricity-based scenarios do have a major impact on import dependencies in the situation without disruptions. Largest differences are visible for the coal import; in the gas extreme scenario imports are about 6-9% lower than in the reference scenario, while in the nearly all-electric scenario import dependencies are about 14-19% higher than the latter. This reflects the fact that both the capacity of electricity-based options and the share of coal-based generation capacity is much higher in the nearly all-electric scenario, while the opposite holds for the gas extreme scenario. Concerning gas, the gas imports in the gas extreme scenario are about 4-8% higher than in the reference, while in the nearly all-electric scenario these are about 4-9% lower. This result is also in line with expectations. Likewise coal imports, differences in gas imports can be explained by differences in amounts of absolute capacity from electricity based options as well as differences in the generation mix. Concerning oil and biomass, import dependency of oil is about 5-6% higher in the nearly all-electric scenario compared to the reference scenario, while import dependency of biomass is not significantly affected. This result is not significantly affected by a gas price disruption, while the coal price disruption leads to a shift from coal to gas, and mainly oil. Import dependency of gas increases for the gas extreme and nearly all-electric scenarios. Import dependency of oil increases as well in the gas extreme scenario, but decreases in the nearly all-electric scenario. After the coal price shock, import dependency of coal decreases in gas moderate, gas extreme and nearly all-electric scenarios. The decrease is the highest in the nearly all-electric scenario (about 5% compared to situation without shock). Coal is replaced by gas and, more significantly, by oil. Both the gas extreme and nearly all-electric scenario show a limited increase of the import dependency of gas. Somewhat unexpected, oil imports as fraction of primary energy supply increase the most in the gas extreme scenario, while the nearly all-electric scenario shows the largest decrease of import dependency of oil.

Energy security market concentration

Energy security market concentration (ESMC) has been defined as the percentage share of each supplier i in the international market for fuel f defined by its net export potential (IEA, 2007) and corrected for its political stability. Since the shares of primary energy supply for each fuel f in total primary energy supply do not change significantly after price hikes, ESMC results do not change either. Consequently, total $ESMC_{pol}$ is in the range of 2140-2220 depending on the scenario and emission target level selected, and differences between scenarios and emission target levels remain insignificant. Furthermore, since this range is well above the value of 1800, the market for fuel supply can be considered to be strongly concentrated in all scenarios and under all emission target levels.

Implications of the evaluation of security of energy services for energy policy, taking into account sustainability and affordability aspects

Orientation of energy transition scenarios towards gas or electricity has limited impacts on security of energy services

The analysis suggests that orientation towards either gas or electricity in energy transition scenarios for 2030 has often fairly limited impacts on security of energy services. Overall, differences between indicator scores for different scenarios, with and without shocks, are often insignificant or small. Scenarios that deploy a higher amount of gas-based options do generally not score better on either system resilience, flexibility, and redundancy indicators or resource concentration indicators. The only exception is the lower import dependency from coal in gas oriented scenarios. Therefore the hypothesis that a future energy system with deployment of both electricity and gas for energy services provision would be more robust to mitigate random security of supply failures than an energy system that is mainly based on electricity, cannot be confirmed. Indeed, the gas moderate and gas extreme scenarios do not score significantly better than the reference and nearly all-electric scenarios.

.. while gas oriented scenarios may reduce overall system costs but may increase marginal CO_2 emission costs

When comparing energy transition scenarios on overall system costs (as indicator of affordability) and CO_2 emission costs, it can be seen that the overall system costs of the gas extreme scenario are generally lower than in the other scenarios, while the marginal costs of CO_2 emission reduction are considerably higher in the gas extreme scenario. This can be explained by the fact that in case of less stringent emission reduction targets the gas extreme scenario deploys to a lower extent technology options that simultaneously reduce CO_2 emissions, increasing the marginal costs of further CO_2 emission reductions, but to the advantage of lower overall system costs. However, it should be kept in mind that this comparison is somewhat blurred by different degrees of freedom of both the gas extreme and nearly all-electric scenarios.

Results should be interpreted with care due to different assumptions made for scenario construction and calculation of SoS indicators

More generally, results should be interpreted with care due to the inherent uncertainties regarding several assumptions in the scenario construction and modelling as well as the SoS indicators. Results are partially explained by OPERA modelling constraints on quality of supply, realization of technology potentials, minimum and maximum shares of gas and electricity consumption in various sectors, and the availability and prices of fuels and CO_2. A critical assumption is the larger availability of biomass for the gas extreme scenario. It remains to be seen whether the biomass supply can be increased substantially, given potential negative consequences for food supply. Adequate containment of this risk by biomass certification is required to allow for such substantial increases of biomass supply. If this requirement is not met, it would be increasingly difficult to achieve stricter emission reduction targets with the gas extreme scenario. Furthermore, although uncertainties around assumptions for SoS indicators are substantially reduced by deploying seven different SoS indicators and by performing part of the analysis in a qualitative way, still some uncertainties remain due to complexities in modelling of regulatory (N-1) conditions to secure gas supply during disturbances.

Security of energy services in gas oriented scenarios can be improved by diminishing the dependency of gas on electricity
For structurally improving security of energy services it is advised to take measures to diminish the dependency of the provision of gas-based services (like heating and cooking) on the availability of electricity since gas-based services currently can often not be provided without the latter. One could foresee that gas-based devices are equipped with devices (e.g. a battery) to function independently from electricity. Likewise, by decoupling electricity demand (partly) from supply through implementation of flexibility enhancing technology options such as storage and demand response, security of electricity-based services can be improved.

A longer term perspective is advised to explore the development of security of energy services
Finally, it is advised to take a longer term perspective in future security of energy services' analyses. Given the fact that 2030 is relatively nearby, and therefore affected by current policies and policies foreseen for both 2020 and 2030, degrees of freedom are limited and therefore the differences between scenarios, the optimal mix of technology options, and its resulting security of supply level. Towards 2050, the scenario space would increase dramatically, and therefore also the likely divergence of security of supply aspects of gas versus electricity based scenarios. Consequently, in future research it would be useful to explore the development of security of energy services towards the 2050 horizon.

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Abbreviations

CCS	Carbon capture and storage
CH4	Methane
CO2	Carbon dioxide
DSM	Demand-side response
ETS	Emission Trading System
GHG	Greenhouse gas
HFC	Hydrofluorocarbons
ICE	Internal combustion engine
N2O	Nitrous oxide
PFC	Perfluorocarbons
PV	Photovoltaics
RES-E	Electricity from renewable energy sources
SoS	Security of supply

Appendix A. Timeslice approach adopted in OPERA

Explanation of adopted Timeslice approach

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

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

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

Intermittent energy supply profiles

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

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

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

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

where N_w and N_s are the normalization factors.
An overall aggregated supply profile is then created using the following equation:

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

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

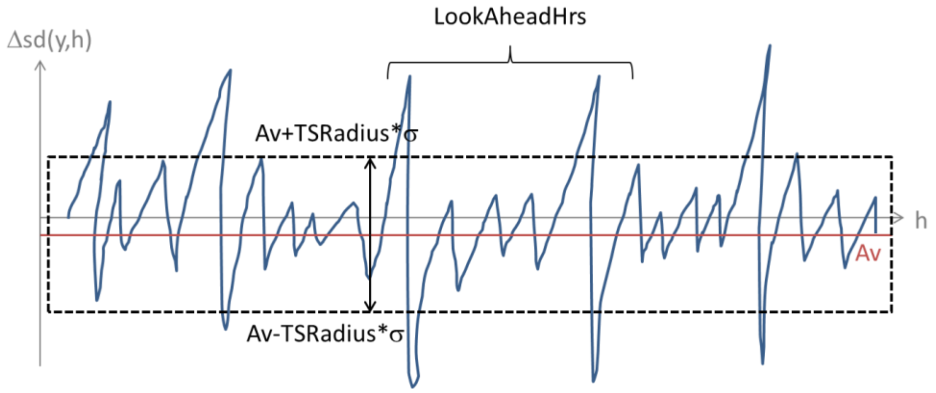
Energy demand profiles
Hourly demand profiles for electricity and heat are provided per year and sector. Following an analogous procedure as for the supply, aggregated profiles for electricity and heat demand, d_e and d_h respectively, are created by summing over the sectors and normalizing. An overall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

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

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

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

Allocation algorithm



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

- Av = Average of Δsd.
- σ = Standard deviation of Δsd.
- *TSRadius* controls the height of the black dashed rectangle; initial value = 1. The values outside the rectangle correspond to extreme situations. Maxima, or *valleys*, are likely excesses of intermittent supply. Minima, or peaks, are likely shortages of intermittent supply vs. demand.

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

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

ECN

Westerduinweg 3
1755 LE Petten
The Netherlands

P.O. Box 1
1755 LG Petten
The Netherlands

T +31 88 515 4949
F +31 88 515 8338
info@ ecn.nl
www.ecn.nl