THE BIG PICTURE

THE FUTURE ROLE OF GAS

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Disclaimer

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EXECUTIVE SUMMARY

This report documents the research of one of the EDGaR research projects, namely 'The Big Picture'. This project was developed by the project partners Gasunie (in collaboration with DNV GL), Rijksuniversiteit Groningen (RuG) and Hanze University Groningen (HUG).

The outlook for the energy market in general and more specifically the position of gas is difficult to foresee. Gas market parties and stakeholders do not have a clear and shared view of the future 'big picture' regarding the developments in energy markets and potential energy transition end states. This hampers a consistent and effective approach to long- term decision making. This raises the question whether the existing and potentially discovered gas reserves will be used efficiently and effectively, and how it is possible for gas to play a role in a sustainable and secure energy supply, as well as how this role will develop over time.

This project identifies and categorizes possible end states after the energy transition from literature and derives implications from these end states in terms of technical, economic and socio-political factors. The aim of this research is to provide the gas market parties and stakeholders with a view on the long- term 'big picture' of potential end states after the energy transition with the focus on the role of gas. Such view would create a solid base for making substantiated and business wise decisions in the context of energy transition. The main research question of this report is as follows:

"*What are potential robust energy end states after the transition and what will be the role and share of both renewable energy and in particular natural gas in Europe*?"

In order to understand the dynamics behind the forming of energy end states this research firstly introduces drivers of change impacting the energy environment. A plethora of drivers of change will shape energy systems of the future. This report discusses the relevant drivers of change and their possible influence on the future energy systems. The five areas are: Politics, Social factors, Economies, Resources and the environment, Energy systems and technology. A key finding is that the international political and economic order is becoming more multipolar than three decades ago, and that drivers of change can have a different effect in different parts of the world. Also, the role of social and political actors on energy systems is likely to be more prominent. In Europe, this will be noticeable at the local, national and international level. At the local level, high-impact social ideas like green consumerism and limited acceptance of energy systems that result in major trade-offs, could be important drivers of change. Nationally, the empowerment of individuals and communities relative to the state and as producers of some forms of energy and the politicization of energy-related issues will be key drivers of change. Internationally, energy issues will at least remain important or become even more so in the foreign and security policies of countries and the geopolitics of non-state actors.

To derive at potential robust end states this report explores numerous energy scenarios to distil three energy transition end states. These end states are scrutinized by examining their implications and potential limitations. The end states that emerged from the analysis are:

1. **Renewables (RES) -** Somewhat stabilizing energy demand and strong increased share in renewable energy.
2. **Business as Usual (BAU) -** Increasing energy demand supplied by a balanced mix of energy sources.
3. **High Gas (GAS) -** More than doubling energy demand and satisfied by a large share of natural gas.

The end states were derived using primarily quantitative analysis, but they are also characterised by the principal factors of the PESTE framework (Political, Economic, Social, Technological, and Environmental).

Although the end states differ in their final energy mix and absolute amount of energy consumption, there are several similar factors. From an economic perspective, all three end states assume an increase in global population and GDP. Similarly, CO_2 prices and energy efficiency are expected to increase as well and there's a continued support for renewable energy sources under all three end states, albeit to various degrees.

On the other side though, there are differences as well. While emissions are expected to decrease in the RES end state, they are set to moderately increase under BAU and GAS. Also, unconventional fossil fuels are projected to play an important part under BAU and GAS, whereas, unsurprisingly, renewable energy technologies are projected to mature under the RES end state.

A more detailed look into the GAS end state shows that it is connected to an increase in energy consumption and corresponding increase in CO_2 emissions. Furthermore, in contrast to what is normally assumed, natural gas is projected to play a significant role primarily when climate awareness is lower on the agenda; in contrast to the RES and BAU end states. Also, natural gas seems to play an important role when policy makers are more concerned about energy security than climate change, when no clear choices are made regarding favourable technologies and when limited international coordination takes place.

To describe the role and share of both renewable energy and in particular natural gas in Europe this report describes the implications for each of the three end states, including possible investment requirements in gas and renewable infrastructure.

A model has been developed that allows for a translation of the final energy demand mix into primary energy requirements by adapting the underlying energy system. As may be expected, the RES end state has the largest implications, in terms of end-users requirements and land use. First of all, electrification, as a result of the choices made in this end state, is reflected mainly in the transportation sector as electric vehicles, as well as electric space heating in the residential and tertiary sectors become essential for the realization of this end state. Furthermore, energy use is shifted to land use which is a consequence of the implementation of large amounts of renewable sources. This is especially the case for biomass under the RES end state, in which about 50% of the agricultural land in the European Union is needed for growing energy crops. Furthermore, it is noteworthy that in all three end state, the industrial sector does not change much. Therefore, there are no major changes in the production structure and activities.

Specifically zooming in on the existing gas infrastructure, analysis showed that it is well equipped to support the realization of the RES and BAU end state. Evidently, this is directly related to the decline or stabilizing gas demand in Europe under these two end states. However, the gas infrastructure is also well-suited to support the increasing gas demand in the GAS end state. Although it would be required to build additional importing pipelines, the analysis shows that the internal gas network as presently available in Europe is capable to satisfy this increase in demand. From this respect, no considerable limitations are expected from the availability of the gas infrastructure.

Focusing on the role of renewable energy technologies, analysis revealed that different decentralized renewable energy technologies have different grid implication dynamics relative to varying demand scales. Part of those differences can be explained through differences in weather dependency.

Energy futures involving large shares of decentralized renewable power in the energy mix are likely to involve substantial grid implications. However, part of the power generated on a decentralized platform is consumed locally. Only the part that is not consumed locally/directly accounts towards grid implications. Grid implications for larger shares of decentralized renewables may thus be less than what could be assumed from the gross total of generated power.

In order to fulfil the need for practical examples and analysis of applicable technologies this report discusses the case of power-to-gas, biomass and the local North Netherlands situation.

Innovation of technology trajectory: Power-to-gas

The energy system has to adapt to intermittent energy sources, such as wind power and solar energy, which provide energy in a fluctuating manner. Energy storage is one of the possible solutions. Power-to-Gas is a technology that offers this storage option. The analysis shows that the position of power-to-gas in the future energy system depends on the wind and solar ambitions, power-to-gas technological progress and the development of a regulatory framework for both gas quality standards and investment conditions.

Limitations of biomass availability

Since it is expected that biomass technologies, especially biomass digestion, will contribute considerably to the required volume of renewables in the future energy mix, this report assesses the limitations of large scale biomass use in Europe. For a densely populated country (such as the Netherlands) it is impossible to produce the biomass fuels to supply their own system. This is further complicated by the competition between food and energy. Not only the food and fuel discussion, but also due to competition between feedstock for other applications (e.g. bio plastics).

Local energy system dynamics: Energy Valley

When talking about ‘energy systems’ this analysis takes a broader perspective and looks at ‘energy’ as being embedded in social, economic, and political systems and that such a system could be a district, region, country, or a regional block such as the EU. The analysis looks at ‘energy’ as being located in a specific location with a defined boundary. This research examines Energy Valley as an energy system embedded in a larger energy system. The analysis shows that the future of gas in the energy mix in Energy Valley has become polarized between the local and national economic interests and therefore new ‘coping strategies’ need to be considered where citizen acceptance and national interests need to be balanced (such as the recent man-induced earthquakes).

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LIST OF ABBREVIATIONS

ASEAN	Associations of Southeast Asian Nations
BAU	Business As Usual
BBL	Bacton Balgzand Pipeline
BCM	Billion Cubic Metres
CAPEX	Capital Expenditure
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage
CH4	Methane
CNG	Compressed Natural Gas
CO2	Carbon Dioxide
CSP	Concentrated Solar Power
EC	European Commission
ECF	European Climate Foundation
EDGaR	Energy Delta Gas Research
EE	Energetic Efficiency
EIA	Energy Information Agency
EJ	Exajoule
ENIGMA	European Network and Infrastructure Gas Model for Analysis
ENTSOG	European Network of Transmission System Operators for Gas
ER	Energy Ratio
EREC	European Renewable Energy Council
EV	Electric Vehicles
FID	Final Investment Decision
GDP	Gross Domestic Product
Gt	Gigaton
GWh	Giga Watt hours
H2	Hydrogen
IEA	International Energy Agency
IET	Institute Energy and Transport

IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
M€	Million Euro
MMBtu	Million British Thermal Units
Mton	Megaton
MW	Mega Watt
NCG	Net Connect Germany
NGO	Non-governmental body
OECD	Organisation for Economic Co-operation and Development
OMA	Office for Metropolitan Architecture
OPAL	Ostsee Pipeline Anbindungsleitung
OPEC	Organisation of Petroleum Exporting Countries
OPEX	Operational Expenditure
P2G	Power-to-gas
PESTE	Political, Economic, Social, Technological and Environmental
PJ	Petajoule
PRIMES	Price-Induced Market Equilibrium System
PV	Photo Voltaic
R&D	Research & Development
RES	Renewables
SNG	Synthetic Natural Gas
TAG	Trans Austria Gas Pipeline
TAP	Trans Adriatic Pipeline
TENP	Trans Europa Naturgas Pipeline
TIS	Technology Innovation Centre
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
TWh	Terra Watt hours
VTP	Virtual Trading Point
WEO	World Energy Outlook
WWF	World Wildlife Fund

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1 INTRODUCTION

1.1 About the EDGaR research program

The Energy Delta Gas Research (EDGaR) program is set up by a Dutch research consortium of ten enterprises and research institutes. It coordinates the realization of scientific, applied and technological researches on gas and sustainability. Participants to the consortium come from the industry — Gasunie, GasTerra, Kiwa, Enexis, Liander and Stedin — and scientific institutions — ECN, University of Groningen, Delft University of Technology and Hanze University of Applied Sciences. Since its beginning on 1 January 2010, EDGaR has subsidized 29 original multidisciplinary projects in the domains of natural science, engineering and social sciences.

EDGaR's goal is to make out a case for the energy future of the Netherlands, with respect to the use of sustainable energy sources. Moreover, EDGaR's research program attempts to give the Dutch gas industry a better position in the world and, more particularly, in Europe. It supports its research teams in a spirit of cooperation and exchange of knowledge among them.

This report documents the research of one of the EDGaR research projects, namely 'The Big Picture'. This project was developed by the project partners Gasunie (research performed by DNV GL), Rijksuniversiteit Groningen (RuG) and Hanze University Groningen (HUG).

1.2 Background

The European energy market is undergoing structural changes in many areas, which affect both the market as a whole and the individual industry players. The environmental concerns and the climate change mitigation drive are high on the political and social agenda. The European Union and the individual member states introduce increasingly demanding requirements in relation to the use of renewable energy sources in the fuel mix, energy efficiency and CO_2 emissions reductions. However there is also another side of the coin: increasing standards of living across the globe, increasing competition for energy resources due to the wealth accumulation by the developing countries, as well as public discussions about the energy poverty and food versus energy, are putting pressure on the global availability of energy (both fossil and renewable). In the light of these developments the availability of significant reserves of both gas (conventional and unconventional) and alternative energy sources gain importance.

Gas still remains the cleanest of the fossil fuels, and it is and will be an important source of flexibility, crucial for developing the renewable energy sources and incorporating them in the energy mix. Moreover, in most cases the production price of the gas reserves is still less than that of the renewables, with an additional downward pressure on the price being exercised by the development of significant volumes of unconventional gas at a competitive cost. This raises the question whether the existing and potentially discovered gas reserves will be used efficiently and effectively, and how it is possible for gas to play a role in the sustainable security of energy supply, as well as how this role will develop over time.

All these developments, occurring in parallel, make the future outlook for the energy market in general and more specifically the position of gas in the market difficult to foresee. Gas market parties and stakeholders do not have a clear and shared view of the future 'big picture' regarding the developments in the energy markets and the potential energy transition end states. This hampers a consistent and effective approach to long- term decision making.

The central research question therefore is *"what are potential robust energy end states after the transition and what will be the role and share of both renewable energy and in particular natural gas?"*

Against this background the project partners developed the EDGaR-project 'The Big Picture'. In short, this project identifies and categorizes possible end states after the energy transition from literature and derives implications from these end states in terms of technical, economic and socio-political implications. The aim of this research is to provide the gas market parties and stakeholders with a view on the long-term 'big picture' of potential end states after the energy transition with the focus on the role of gas. Such view would create a solid base for making substantiated and business wise decisions in the context of energy transition.

1.3 Project approach

The shifts in the patterns of both energy supply and consumption can develop in a number of ways, each of them having specific consequences for the energy market as a whole, and for the gas market in particular. The focus of this project is not on building scenarios and deriving end states ourselves. The first step in our methodology is to select a number of potential stable end states of the energy transition from well-known literature sources. End states from well-known and accepted literature will be the starting point for this research.

The project is organized in three individual work streams. These three work streams are set-up in order to address different aspects of the research question from a multidisciplinary perspective. The three work streams are based on the same set of assumptions, and have as a starting point the energy transition end states. Selecting literature input for the three end states of scenarios mentioned above will be a joint activity prior to starting the individual work streams. The approach towards selecting and specifying these end states will be elaborated in the description of work package 0 below. After specifying the end states the three work streams will be developed as a synergy, with rich cross-fertilization ambition. Namely, the intermediate results of the work streams will often be used as input for other work streams. Moreover, the conclusions of the each individual work stream will be incorporated in a joint assessment of the end states.

The three individual work streams are depicted schematically in the figure below, followed by an elaboration of the detailed approach and methodology for each work stream separately and how these work streams contribute to the overall research question.

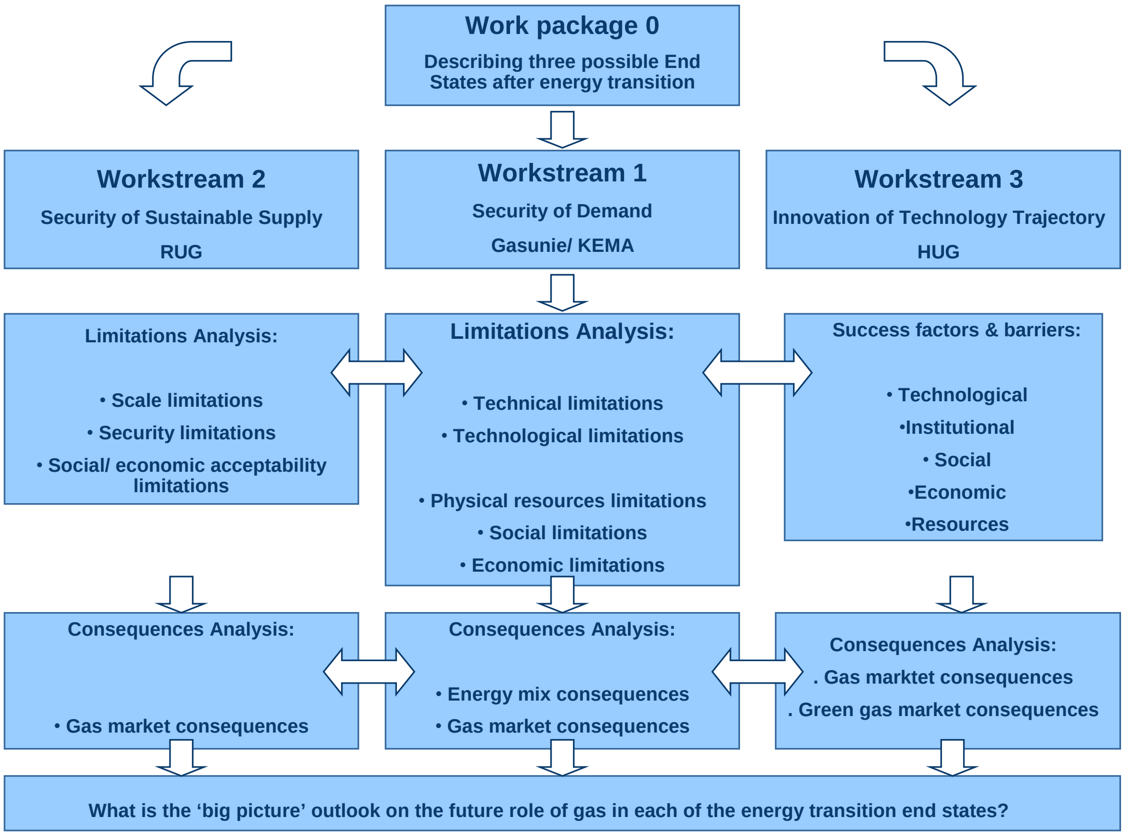

Figure 1: Schematic representation of the work streams

Work package 0 - Describing three possible End States (Combined effort)

As already mentioned, the focus of this research is not to identify and quantify three potential end states of the energy transition ourselves, but rather on the limitations and consequences of such end states for the energy market in general, and the gas market in particular. In order to arrive at a common starting point for the work streams 1, 2 and 3 the project partners will jointly detail the end states for the project based on literature.

Work stream 1- Security of Demand (Gasunie / DNV GL)

The long-term availability of energy is rapidly gaining weight and priority on the global agenda, especially in the light of depleting fossil reserves, climate change concerns and increasing demand for energy. Numerous studies and energy outlooks focus on the security of supply, assessing if there will be enough supply to satisfy the overall energy consumption. The demand side of the analysis is often less pronounced, however not less important. This research will investigate the demand for energy and will focus on the type of energy carriers and the energy carriers that are utilized downstream by consumers (households, commercials, industry and power plants) in potential end states of the energy transition.

Work stream 2- Security of Sustainable Supply (University of Groningen)

The current energy use patterns put pressure on the environmental systems and cycles that may result in an unacceptable global (climate) change. Potential depletion of the fossil resources and lack of security of fossil supply because of geo-political reasons are the worries related to the current energy use patterns. However the security of supply concerns will also remain on the agenda in the context of the energy transition.

Therefore the focus of this work stream is on answering the question of how robust is the supply system in each of the energy transition end states, and to what extent will it comply with the demands of sustainability, security and reliability, availability and affordability, when applied on large scale.

Work stream 3- Innovation of Technology (Hanze University Groningen)

Each end state of the energy transition presumes a considerable degree of technological innovation on a large scale in order to be achieved. This work stream will focus on identifying the trajectory which in particular biomass digestion has to follow from the current situation until large scale implementation. The success factors (‘drivers’) which make it possible for biomass digestion to leave the early stages of development behind and become an incumbent technology will be identified, as well as the potential factors which can hamper such a process (‘spoilers’).

1.4 Structure of this report

This report is structured into ten chapters. Chapter 1 (this chapter) describes the introduction to this research. Chapter 2 provides an overview of the drivers of change impacting global energy systems. In Chapter 3 the energy end states, which serve as the basis of further analysis, are derived and presented. Chapter 4 assesses the bottom-up implications of the energy end states in Europe for the year 2050. In Chapter 5 the impact of the energy end states on the European gas infrastructure is assessed. Chapter 6 presents a case study on the availability of biomass for the production of bio CNG for the use as a transportation fuel in Europe. The grid implication of decentralised renewable energy generation is assessed in Chapter 7. In Chapter 8 the technological innovation system of power-to-gas is set apart. Finally Chapter 9 dives into the contextual and systemic forces of the Energy Valley region. Chapter 10 presents the integrated key findings of this combined effort and draws conclusions on the future role of gas.

2 DRIVERS OF CHANGE IN ENERGY SYSTEMS UNTIL 2050

Author: Dr. H. Matthee – Hanze University Groningen

2.1 Introduction

A plethora of drivers of change remain likely or probable in shaping energy systems and futures. Drivers of change are defined here as any human- or nature-induced factor that cause changes. In this chapter, the drivers discussed could cause changes that would shape energy systems until 2050. Drivers here include those that cause change directly or by altering one or more direct drivers. Implicitly, some drivers discussed below are endogenous, where decision-makers influence some drivers, and others are exogenous, where drivers influence decision-makers. The drivers could have a positive or a negative effect at different stages and during different interactions and iterations.

The World Energy Council's publication on global energy scenarios until 2050 is based on 116 drivers, grouped in five areas.[1] This chapter is structured along the WEC framework, using the five interlinked areas, but with some changes in formulation, sub-elements and emphasis. The five areas are:

1. **Politics -** including international, regional, national, local and group politics and security challenges
2. **Social factors** - including demographics, consumer behaviour and high-impact ideas and institutions
3. **Economies** - including roles, cycles, finance and trade;
4. **Resources and the environment**
5. **Energy systems and technology**

2.2 Politics

2.2.1 International politics

International politics[2] will produce several important drivers of change, which could impact on energy futures until 2050 in direct and indirect ways. Energy is directly tied to the state security and foreign policy concerns of governments in Asia, Russia, the Middle East, North and South America, and Africa. The same is the case for European governments, including those of Germany, France, Britain and the Netherlands. The global energy sector will remain one of the most-politicized sectors until 2050.[3]

This means that issues from outside the energy sector may quickly embroil the sector in unforeseen and fast-moving shifts and escalations. This could affect the security of supply, but also change the nature of ownership, energy alliances, the relative importance of energy actors and the relative priority of developing different forms of energy.

International politics could also have a significant weakening or strengthening influence, in seemingly unrelated economic sectors, with a direct or indirect effect on the energy sector. For example, during the current stand-off between the Russian government of Pres. Vladimir Putin, the USA and EU member states over the Ukraine and Crimea, Russia's energy sector has become a key target for Western sanctions and also a key means of Russian pressure. Russian counter-actions have resulted in Western agricultural and other sectors being directly affected. They have also including the pursuit of a potentially stronger Russia-China energy alliance, efforts to strengthen the civilian nuclear sector in South Africa, competing with France in this regard, and renewed involvement in the civilian nuclear sector in Iran, against the foreign policy aims of most EU member states.

The shift of international power from the West to Asia and from an almost unipolar world to a multipolar world will be an important driver of change.[4] It is expected that China and India specifically will become more influential in regional and international politics until 2050. They will also experience a high absolute increase in energy demand during this period, which will reinforce the wider impact of developments in the energy sector.

One hundred years ago European actors constituted a much larger component of the world population and politically and economically dominated both the larger West and vast parts of the world and international energy sector. Today, Europe's global power has weakened and is weakening. The renewed strength of the USA, its focus on the Asia-Pacific, and the rise of Asian and other powers in a multipolar world order will reinforce Europe's weakened position.[5]

In individual cases, this could be reflected in the bargaining power of Europe-based actors. It could also weaken the commitment of other actors to political transparency, rule of law, protection of property rights, climate change, minority group rights and human rights. This could result in more reputational and operational dilemmas and risks for Europe-based energy actors in their external interactions, projects and partnerships.

The importance of state-linked corporations or privately-owned national corporate champions outside Europe could also act as a driver of change. In many states of Asia, Africa and the Middle East, energy remains a key source of government income and/or a key factor in maintaining domestic services and socio-political stability. In addition, state or state-linked corporations dominate the energy sector, whether in oil, gas or renewable energies. These companies often form part of the government's foreign policy, and operate in accordance with both strategic and economic imperatives. This is the case in China, Russia, India, Iran, Algeria, the Gulf Arab monarchies, Nigeria, and Brazil, among other countries. More than 80% of the world's oil and gas reserves are now controlled by national energy companies.[6] These companies will be competing and sometimes cooperating with EU-based energy companies.

National policies and their impact on property rights and protectionism will also be an important driver of change in the international energy sector. Governments, for political and economic reasons, have a long history of interfering with private property. Since 1990, over 75 emerging economy governments have nationalized foreign investments or been sued for unlawfully devaluing foreign holdings.[7] This approach could involve creeping expropriation in the form of regulations, taxation and local content or local ownership requirements, as in Iraq, South Africa and Russia, or outright expropriation, as in Russia, Bolivia, Ecuador and Venezuela. The economic failures due to such an approach could result in privatization projects, but privatizations carried out in those countries plagued with political instability could be renegotiated once a new government with different motivations and interests is installed.[8]

New alliances, new roles and new actors that emerge will also be important drivers of change. For many years after Western decolonization in the 1950s, Iran played the role of a guardian of Western interests in the Middle East. This changed after the Islamic Revolution of 1979. Similarly, Russia's role in Eastern Europe has changed with its actions in the Crimea and eastern Ukraine since early 2014. This state of affairs has had major political and economic repercussions, among others a closer energy alliance between Russia and China. Similarly, since the Arab Spring of 2011, energy-rich Arab monarchies in the Gulf, but also in Morocco and Jordan, have realigned in an effort to stave off the kind of revolts that appeared in Egypt, Tunisia and Yemen. Meanwhile, new actors like the south of Sudan's emergence as a state and the rise of the Islamic State of Iraq and Syria have changed the effective boundaries of authority in these three countries.[9]

2.2.2 Regional politics

Regional dynamics are likely to have an increased impact on international and national politics, and will therefore be an important driver of change. This was especially visible during the so-called Arab Spring or Arab Rebellion of 2011, when events in one country had considerable impact on other countries in a region.

The nature and effectiveness of regional governance arrangements will be an important driver of change. In principle, such regionalism is closer than international institutions to the sources of the problems to be tackled. Neighbouring countries are directly affected by threats stemming from respective regions. National leaders may be more familiar with one another in regional institutions, formal and informal. Regional instruments may also be mobilized faster than those of larger organisations.

Regionalism will however be weaker in some regions and sub-regions than others. ASEAN, for example, has developed over decades a distinctive style of regional cooperation based on a low level of institutionalisation, a non-intrusive agenda, informality, permanent consultation, and aversion to conflict. The dynamics between China, the two Koreas and Japan will be especially important for East Asian regionalism.

Brazil would be the only country with the critical mass to strengthen regional cooperation. However, the potential for regional fragmentation also remains strong, currently demonstrated by the Bolivarian Alliance, which only include a selection of South American countries.

In the Middle East, Turkey and secondly Iran will be the states with most potential influence in the period until 2050. However, it is likely that different sub-regional alliances will persist, of which Israel would also form at least an ad hoc part, either formally or informally. Similarly, no African country has sufficient influence and resources to steer regional cooperation at the continental level. Instead, alignments around Nigeria, South Africa, the Democratic Republic of Congo, Egypt and Ethiopia among others, will be important for the future of the continent.[10]

Another driver of change will be the decline or re-emergence of Russia as a regional power. If it declines, instability may give East European alliances led by Poland the need and the opportunity to adopt a more assertive policy to the east. The balance of power in Europe may in time move slightly eastwards, with Eastern Europe relying on US support and becoming more important as the demographic weakness of Germany and France has effect, while Turkey becomes stronger in the Caucasus, and areas to its northwest and south.[11]

Neighbouring states to the south and the east of EU are likely to experience considerable internal and regional turbulence during the period until 2050, constituting another driver of change. This applies to most states in these regions, and also to particular states that are important in European energy supply and transit, including Russia and Algeria. While the development of renewables will remain a component of EU global energy policies, these policies will focus on institutional, regulatory and investment predictability in energy producer and transit states to its east and south, rather than just a free market.

An interesting exception in this regard is Iran. It is quite possible that Iran, which already experienced an early "Persian Spring" of internal upheaval after the 2009 elections, will experience significant internal and regional political shifts in the period until 2050. The outcome could lead to the removal of Western sanctions against the country. Iran has the second-largest gas reserves in the world and the fourth-largest oil reserves.[12] Thus, such a shift could significantly influence the gas market, at least in Asia, but possibly also in Europe.

2.2.3 The EU as a region

The alignment and integration of member states in the EU will be an important driver of change. To date, the EU as a regional institution has been shaped and sometimes constrained by several factors. Some of them will be drivers of change: the interests of national governments, also in response to political shifts among their citizens and in the relationship between different parties; the capabilities of the relatively small bureaucracy and executive arms; clashing visions of the EU as enhancing economic competitiveness and a free market versus considerations of social cohesion, or of EU supranational governance versus responsiveness to national democracies.

The EU also quickly expanded in the past decade, with wide divergencies and sometimes tensions between individual countries and their institutions in the northwest, southeast and south of Europe. Some member states could come to diverge considerably from the liberal multiparty models dominant in the northwest, as indicated at present by the example of Hungary.[13]

Many of the key national governments in the EU, including those of Germany and France, are strongly engaged in maintaining or re-gaining national power over the EU. This is especially true for energy policy, which remains closely allied to foreign and security policy. In these policy areas, as Giles Merritt, the head of the Friends of Europe think-tank recently put it, the EU does not speak with a single voice, sometimes not even with a single squeak.[14]

Political decision-makers are also sensitive to their constituencies. European Parliamentary elections in 2014 reinforced a trend of limited participation by citizens of the member states, and saw the rise of EU-sceptic or –critical opposition parties. In many other parties in the Christian democratic, social democratic or market liberal traditions, national considerations largely trump EU ones.

Both important political decision-makers and their political constituencies thus do not seem primed for considerable stronger EU institutions. Strong corporations in the diverse energy sector of national states also have diverging interests and ambitions. As a result, national energy policies in Europe are likely to pursue several different routes simultaneously.

The relative resilience, skills and creativity of political elites in Europe will be a driver of change. For decades they have enjoined relative stability and prosperity in most of the EU, largely faraway threats, the remnants of post-colonial networks and influence in Africa, Asia and the Middle East, and the US-led NATO security umbrella in a bipolar and later unipolar world. This will change in the period until 2050, while political elites in Asia and other parts of the world, will become relatively more influential.

The EU's overall policies reflect the differences between member states and also different parties and stakeholders in member states between the competitiveness of markets and corporations, and social cohesion; and between supranational governance and regulation, and national democracies responsive to their citizens.

The fragmentation or alignment of EU-wide energy policies will be an important driver of change. Until about 2007, there was a consensus driving energy policy primarily with climate change in view, but the consensus has become fragile since the start of the economic crisis.[15] Internal energy policies in the EU, like foreign policies, could remain relatively fragmented until 2050. The capacity of EU institutions is limited, and further restrained by current economic conditions in many EU member states.

By 2010, most EU member states considered moving back into nuclear power. After the Fukushima disaster in April 2011, states like Germany, Belgium and Italy backtracked. However, France, the second-most powerful EU member state, also remains the most nuclear-dependent country, and countries like the Czech republic also remains committed to nuclear energy. To reduce geopolitical dependence on energy from unstable regions to the east and the south of Europe, nuclear energy could in future again constitute an attractive option in some European countries. This could in some ways align with the expressed aim of several Middle Eastern and Asian states to increase the role of nuclear power.

To date, the gas and electricity market in the EU are regional markets and also subject to national policy instruments. Renewable energies constitute a part of local or national markets. In contrast, oil and coal remain embedded in global markets.

2.2.4 National politics

The European Commission's *Roadmap for moving to a competitive low-carbon economy in 2050* suggests that, by 2050, the EU should cut its emissions to 80% below 1990 levels through domestic reductions alone. It sets out reductions of the order of 40% by 2030 and 60% by 2040. It also shows how the main sectors responsible for Europe's emissions - power generation, industry, transport, buildings and construction, as well as agriculture - can make the transition to a low-carbon economy most cost-effectively.[16] In the EU's electricity system, the rate of renewable energies of between 13 and 15% is still far off the current political goals under discussion of 45% for 2030 or 65-86% for 2050.[17]

However, national politics in Europe are likely to branch out in several directions simultaneously and remain an important driver of change. Even in the US, the shale gas revolution was enabled by support from the US Energy Department, the role of gas authorities, and exceptions to the Clean Water Act being allowed.[18]

The stakeholders and interest groups related to different forms of energy will also be an important driver of change. For example, coal production remains an important part of the energy sector in Germany, Spain, Poland and others, with a reluctance to reduce state aid. While many states have reduced carbon-production on their own territories, they have also increased carbon consumption by importing goods from carbon-rich producers in China and elsewhere.

National and corporate policies about the production and transmission of renewable energies will be another important driver of change. Many countries in the EU have access to renewable energy sources, but some more so than others, and with more efficient harvesting in some countries compared to others. Most countries may face a decision between cheaper electricity imports and the security of supply of domestic production. Thus, renewable markets are more likely to be buyer's markets and a view of electricity as a commodity, not a strategic good. 'Concerns about security of demand and supply are not expressed in diversification policies and the like, but in a power struggle over the ownership and decision rights with regard to control and management of the grid.'[19]

Another driver of change would be the greater impact of supply storage and disruptions where renewable energies are being used. When renewables form an important source of countries' energy, geopolitical interdependencies may then shrink to the size of the grid that connects producer, transit and consumer countries. On the one hand, this would increase the reliance of participating countries in a well-functioning electricity grid. On the other hand, any cross-border issues regarding energy supply would be more acute, because an interruption would directly lead to black-outs, and the difficulty in storing electricity would remove the option of strategic reserves.

One implication would be that countries with certain capacities would become more influential, changing the patterns of influence and power in Europe. For example, better-placed countries would be those with considerable storage capability, high reserve capacity, the ability to produce renewable electricity at times of high demand, or large interconnector capacity that allows the balancing of outputs of different areas.

An important driver of change would then be the role of large business with the experience in building and operating large power plants, and, implicitly, the viability or not of smaller alternatives. Most likely, the utilities will play a prominent role, and because of the strategic interests, states too. New roles for Distribution System Operators (DOS) in forecasting, local allocation of distributed generation in the network, and local balancing of generation and load, will also influence developments. Grid support services will become more important to address concerns about operational security and reliability.[20]

Access to components of the generators and transmitters of renewable energy will be a driver for change. Rare earth minerals are a crucial input for certain wind turbines, solar panels and batteries for electric vehicles. China has been active in acquiring control over a large share of the world's resources. If this would become a tool of geopolitical pressures, European energy sectors would be affected.[21]

2.2.5 Local/group politics

The shift to non-state actors as agents or spoilers of cooperation, reinforced by the communications revolution, will be an important driver of change. Transnational non-governmental organisations, faith-based organisations, multinational corporations, interest groups and civil society organisations will continue to be effective in reframing issues and mobilising public opinion. Opportunities will exist to expand the interaction between state and non-state actors and public-private cooperation. Those with hostile political or criminal agendas will be empowered by existing and new technologies and pose serious security threats.

Minority group politics could be an important driver of change in Europe, as well as in parts of Asia, the Middle East and Africa.[22] In the case of the US, the strong Hispanic minority, with its territorial and family links to Mexico and further south, will change the political landscape of the USA. Friedman and Huntington[23] foresee a strong possibility that the borderland between the US and Mexico, extending far into the US could become predominantly Mexican, with the US becoming a bicultural nation with other smaller minorities. Different constituencies could eventually influence energy choices at a federal state level.

In some cases, forms of class and generational politics could also combine with or oppose identity politics to influence energy policies. In the recent case of the referendum over Scotland's independence, for example, a political dispensation that had been in existence for almost 400 years was almost destroyed. The result would have been a new energy dispensation in the United Kingdom, due to the location of many of its energy resources close to Scotland. Even though the pro-independence camp lost, its substantial growth in support, especially among younger voters, the need felt by British politicians to make big concessions regarding devolution indicate that the issue is likely to re-appear on the agenda until 2050. In Spain, Belgium and Italy, among others, local and group politics could also strongly reshape the political order and local energy policy choices in the period until 2050.

Another driver of change would be the capacity of countries or even local communities to be able to become more self-sufficient in the production, transit and consumption of renewable energy. Where this does occur, the geopolitical considerations would reduce significantly compared to the current system, with its many dependencies in the supply chain.

A linked driver of change would be the choice of countries between using centralized, large-scale solar farms or wind parks to generate electricity, or using decentralized, small-scale individual solar panels and turbines. In the first case, geopolitical issues would largely revolve around communities wanting such forms of energy to generate revenue and jobs, or those, for example in part of western and southern Germany, who do not want it in their backyard. In the second case, it would be relevant whether the renewable energies generated are fed back into the grid, or whether net production would evolve into local energy markets and new regulatory frameworks.

An important driver of change would be to what degree the incentives of producers and consumers to cooperate weaken or overrule the incentives to compete. Producers compete for markets, but they share an interest in keeping prices high. Consumers compete for access to resources, but they also share an interest in keeping prices low. Producers and consumers rely on each other for revenues and energy, but also try to minimize their mutual dependence.[24]

2.2.6 Security challenges

Conflicts in regions that are major producers or consumers, is likely to be a driver of change until 2050[25]. This will especially be the case in the context of resource-scarcity. Such areas often become rife with corruption and organized crime, also in government institutions, so that the reputational risk and political risk to energy companies will remain high. Such conflicts will not only create short-term issues of supply, but shape energy security policies and preferences, as well as the operating practices of international and national energy companies.

Failed and failing cities outside Europe will constitute a key driver of change, also reinforcing migrant streams to developed countries. There will be an increase in the size and importance of ethnic minorities in many countries, also in Europe. A high proportion of young adult men in the Middle East and North Africa will reach its peak in the next decade, also in migrant communities in some European cities.[26] Some of them will be well-integrated and/or economically successful, while others may not be, with resulting social tensions.

Technological developments will allow migrants to maintain close links with their home communities and to transfer issues from the home country into the host country. Depending on the interests concerned, sometimes the energy interests concerned, governments of the host countries will have the impetus to intervene in the countries of origin or not.[27]

The rise of private security actors will be a key driver of change. In many locales outside Europe, they will constitute an important provider of security and enabler of robust operations and resilience during instability. Somewhat related, the interaction between asymmetric and symmetric forces and operations during conflicts will be an important driver of change.[28]

The expansion of alternative currencies will be a driver of change. It may make it easier to transfer and retain funds anonymously, harder to freeze the assets of criminals and rogue regimes, and reinforce the flexibility of actors and markets linked to forms of energy smuggling.[29]

The growing use of nuclear energy raises the possibility of fissile material obtained by non-state actors and countries hostile to the existing international order.[30] Unmanned energy-using systems will be a driver of change, paying an increased role during conflict, perhaps transforming the way battles are fought. Dual-use technologies and the military application of available civilian means may also play a role in this regard. In addition, there will be an increased reliance on space and cyber technologies, creating some vulnerabilities and an increased chance during conflicts of disruptive attacks with an effect on the energy sector.[31]

2.3 Social factors

Demographics will be a key driver of change. The global population is expected to increase considerably, with numbers including a rise from 7bn in 2011 to 9bn in 2050. Such an increase would result in a huge increase in energy demand, according to Shell by as much as 80% by 2060.[32]

Due to the huge increase in demand, investment in infrastructure will also be a key driver of change. An estimated two-thirds of demand will be in non-OECD countries, which are expected to outperform OECD economies by 2030. Increased access to energy sources and clean water, and affordable, safe and convenient mobility choices will be challenges. Managing pollution and traffic will be too.

The impact of demographic decline on Europe's working-age population is different. A lower potential growth rate is implied, and a lower-investment-to-GDP ratio is needed to keep the capital/output ratio constant. In some countries of Europe, higher investment may only lead to higher captal-output ratios and imply lower returns on capital.[33]

Income inequality will be an important driver at regional and local levels outside the OECD countries, and may shape the preferences of potential consumers.[34] The growth of a 'new middle class' will put pressure on prices, as a result of the increased demand. The middle class in many societies will also increase in influence. Estimates are that an additional 2.6bn people will attain at least middle income levels by 2050. Individuals also tend to consume most in their lifetime between the age of 16 and 40, and before consumers really begin saving for retirement.[35]

Government incentives and social activism to stimulate consumer demand for green goods and services, and public perception and corporate social responsibility as competitive differentiators could also be drivers of change in consumption, especially in some European countries.[36]

However, the acceptance of consumers or citizens, their willingness to tolerate a technology in their own environment, could play a major role when launching new products and manufacturing plants and services. The public takes a critical view of extensions to the grid infrastructure and the construction of wind farms and pumped-storage power plants in their immediate vicinity. People could use consumer pressure groups but also political and administrative opportunities to question decisions after the event, hindering both conventional and renewable energy projects and increasing the risk of total or partial failure.[37]

High-impact ideas will be a key driver of change. However, one cannot foresee all or even most ones in future, since many of them will result from complex interactions between people, symbolic systems, structures, and as yet-undeveloped technologies. However, at present, there are certain clusters of ideas with a probable high impact in future, also on the environment of energy. One idea would be derived from individualist and family-oriented traditions, and the formation and lifestyles of individuals, nuclear families and extended families. For example, in Indonesia, as people move upward into the middle class, they initially focus their spending on improving living conditions for their families rather than themselves.[38] In India, young consumers are both very competitive and motivated by the desire to make their families proud, whereas older Indians also have a family-oriented focus.[39] However, even in Europe, locational and regional variations play a role in this regard.

The second high-impact idea, related to individualist and family orientations, would be the position of women. Globally, in the labour market and unpaid household work, gendered division is the rule. Women are also underrepresented in the energy sector. In many cases, professional access to the energy sector is mainly based on a scientific or engineering education, in which women are under-represented, sometimes extremely so. The fields of skilled trade relevant to the energy sector such as construction, electric installation, plumbing, and installation of energy control or heating systems are dominated by males. [40]

Women as consumers may have closer knowledge about the energy services that are needed for different members of the family, different energy needs and different ideas about sustainable livelihoods. Another important question concerns the influence of women on policy concepts, planning, decision-making, and implementation, which is limited.

Gender, age and communitarian preferences may also shape the preferences and behavior of energy consumers. More men than women believe it is important that programs include the latest technologies, while more women than men are looking for programs that simplify their lives and are easy for the whole family to use.[41] Younger respondents prefer programs that use the latest technologies, are fun to use and are regarded as trendy. Consumers in emerging markets are also keen on programs that enable them to connect with a community.[42]

Cultural, religious and even political ideas may also shape production or consumption processes.

Islamic consumerism, cultural production and lifestyle choices may play a role.[43] Techno-nationalism or techno identity politics, where research and innovation are driven by sentiments and ambitions to service the greater good, are already visible in the civilian nuclear sector of Iran and other countries. It will also impact on the willingness to infringe on intellectual property rights and turn to industrial espionage and protectionism.

Themes of human rights, cross-sector partnerships, corporate social responsibility, sustainability and inter-generation equity and alternative business models form part of idea clusters that can have a major influence on future energy business models. However, it would be myopic to think that such models need to be compliant with the current dominant models in Western countries. In Malaysia, models of Islamic business governance have emerged. In China, strong sentiments of a social hierarchy, ethical structure, and a strong sense of family as the basic unit of production, with its rights of inheritance and views of the extended family, still pervade much of Chinese thought. Hinduism and the traditional caste system still influence power distance and hierarchical business practices, the concept of time and fatalism, and a smaller concept of personal space and group orientation. [44]

The empowerment of individuals *vis-à-vis* the state will be an important driver of change. Global literacy rates have improved from an estimated 73% in 1990 to about 84% in 2010 and an estimated 90% by 2030. Access to independent media and means of mobilization have enhanced the ability of actors. Greater interpersonal transnational flows and many networks connect more people. However, this should not result in assuming similarities in outlook or the disappearance of competing visions and ambitions. In many European countries, this empowerment is reinforcing dimensions of individualism; in Asia, Africa and the Middle East, many social institutions and norms of solidarity retain their influence and shape the conduct of empowered individuals.

Greater individual empowerment without sufficiently strong social institutions will also amplify overload and confusion, an unusual intensity in volatility due to the environment, sharp swings in confidence and demand and possibly herd behavior.[45]

In several ways, the balance of power has been slowly shifting from companies to consumers. Tools allow consumers to gain information about products, services and purchases. For example, they see their electricity expenditure, compare prices, and track their home energy use. They can make better decisions or even automate the decision process based on certain preferences.

However, several trends have also converged to create a field in which the so-called hyper-individual or hyper-consumer would participate. An individual can use skills and the value of freely available information to regain control in the market-place. One trend is maximizing behaviour for high-value purchases. Another is the rise of websites, apps and services that can mine data. For example, a real-time online price-monitoring service could suggest the best choice. The third trend is the quantified self, who is able to track and quantify many aspects of their lives now, whether through technology or legislative prescriptions. People learn and apply new methods of choice, self-monitoring, and information-gathering in their everyday lives. Modern lifestyles also pressure people to lead a more streamlined life. The expanding middle class will also expand the number of such consumers in emerging markets.[46]

A significant finding is that socio-economically and demographically, a person in the middle class of one country has more in common with a person in the middle class of another country. However, in terms of values and aspirations, people in the middle class or poorer classes in one country have more in common than people in the middle class in some regions. In addition, due to its low quality, many have opted out of public health and education systems, turning to private options. This has even been the case regarding electricity, where purchases of electricity generators have risen with income.[47]

2.4 Economics

Due to the extensive role of the government in most economies of Asia, the Middle East, Russia, Africa and South America, international, regional and national politics will remain an important driver of change in economies.

The state of Asian economies in general will be an important driver of change for Europe. However, the economic centre of gravity, in terms of the location of economic activity and average GDP, continues to move to Asia. China and India will be the most important countries to make the biggest changes to the overall energy landscape up to 2050. According to the World Energy Council, the total primary energy demand of China is expected to double by 2035, and that of India to increase by almost 150% during the same period.

Economic turmoil in emerging markets may also inhibit the projected growth in Asian countries until 2050. For example, inflows of capital have currently created substantial credit and real estate bubbles in China, Singapore and Hong Kong. The quality of economic growth and economic institutions has not always been controlled, in the case of China also due to ambitious local governments. Foreign exchange reserves are being reduced, often an indicator of worsening times. The IMF has warned of potentially prolonged market turmoil in emerging markets.[48]

An important driver of change would be the absence or presence of a second economic slowdown or crisis in Western countries, and a concomitant decline in energy demand. A second economic crisis cannot be ruled out yet. While governments have taken measures and consumer debt and financial sector debt in the US have since the 2008 crisis reduced by about 12% and 19% respectively, Western banks still remain too big, too interconnected and too undercapitalized, according to some experts. Some of the type of products that contributed to the crisis, like synthetic collateralized debt obligations, have re-merged in Wall Street, and federally guaranteed mortgages requiring small deposits are back in the USA. Meanwhile, volatility in major emerging markets and in Russia are impacting on the export-oriented European economies. [49]

Market movers will be a very important driver of change. Market movers include global companies with international supply chains; banks who can provide much-needed capital for increasing economy activity, venture capitalists who fund breakthrough technological research in order to gain larger shares in successful new market entrants, and entrepreneurs who offer new goods and services. The institutional rules of the game or incentive systems of global companies and entrepreneurs may be especially important for innovation in particular countries.

Economically interlinked mega-regions will be another driver of change. These include the meta-region spanning Amsterdam-Rotterdam, Ruhr-Cologne, Brussels-Antwerp and Lille, the English mega-region spanning London, Leeds, Manchester, Liverpool and Birmingham, the German mega-region encompassing Stuttgart, Frankfurt and Mannheim, and the Italian mega-region from Milan through Rome to Turin.[50]

An important driver of change will be the retention or possible substitution of the petrodollar system by a more independent currency system not based on the US dollar. Already, there have been efforts by countries ranging from China and Russia to India, Iran and Venezuela to do so. To date, the US political and military umbrella over Arab Gulf states combined with the US dollar-based investment fund holdings and bilateral trade agreements of these states, have acted as a strong constraint. However, as China's regional and global influence grows, this may not remain the case until 2050.

Investment to address growing energy demand and gaps in the infrastructure needed for the generation, transmission and distribution of electricity will be a key driver of change. It is notable that the new European Commission since late 2014 has expressly indicated its ambition to create a more attractive environment for foreign and local investment in the EU. In this regard, energy-related infrastructure, R&D and renewable energies are specifically mentioned.[51]

Infrastructure spending is most expected in Europe from the target set of achieving 20% of the energy production from renewable energy. Numerous projects are in the pipeline that range from tidal, solar, wind, bio fuel, bio waste, geothermal, and other resources. Carbon Capture and Storage systems will both require and be facilitated by a large-scale infrastructure. The choice of public and private financing instruments depends on the stage of development of the technologies or projects, but could also be shaped by EU CO_2 credits, spending priorities and regulatory hurdles.

Greater economic volatility and cyclicality and more uncertainty and risk will be an important driver of change. The recession has also provided governments, anxious to weather the downturn, with opportunities to take regulatory measures. Concerns about employment, debt, economic competitiveness, energy security and climate change are now being used to justify this. These measures are accelerating or delaying energy system change, depending on the political or economic circumstances.

2.5 Resources and environment

Rare earth elements will be a driver of change. China's policy of limiting REE exports has resulted in high prices, with an impact on the cost structure of the clean-tech industry which uses REE for manufacturing magnets and solar PVs. Reopened mines and development of resources will not affect this state of affairs in the short term.

Mining will be an important driver of change regarding the environment.[52]

Farmland will become a scarce resource and a driver of change, also because of non-OECD economies increasing their consumption of meat and agricultural commodities. As populations continue to grow, more pressure will be put on land, water, and forest resources.

Agriculture is still of major importance in the livelihoods of people in Asian and African countries, and more energy-intensive than manufacturing. Major projects of industrialization are also expected in non-OECD countries, concomitant with the emergence of new middle classes. With an apparent emerging stress nexus between water, energy and food[53], tightness of supply could feed off each other.

By 2050 it is expected that there will be an extra 2 billion people to feed worldwide. If they would want to consume as much nutrition as today's developed countries, global food production will have to rise by 110% over today's levels in the next 40 years. However, global food demand has been met by an increase in productivity and not an increase in the amount of farmland. Already, Middle Eastern countries and their sovereign wealth funds have begun to look overseas for growing crops needed for domestic consumption. Foreign ownership frameworks may be affected, with some flow-over potential to the ownership of foreign energy companies, as currently in South Africa. Demand for fertilisers will also increase, influencing the price of oil.[54]

Future energy emissions hinge on a patchwork of policy frameworks developing, especially in Asian economies. CO_2 policies adopted in the OECD over the next decades will be a key driver of change. This will slow overall emissions growth.[55] However, different countries will develop different strategies for decarbonising transport. Some countries will impose carbon taxes, others will develop or join emission trading schemes, while others will put in place technology or resource targeted plans. More expensive renewables could be favoured with technology developers chasing government subsidies and feed-in tariffs. There is a higher level of low-carbon technology transfer into developing nations.

Energy supply security could surpass environmentally-friendliness as a policy priority in most countries of the world. According to the World Energy Council, this is the result of scandals about the reliability of the science calling for climate change and failures in reducing emissions, as well as the increasing pressure on policy-makers to address economic recessions.[56]

As stated by the Word Energy Council, global energy until 2050 will be influenced by three aspects, namely growing complexity in energy systems, the high speed of change, and institutional tipping points and the failure to deliver of existing institutions.[57] Shell already indicated one of the implications in 2008, by indicating *There are No Ideal Answers* (TANIA).[58]

2.6 Energy and technologies

Selective government policies will be a very important driver of change, regarding the energy domain in general but also regarding technologies specifically. The energy policies of major powers like China and India are going to be of interest, given the shift in both power and economic importance to Asia.

China is estimated to be home to the most technically-accessible shale gas in the world. [59] At present, shale gas exploration has met with limited success. However, these initial setbacks also were the case in the US, and shale extraction technologies are developing at a high pace. As in the US, marked shifts could be possible in future. As indicated by Shell and BP but also by academic experts, gas, rather than oil, will be crucial for China's push away from coal, currently used for the major part of power generation. Gas will be important not only in reducing emissions, but in aligning grids to be more reliable when supplying alternative energies.[60]

In some scenarios for China, moderate growth could mean a slight decrease in coal, an increase in the next decade in the use of gas from 3% to 13%, of wind energy from 4% to 15%, of nuclear energy from 1% to 7%, of solar energy to 3%. Such a major increase is not foreseen for oil in the case of China under conditions of moderate economic growth.[61]

India's energy policy will be important regarding the position of coal in the global energy mix. Coal is the mainstay of India's energy sector and accounts for more than 50% of primary commercial energy supply, 69% of total primary energy supply (TPES) comes from coal-based thermal power stations and import dependency is growing. The new activist and business-oriented government of Narendra Modi in India, experiencing popular frustration about uneven energy services, are focusing on drastic measures to resolve the situation. Modi, after successes with solar energy in his state Gujerat, has now also envisioned solar energy and to a lesser degree wind energy as the most important sectors to address energy issues in India. This could be costly, but if so, in the case of India, the development of the nuclear energy sector would be the cheapest alternative of all.[62]

The global position of coal and nuclear energy, especially the former, are two variables that could rend the three end-state scenarios less accurate. According to the World Energy Council, China is expected to overtake the US to become the world's largest economy by 2020, but China itself is likely to be overtaken by India by 2050. This could result in a resource crunch between domestic energy resources and demand, especially for coal. Demand for coal in South Korea and Japan is also likely to remain strong. The global steel sector is also expected to continue to influence the demand for coal.

The exploration and production of unconventional gas from shale formations will also be an important driver of change. Rapid developments in technology have allowed the USA since about 2000 to strongly increase the recovery and production of natural gas from shale formations. Unconventional gas is relatively clean but will prolong the reliance on fossil fuels. It will reduce the drive toward renewable energy in the USA. However, much and expensive investment will be needed. Existing reserves of shale gas are often far from existing pipeline infrastructure and refineries designed to process heavier crude oil. Shale gas is also produced with fewer additional potential products than orthodox oil, and existing reserves in the US at present also seem to have a shorter lifespan.[63]

The impact of the US shale gas revolution on European energy policies and prices is another driver of change. The success of North America's shale gas production may inspire responses by other countries in the northern and southern hemisphere. Many European countries already have a high motive to redirect their energy security away from their current reliance on Russian gas. The current crisis over Ukraine and the Crimea, which is impacting on European economies due to a spiral of sanctions and counter-sanctions, is reinforcing this motive. However, it is likely that the situation will differ per country in Europe. In some cases, like Austria, Croatia, Greece, Hungary and Bulgaria, the motive was previously lower and mutual gas projects with Russia were supported, even though they could reinforce energy dependence. [64]

The aftermath of the shale gas revolution could influence the mix between gas and other energy elements in consumer countries, promoting a greater share for gas in these mixtures. At present, gas contracts are often linked to long-term high-priced oil contracts. However, rising gas supplies and the option of several suppliers may result in many consuming countries becoming less willing than at present to contract large volumes of gas over a long period or to link it to oil supply contracts.[65]

Competition and sometimes cooperation between and International and National Oil Companies (IOCs & NOCs) will be a key driver of change. Trends that will shape their performance will be business models, diversification into other forms of energy, joint ventures, the stipulations of negotiated contracts, and changing business practices.

Oil supply and oil prices will be an important driver of change, the latter also in decisions to produce shale gas. How OPEC responds to oil prices could influence events. However, the current geopolitical divisions between Saudi Arabia and other GCC states on the one hand and Iran, Syria and Iraq on the other, could also be reflected in OPEC finding it difficult to respond to a crisis. Just after the shale gas revolution in the US, Iran, Venezuela, and some North and Sub-Saharan African producers differed strongly from Saudi Arabia and other GCC states in OPEC.[66] Likewise, OPEC members' different interests may be difficult to reconcile if some of the above drivers and enablers are active.

Oil demand will be another important driver of change.[67] Oil demand projections by energy majors often do not take into account the major impact new government policies could have, also in India and China. Other factors could reinforce the effect of oil demand destruction. These would include current economic turmoil in key oil markets, political pressures that may make alternative energy sources more attractive, the counter-productive effect of high oil prices, and the potential oil substitution impact of renewable energies and policies related to them in key markets.

Oil demand destruction could result in significantly falling oil revenues for states in the Middle East and North Africa, affecting available budgets and the ability to provide sufficient services for often growing populations. The cost of social stabilization systems and other needed investment as oilfields decline may sharply reduce the actual benefit from even high oil prices. This is evident in Saudi Arabia, where the estimated cost of the social stabilization has increased from about $50 per barrel of oil in 2002 to $94 per barrel in 2012 and $98 today.[68]

This, in turn, could trigger instability in one or more countries of the region in the next decade, reinforcing insecurity on Europe's southern border. Given the social and demographic situation of the region, the soft warning in the IEA's *World Energy Investment Report* in 2014 remains relevant. If the oil price stabilizes around current levels and increases only moderately to 2035, "governments that have become accustomed to burgeoning hydrocarbon revenues could be in for a difficult period of adjustment." [69]

The possibility of oil demand destruction in many ways challenges the accepted wisdom that oil demand will continue to grow, especially in Asian countries. However, this is a complex issue involving many actors, possible interactions and less visible feedback loops. Unintended consequences and new events could result in many quick shifts, as has happened in the energy markets in the past decades and also with the shale energy revolution, which was largely unforeseen in the 1990s.

As indicated by Paul Stevens, higher oil prices and/or oil price volatility could persuade governments to turn to alternatives.[70] The International Energy Agency has developed several possible scenarios, based on governments' choice for renewable energies. In the so-called *450 Scenario* governments introduce policies until 2035 to reach the globally accepted aim of not more than a 2 degree Celsius increase in global temperatures. Oil demand in such a scenario would drop by 13% compared to today.[71]

However, the majority view among analysts still is a tremendous rise in oil demand. Non-OPEC conventional crude supply will then also be a driver of change. It has been falling, but the fall could be slowed by new discoveries like that in deep water off Brazil and reserves in existing fields being upwardly revised with the application of new technologies, viable in higher oil price environments. This decline could also be mitigated by supplementary sources like unconventional oil and biofuels. Interactions between individual types of energy, their markets and their prices will reinforce complexity, also the virtual impossibility of forecasting the future nature and extent of global demand.[72]

Drivers in the technology domain have the potential to significantly change the energy sector but also its position relative to other sectors, like electricity, transport, construction, and telecommunications. Important new developments, the convergence or re-constitution of different domains in production or consumption, and disruptive innovations and breakthroughs are assumed until 2050. This is due to the current state of technologies, the time period involved, continuous challenges and the current speed and scope of new knowledge generation.

Some areas of potential technological developments or breakthroughs would be continuing engine developments with improved efficient combustion, electric vehicles, 'plug-in' hybrids and mass market fuel cell hybrid vehicles, oil recovery- horizontal drilling, 4-D seismic, downhole enhancements and shale gas technologies. They would have strong implications for improved recovery.

The outsourcing of R&D to Asia will be an important driver of change. Already increasing, this will include the transfer of entire laboratories, subcontracting to Asian research organizations, and through collaborative R&D projects. Uncertainties over human resources, fraud, and unclear property rights will only have a limited effect on this trend. However, the extent to which innovation is strongly guarded or extensively shared or copied will be important. Such an outsourcing will interact with the extensive focus on R&D in the policies of China and other Asian countries.[73]

The reversal of an Asian brain drain to some Western countries will be an important driver of change. Asian knowledge elites increasingly leave their mark on the world's top multinationals, high–tech companies, and universities. Conditions for research and innovation in Asia still leave much to be desired. Whether it is solved by a more open and competitive approach, or a closed and exclusionary one, will shape change.

The speed, lead-time and direction of development for new energy technologies will be an important driver of change. New energy technologies must be demonstrated at commercial scale and require thirty years of sustained double-digit growth to build industrial capacity and grow sufficiently to feature at even 1-2% of the energy system. The policies in place in the next five years shape investment for the next ten years, which largely shape the global energy picture out to 2050.

Energy efficiency will be a very important driver of change in most corporations and economies.[74] In several countries, the potential gains in this regard are still substantial. The relevant technologies and learning curves could change quickly.

2.7 Key findings

This chapter identified multiple drivers of change in energy systems until 2050. They would cause change directly or by altering one or more direct drivers or recombining in diverse ways. Drivers could influence decision-makers, and in some cases decision-makers could influence drivers. The drivers could have a positive or a negative effect at different stages and during different interactions and iterations. They could shape but also be shaped by energy systems in complex ways.

A key finding is that the international political and economic order is becoming more multipolar than three decades ago, and that drivers of change can have a different effect in different parts of the world. If one looks at the world as a whole, components of end state 2 (Business as Usual) and end state 3 (Gas) seem more plausible than those of end state 1 (Renewables).

Given the policies and strategies in the EU, the EU may differ from the world as a whole in this regard, with components of end state 1 also being plausible there. Internal energy path dependencies, forces and interactions in the EU are not aligned, and not likely to be aligned well soon. There is a significant chance that end state 1 could at least partially emerge in some member states or regions of the EU only, rather than in the whole of the EU. In this regard, it is also relevant that renewable energies constitute a part of local or national markets, whereas oil and coal, for example, remain embedded in global markets. It cannot be excluded that at least parts of Europe would reach a significantly different end state compared to major parts of the world by 2050.

The role of social and political actors on energy systems is likely to be more prominent, based on global trends. In Europe, this will be noticeable at the local, national and international level. At the local level, high-impact social ideas like green consumerism and limited acceptance of energy systems that result in major trade-offs, could be important drivers of change. Nationally, the empowerment of individuals and communities relative to the state and as producers of some forms of energy and the politicization of energy-related issues will be key drivers of change. Internationally, energy issues will at least remain important or become even more so in the foreign and security policies of countries and the geopolitics of non-state actors.

What does this mean in practice for European energy planners and policy-makers? The variable impact of drivers of change, but also of path dependencies, diverse frameworks of global and EU-level actors, and the increased potential for self-organization, means that the scope and impact of known unknowns, unknown knowns and unknown unknowns in energy systems until 2050 can be potentially vast.

The identified drivers of change and the complex ways in which they can interact and reshape futures confirm that lock-in effects remain among the greatest risks. In EU member states, flexibility and modularity, rather than energy platforms only focused on one end-state, would be highly advisable.

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3 ENERGY TRANSITION END STATES

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3.1 Introduction

Numerous long term energy scenarios have been published by many different industry players, governments, lobbying organizations, and research institutes. As a starting point for the project, these different long term projections, which are publicly available, were surveyed. The aim was to identify and categorizes possible end states after the energy transition from literature. The end states form the starting point for the subsequent implications and limitation analysis as discussed in the following chapters.

3.2 General approach

The identification of the energy transition end states was performed in the following steps:

- *Establishing the definition of the 'energy transition end state'*

  In order to identify what the energy transition end states are, one should have a clear understanding of what exactly is meant with the words 'end state'. Several definitions of an 'end state' are available from the academic literature.

- *Establishing the basis for the end states' identification*

  As previously mentioned, the focus of this project is not on building scenarios and deriving end states: it is rather on identifying a number of potential energy transition end states based on the analysis of the existing scenarios produced by various authors from different backgrounds.

  The topic of energy transition is high on the social, political and academic agenda, which catalyses a significant number of publications and views on the topic. Such publications range from visionary documents with different time focus (e.g. Europe 2020 - A strategy for competitive, sustainable and secure energy) to studies which elaborate the development scenarios (e.g. Roadmap for moving to low- carbon economy in 2050). Making a sample overview of the available publications and the assessment of their relevance to the gas sector in particular is an essential step of this research.

- *Defining criteria for selecting the scenarios to be analysed*

  Due to the many scenarios produced on the energy transition, it is impossible to analyse all of them. It is therefore necessary to establish valid criteria for the selection of the scenarios to be further analysed.

- *Establishing a methodology for the analysis of the scenarios and the identification of the end states*

  No suitable methodology appeared to exist to compare scenarios with each other in the way this research intends. The existing studies[1,2,3] which engage into scenario comparison do not provide a uniform approach, neither do they justify and explain their approach to the process of comparative analysis of the scenario. Therefore, a methodology for making a comparative analysis of the scenarios was developed. This methodology is elaborated in Section 3.5.

- *Applying this methodology to the selected scenarios and analysing the results obtained*

  As the developed methodology has not previously been validated, it was applied to the selected scenarios in an explorative manner: some aspects of the methodology proved not to provide sufficiently conclusive results, whereas other aspects proved effective. This exploratory path will be further elaborated upon in Section 3.5.2 and onward. The results obtained on the basis of the comparative analysis methodology's effective aspects were further analysed with the view of identifying the energy transition end states.

- *Identifying the end states, based on the results of the analysis*

  On the basis of comparative analysis, three energy transition end states have been identified. These end states are discussed in detail in Section 3.6.

Below each of the steps are described in detail.

3.3 Definition of and 'end state of the energy transition'

In order to define an end state of the energy transition, it is necessary to first focus on the phenomenon of the energy transition as such. There is no uniform definition of an energy transition:

Fouquet distinguishes minor, intermediate and major energy transitions.[4] The shift from coal to gas in heating is considered a minor transition. The adoption of electricity or the switch from a horse to a car for transportation is considered an intermediate transition. Major energy transitions are the invention of fire, the development of agriculture and the Industrial Revolution.

Grubler identifies two grand energy transitions in modern history.[5] The first is the steam engine powered by coal which was a radical technological end use innovation at that time. The second transition was the greatly increased diversification of both energy use technologies and energy supply sources (wood, coal, oil, gas, nuclear, hydro etc.).

Meadowcroft makes yet another distinction of energy transitions[6]:

a) a movement from a fossil fuel based (or dominated) energy system to a non-fossil fuel based (or dominated) energy system

b) a shift from a carbon emitting energy system to a carbon neutral (or low carbon) energy system

c) a transition from a non-renewable energy system to a renewable energy system

d) a movement from an insecure (vulnerable) energy system to a secure (robust) energy system

e) a change from centralized energy provision to a decentralized energy system

As can be seen above, Fouquet focuses on the scale of a transition with a historical view, Grubler on technology, and Meadowcroft is describing options where the society can go from here.

Today humanity is at a point in history where many believe that the current energy system based on fossil fuel has come to an end, or at least should come to an end because of climate change and security of supply concerns.

Most of the demand for fossil fuels comes from technologies that have been in use for several decades or even a century, such as the steam turbine and the combustion engine. One could argue that today humanity is not inventing new branches of technologies (electricity, heating, road and air transport, chemical industry, plastics) for fossil fuels that could significantly increase or alter the consumption of fossil fuels or change the ways we use it as it did with the combustion engine for example. A possible element of a definition of an end state could thus be *an energy system or energy mix where no new applications are introduced in the market that significantly alter the ways of consumption of a specific energy source or change the ways we use it.* The current state of affairs is then perceived as extending or prolonging the use of fossil fuels for existing applications.

The existing literature sources on energy systems often refer to the term carbon lock-in.[7] Unruh writes that "industrial economies have been locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale."[8] Unruh continues by explaining that large technological systems such as electricity production and consumption cannot be understood as independent technological artefacts but have to be seen as complex systems of technologies embedded in a powerful conditioning of social context of public private institutions. Once certain systems are locked-in they can have the effect of *locking-out* alternatives. The Oak Ridge National Laboratory mentions that incumbent technologies are locked-in into systems of positive feedback between government, financial institutions, suppliers, and existing infrastructure support and sustain status-quo technologies even in the face of superior attributes.[9]

The concept of lock-in is often used to explain the difficulties to replace a fossil-fuel based energy system with a renewable based energy system. The concept could also be useful for establishing a working definition of an energy transition end state. Locked-in energy sources/infrastructure makes that system more inflexible, stable or robust. This research is looking exactly for robust end states. Any energy transition end state in the future will have, to a certain extent, the lock-in of the dominant energy sources in that end state to make that specific end state robust.

The above elements say nothing specifically about changes in demand for specific energy sources. Personal car use exists for about a century. In Europe gasoline consumption for cars will most likely not increase significantly and could decrease due to increasing efficiency. In emerging countries such as China and India, gasoline consumption could increase a lot due to economic development. This suggests that gasoline consumption is in an end state in Europe while still on a growth trajectory in other regions of the world. Another element of a definition of an end state therefore could be *a situation where (on a regional scale) the use of dominant energy sources in existing applications will most likely not increase or will begin to phase out and lose its dominance in the energy mix.*

A radical end state could of course happen in case of *physical depletion of a specific resource*. Most scenarios from the existing literature are built to model the energy mix up to around 2050 and a physical depletion of any of the fossil fuels is not likely before 2050, therefore this definition might not be relevant for this study. However, lack of confidence in resource availability (in the perception of the public) could be a driving factor in energy transitions. Today the general public is concerned about peak oil and security of supply. Those concerns put a pressure on politics to strive for an energy transition making this specific end state less robust (even when it appears robust in terms of technology and economics). Another element of an end state definition could thus be *when there is broad public consensus that we have reached a new end state or status quo*. This definition is of course not quantifiable, however, it could still be of importance.

This study identifies future changes in the energy infrastructure. The identified end states should not only quantify the future energy mix, but also to clearly state how a certain energy source is used. For example, two end states differ in the amount of gas consumption in the Netherlands between, say, 50-80 bcm/year. This gives us no information on *how* the gas infrastructure will look in the future. Will gas be used as flexible back-up generation to compensate for renewable intermittency, will there be large increases of biogas injected in the low-pressure grid, or will it be more or less business as usual? An end state thus requires a qualitative description of the energy system, combined with quantitative information on consumption and production etc.

Energy markets are always changing, and therefore the end state of the energy transition should not be interpreted as a point in the future when all developments in energy markets have come to a halt. Synthesizing from the elements above, the end state should be interpreted as a time period in the future where humanity has altered the technologies with which it consumes energy, the quantities of energy it uses per region/technology, the energy sources it uses, a certain technological lock-in of vital parts of the energy system, confidence that the end state is 'sustainable' for the time being (be it just a few decades or longer) and a public consensus that we have reached a new status quo and no large systematic changes are expected from economic and technological perspectives and no more large changes are demanded by public opinion and politics (in their respective short term future). This definition of the energy transition end state will be used in this study as leading.

3.4 Basis for identification of end states and criteria for selection scenarios

A manner of validating the energy transition end states is to derive the end states from existing scenario publications. Taking into account the global impact of the energy transition issue, it would be correct to assume that many different actors in various countries produce studies, opinions, scenarios, etc., related to the possible outcomes of the energy transition. Already at the initial step of setting up an inventory of existing future energy scenario publications, two boundary conditions need to be acknowledged for selecting scenarios to be analysed. One of these conditions is the publication language. The researchers' linguistic range is limited to North-West European languages (English, French, German, and Dutch). Therefore publications written in other languages (e.g. Japanese) are outside of the selection process. Another condition, perhaps again somewhat obvious, but nevertheless worth mentioning, is linked to the fact that the search for the relevant publications is confined by the researchers' background knowledge of the energy sector. For example, in case the researchers are not familiar with a certain academic journal, research institution or other party who has published a study, the publication in question has a higher chance of being missed simply because the researchers are looking at other academic journals or research institutions.

However, even when applying the above mentioned 'filters', a larger number of publications surfaces than can possibly be analysed, creating the necessity for a structured approach in further selecting the publications suitable for this research. Therefore a 'publications selection funnel' is defined, as depicted in Figure 2. The publication selection funnel revolves around three selection steps, each subject to increasingly stringent criteria in order to compile a representative sample of energy scenario publications.

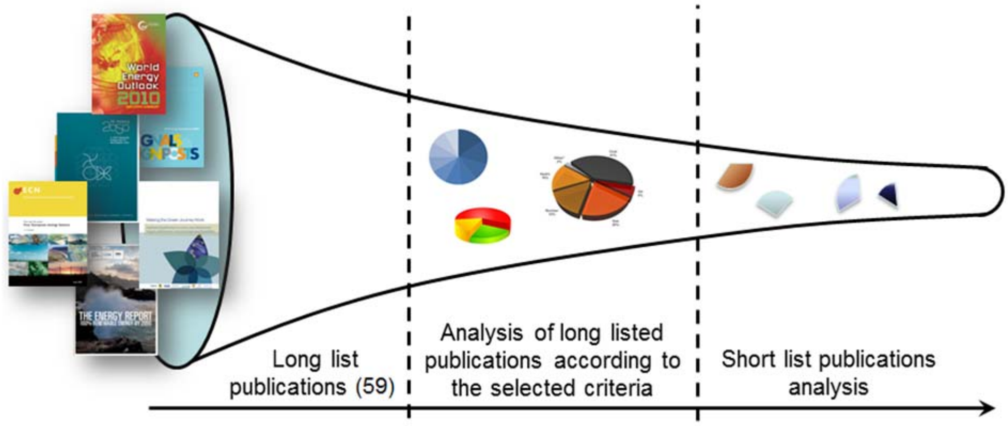

Figure 2: Publication selection funnel

3.4.1 'Long list' of publications

The aim of making the 'long list' of publications is to create a limited pool of scenarios, potentially relevant to this study. In order to qualify for the long list, the publications should correspond to the criteria listed in Figure 3.

1. Author / type of stakeholder and country of origin: a wide representative sample
2. Year of publication: aiming at recent scenarios
3. Time scope: aiming at 2100
4. Geographic scope: world, Europe, Netherlands
5. Energy mix vs. energy source: scenarios focusing on energy mix / gas

Figure 3: Criteria applied to the selection of publications for the 'long list'

The criteria illustrated in Figure 3 above are chosen with a two aims in mind:

1. A wide representative sample both from the perspective of author and the perspective of geographic scope
2. Quality of the publications and their relevance for the current study

In order to achieve a wide representative sample, a 'filter' of author/ type of stakeholder is applied to avoid only including publications produced by academia, or only produced by the non-governmental organizations (NGOs) or international organizations. The chart in Figure 4 represents the shares of backgrounds of the publications in the long list. Also the 'filter' of the country of origin is applied: i.e. energy producing countries versus energy consuming countries.

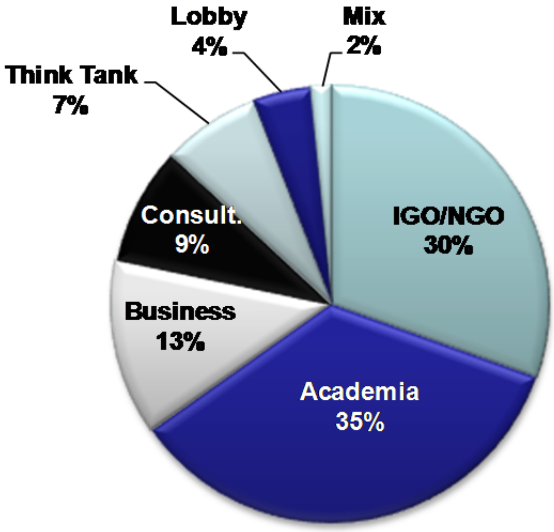

Figure 4: Publications from the 'long list' per author type

As illustrated in the Figure 4 above, more than one third of the publications included in the long list are produced by academia. This outcome is due to the fact that the number of publications from academia is larger in absolute terms compared to the publications from other types of authors. 30% of the long list publications are produced by various non-governmental and inter-governmental organizations. It is notable that relatively fewer publications are produced by businesses and consultancies (13% and 9% respectively).

The publication year of the scenarios is taken into account as well: in order to ensure that recent 'game changers', such as Fukushima, are considered, the energy scenario needs to be relatively recent. The compilation of the publication years of the long-list are depicted in Figure 5.

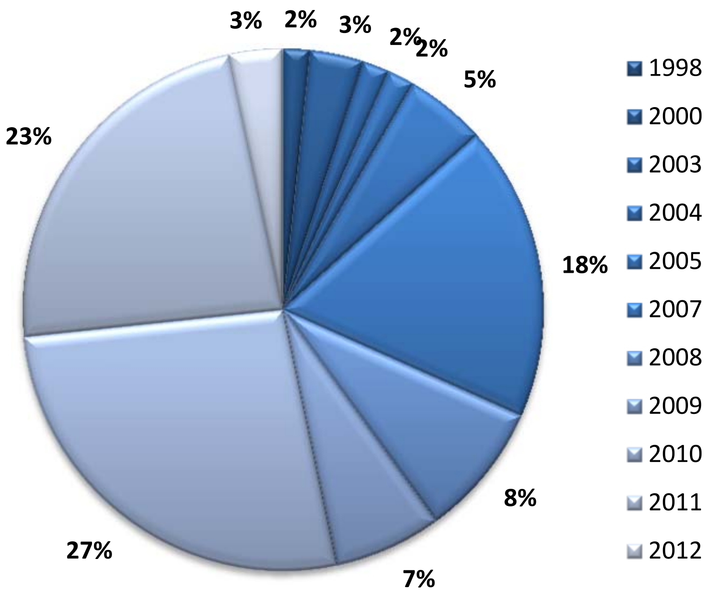

Figure 5: Publication year of the scenarios in the long list

As the time scope of the scenarios should fit the research's time scope, e.g. until 2050/2100, preference is given to the scenarios extending as far as possible into the future. Scenarios that cover only a relatively small geographical area (such as those focusing on a single country or region) are not considered.

Another important criterion for the long list scenarios' preliminary selection is the presence of a quantified primary or final energy mix, as it this forms the basis for the scenario comparison. Figure 6 and Figure 7 present the availability of quantified primary or final energy mix in the scenarios included in the long list.

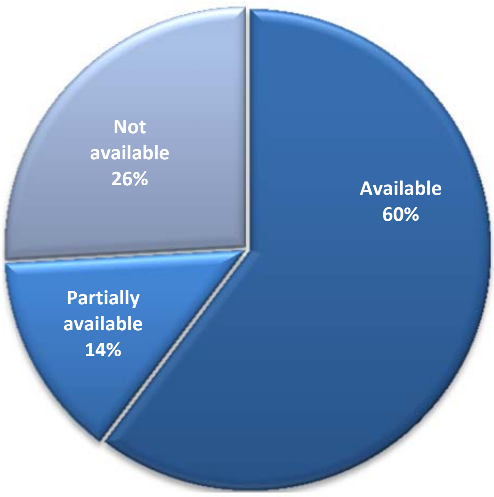

Figure 6: Availability of a primary energy mix

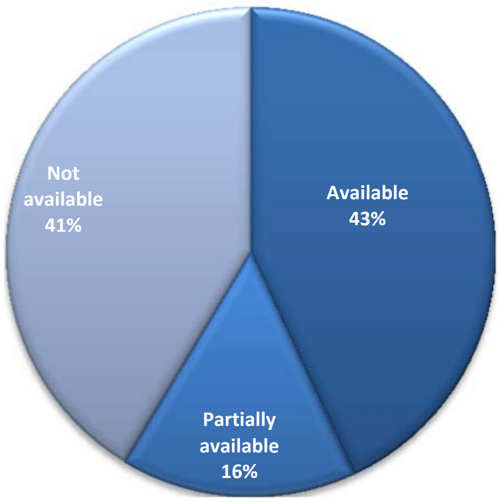

Figure 7: Availability of a final energy mix

As illustrated in the Figure 6 above, 60% of the long list publications contain sufficient information on the primary energy mix. However, only 43% of the publications contain sufficient specification of the final energy mix (Figure 7).

3.4.2 Short list of publications

As previously mentioned, there are two objectives in making a long list of the publications: First of all, the sample should be representative both from the perspective of author and the perspective of geographic scope. Secondly, the publications should be of sufficient quality and of relevance for the current study. Thus, the publications to be included in the long list correspond both to the criteria of wide representative sample, and quality and relevance.

It should also be mentioned that the processes of the selection of publications and that of the elaboration of the methodology are done in parallel rather than in a sequential manner. Therefore, the elaborated methodology largely shapes the criteria applied to the selection of the scenario publications to be analysed. Respectively, the choice of the final selection criteria for the publications' 'short list' is motivated by the requirement of applying both a quantitative as a qualitative analysis, and included the requirements of Figure 8.

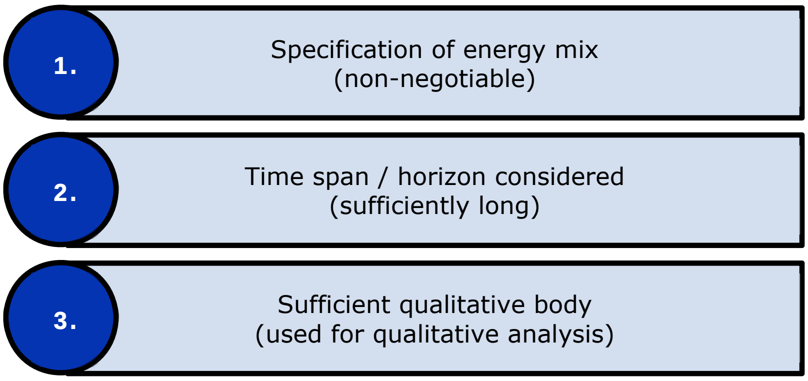

Figure 8: Criteria applied to the selection of publications for the short list

As the above mentioned criteria allow for both quantitative and qualitative analysis, they have been made leading in the creation of the short list. So, to arrive at the short list, the publications are further analysed using these criteria. It should be noted that many publications in the long list contain more than one scenario. In this step of the analysis, individual scenarios are labelled and analysed individually.

Furthermore, each scenario is concisely described in an Excel sheet and scored accordingly. The score, along with final selection criteria, is used as the basis for short-listing the scenarios eligible for further investigation.

In addition to the above criteria, the following characteristics are used for describing the scenarios:

- Back-casting versus fore-casting: back-casting presumes defining a point in the future (e.g. 80% of renewable energy sources in the total energy mix in 2100) and making a prognosis regarding how to reach this point; fore-casting presumes making a prognosis on the future, based on the development of the current factors;
- Narrative versus descriptive: narrative scenarios are based on the predefined set of assumptions developed by the scenario authors, and these assumptions need not necessarily be based on the current facts (e.g. we assume that in 2100 a drastic change in energy consumption patterns will occur, even though there are currently no indicators that this will indeed take place); descriptive scenarios are based on the set of assumptions based on the current situation and its foreseen development;
- Malthusianist versus techno-optimistic: scenarios which are Malthusianist in nature presume that the fossil fuels are a finite resource; in contrast, techno-optimistic scenarios presume that a technological breakthrough will take place which will allow the continued exploitation of the fossil reserves or will provide for new energy sources.

A number of important observations are made while performing the analysis of the scenario publications in the long list:

- Numerous scenarios present a forecasted progress of a single energy source, which would hamper the comparative analysis. Therefore a detailed numerical overview of the primary or final energy mix is deemed essential. However it should be noted that the scenarios lacking a sufficient overview of the energy mix, but containing a potentially interesting narrative, are not automatically excluded.

- Another observation worth mentioning is that the scenario publications which are widely recognized in the energy world are often produced by established organizations, such as the International Energy Agency (IEA), or successful businesses, such as Shell and BP, which possess extensive human and financial resources invested in scenario development. This leads to a higher recognition of intergovernmental and business energy scenarios than that of the academic energy scenarios.
- Additionally, the majority of the publications in the long-list focuses on political and economic aspects of their scenario(s); few address technology and environmental aspects, while even less take the social aspects of their scenario into account. Policy scenarios are often narrative and regional in nature (e.g. European level) and assume a medium to high policy intervention. Narrative scenarios are mostly back-casting. Most scenarios do not predict a technology revolution nor a high level of technology penetration, but rather anticipate a medium technology penetration level. In addition, a greater number of energy scenarios focus on the supply-side of the ‘picture’ than do on the demand side. Finally, most scenarios are Malthusianist (presume that the fossil fuels are finite), although they do not explicitly state this.

Table 1 presents an overview of the publications included in the short list. It should be noted that the table below presents an overview per publication: most publications contain more than one scenario, which will subsequently be analysed as separate scenarios, thereby increasing the total number of the scenarios in the short list.

Table 1: Overview of the publications included in the short list

Nr.	Author	Title	Year	Category
1	Azar, Lindgren & Andersson	Global energy scenarios meeting stringent CO_2 constraints - cost-effective fuel choices in the transportation sector.	2003	Academia
2	BP	Energy Outlook 2030	2012	Business
3	EC - European Commission	World Energy Technology Outlook – 2050	2006	(Inter) governmental
4	EIA	International Energy Outlook 2011	2011	(Inter) governmental
5	ExxonMobil	The outlook for energy: a view to 2030	2010	Business
6	Greenpeace / EREC	Energy [R]evolution: A sustainable world energy outlook (3rd ed.)	2010	NGO
7	IEA	Are we entering the golden age of gas?	2011	(Inter) governmental
8	IEA	World Energy Outlook 2011	2011	(Inter) governmental
9	IPCC	Special report on emission scenarios	2001	(Inter) governmental
10	Krewitt et al.	The 2℃ scenario - A sustainable world energy perspective	2007	Academia
11	Leimbach et al.	Technological Change and International Trade – Insights from REMIND-R	2010	Academia
12	OPEC	World Oil Outlook 2011	2011	(Inter) governmental
13	Shell	Signals & Signposts	2011	Business
14	Shell	Energy scenarios to 2050	2008	Business
15	WWF / Ecofys / OMA	The energy report: 100% renewable energy by 2050	2011	NGO
16	EC – European Commission	EU Energy trends to 2030 update 2009	2009	(Inter) governmental
17	ECF	Roadmap 2050	2010	NGO

As can be seen in Table 1, the list of publications on the shortlist contains a few "doubles": multiple publications from the same author. For example, *Are we entering the golden age of gas?* and *World Energy Outlook 2011* are both published by the IEA. Examination of the scenarios presented in those two publications reveals that some overlap in original datasets used and even scenarios developments may exist. This suggests an unevenly high impact of the IEA's ideas and projections on the resulting end states. Nevertheless, both publications are deliberately kept on the shortlist for two reasons. First, removing one or both of the two publications would suggest selection on the basis of presumed influence on the results rather than a priori selection on the basis of availability of required data, and as such influence the scientific integrity of the research. Second, despite whatever overlap that may exist between the scenarios, both publications revolve around a different perspective and narrative on future developments of the global energy system and therefore can be seen as being characteristically different to a certain extent. Another "double" is *Signals & Signposts* and *Energy scenarios to 2050*, both published by Shell. The latter is somewhat of an elaboration on the two scenarios presented in the former. Nevertheless, *Signals & Signposts* offers an extended "business-as-usual" perspective on the scenarios from *Energy scenarios to 2050* based on actual developments, and as such can be considered a distinct scenario of its own. For this reason both publications are kept on the short list, augmenting one another.

3.5 Methodology for the analysis of the scenarios and the identification of end states

As previously discussed, it is unknown whether there exists an established methodology which allows to successfully compare the scenarios with each other. The existing studies[1,2,3] which engage into scenario comparison do not provide a uniform approach, neither do they justify and explain their approach to the process of comparative analysis of the scenario. Therefore, a methodology of the scenario comparative analysis was developed. It consists of the following steps:

- Preparatory analysis of the selected scenarios
- Quantitative grouping of the scenarios according to a clustering approach
- Quantitative grouping of the scenarios according to the data dynamics analysis approach
- Analysis and integration of the obtained results into end states
- Qualitative analysis of the end states according to the PESTE categories

The steps of the methodology and their application to the scenario analysis are discussed in detail in the subsequent sections. It should be noted that as the developed methodology has not previously been validated, it is applied to the selected scenarios in an explorative manner: some aspects of the methodology proved not to provide sufficiently conclusive results, whereas other aspects proved effective.

3.5.1 Preparatory analysis of the selected scenarios

As the elaborated methodology includes both quantitative and qualitative elements, the preparatory analysis of the selected scenarios was also performed from both aspects:

- *Preparatory quantitative analysis*

  As not all scenarios have the same choice of energy measure units, all energy mixes are converted into exajoule (EJ). This allows for a straightforward comparison of the scenarios. For most of the scenarios, the energy mix relates to the primary energy mix. However, in cases where only production figures are provided, these figures are used for comparison. It should be noted though that in general more is produced than consumed, as transmission losses occur during transportation.

  After gathering data for all the scenarios' energy mixes, there are some differences found in reporting on the renewable sources. A few authors distinguish renewables per source, such as hydro, solar, wind, biomass, geothermal and ocean energy; most authors did distinguish biomass from other renewables. All specific renewable sources are brought together and are labelled as renewables for the purpose of simplifying the issue. Aggregating renewables as one general source allows comparing the energy mixes with each other.

- *Preparatory qualitative analysis*

  For the purposes of the preparatory analysis, the PESTE framework is used to analyse the driving forces which exist to keep the practice going and the potential forces which could influence it to change.[10,11] PESTE stands for Political, Economic, Social, Technological and Environmental:

  Political: Specific policies that are implemented and the degree of political intervention, for example restrictions placed by countries on importing energy from a specific country.

  Economic: GDP is an important economic driving force. The cost of transportation, marginal costs and the price of a barrel of oil are also important economic driving forces.

  Social: The continuing wave of population growth is perhaps the strongest driving force of our time. It suggests a continuing market for energy, especially because people tend to use more energy with today's luxury goods.

  Technological: Continuous improvement and innovation in the energy sector may shrink the energy use per capita. An example can be efficiency in the transport sector. Technological innovations could have a significantly impact on the future (e.g. CCS and efficiency).

  Environmental: The impact of ecological damage on human affairs, and the increasing public perception of ecological harm, like carbon tax and CO_2 emissions.

In order to facilitate further qualitative analysis, each short-listed scenario is condensed into a storyline. Each storyline contains general information about the scenario (e.g. sub-scenarios, used models), as well as the main assumptions of the scenario described on a high level. Thereafter more detailed assumptions are divided into the PESTE framework. The PESTE categories are chosen to facilitate comparison of all scenarios. In each storyline a division between scenario assumptions and results is made, when possible. Furthermore, a distinction between the world, Europe and the Netherlands is made as well and it is noted whether the scenario addresses Europe or European Union.

3.5.2 Quantitative grouping of scenarios

Data quality

Within the process of data extraction the focus years are set at 2010, 2030/2035, 2050, 2100. The finest grain of 5 years is applied. Coarsest grain is determined by data availability of the scenario in question.

Data between available data points is estimated through interpolation. The time series available from the scenarios analysed are essentially snapshots of data in various years, with some scenarios providing data over a longer time frame or with finer grain than others. In the construction of the multitude of graphs representing a continuous visualization of these time series, data for points in time for which no data is provided are estimated using simple interpolation. Data are not extrapolated into the future.

Notice that not all scenario lines pass through the same point for years that are already part of history, i.e. 2005, 2010. This is due to differences in the publication dates of the literature. Whereas for publications later than 2005, data on for instance global total primary energy consumption of the year 2005 was known, for publication from before 2005 the final figures would have been part of the future scenarios and had therefore been estimated. Regardless of the short-term nature of these predictions, some deviation in the expected figures is unavoidable.

General methodology

A crucial step in processing the scenarios before deriving and defining end-states is restructuring the scenarios into three clusters. Each of these clusters would stand to represent an end-state. Adding to the complexity of this step is that no clustering algorithm exists that would provide results compatible with the project's intentions. Scenario comparisons and analyses in peer-reviewed publications usually revolve around a small set of scenarios, relying largely on descriptive reporting.[1,2,3] For this project, the process is more oriented on the dynamics involved with the quantitative aspects of the scenarios.

Considering data clustering from a purely mathematical perspective, a handful of algorithms exist.[12] However, these methods consider nothing but the static numbers - dynamics, interrelations and semantics are ignored. To compensate for this limitation, a two-pronged approach is used involving mathematics-based clustering algorithms on one hand, and clustering through inspection of data dynamics and qualitative aspects of the scenarios on the other hand. The latter method is devised and designed in an iterative process, tailored specifically to the needs of this project. The combination of these two methods should provide an acceptable balance between mathematical objectivity and the subjectivity of human judgment. Integration of the intermediate results of these two approaches would then lead to the final clustering and the foundation for the three end-states.

Quantitative grouping of the scenarios according to a clustering approach

The field of statistics provides for a number of clustering methods, each with its own specific applications and limitations. Agglomerative hierarchical clustering was found the most conclusive method. This method uses a bottom-up approach, where each 'observation' is a single cluster. In each iteration the closest pair of clusters is merged by satisfying similar criteria. The visibility of the levels within the clustering and an appropriate number of data led to the choice of this specific method for statistical verification. The choice of a distance measurement will influence the shape of the clusters, as some elements may be close to one another according to one distance and farther away according to another. The Manhattan and Euclidian distance measure methods are applied to the relative data of the year 2050. Using the relative energy mix keeps a level playing field for all scenarios more than using the absolute energy mix would.

Analysis of the results reveals that the Euclidian distance measure, which measures distance in the way a ruler would, displays the most logical clusters. However, the majority of the scenarios do not pass the 2030/2035 mark leading to a relatively limited dataset of 2050. By focusing on the year 2030, an optimal balance between looking far ahead into the future and keeping high data density is maintained. Therefore the relative data of 2030 is used as input for the agglomerative hierarchal clustering, applying the Euclidian distance measure and using the following distance measures: Single, Complete, Average, Centroid and Ward.

Observations:

- The Euclidian/Single clustering does not add any value, as it contains four categories of one scenario and one category of 27 scenarios. This clustering method is therefore excluded for further analysis/comparisons.
- The results of the Euclidian/Average and Euclidian/Centroid dendrograms are quite similar, showing two groups and three individually grouped scenarios. The difference between the results of these clustering methods is marginal; in the Euclidian/Average cluster, scenario 13. Azar Lindgren Andersson is grouped, whereas individually grouped in Euclidian/Centroid. In the Euclidian/Average cluster scenario 12. IPCC – B2 MESSAGE is grouped individually, whereas it is placed in a group in the Euclidian/Centroid dendrogram.
- On first sight, the Euclidian/Ward dendrogram appeared to be most useful since it presents relatively even groups compared with the other methods. Further analysis confirms this suspicion. When comparing the results with the groups that the snapshots provide, a remarkable overlap of 90% exists. The scenarios IPCC-B1-IMAGE and Shell-Scramble are the only exemptions.
- The 7. Leimbach – Reference scenario is consequently grouped individually in the results for the 2030/2035 and 2050 energy mix snapshots as well as all clustering methods.
- The 6. Krewitt - 2C scenario is grouped individually through clustering in the Euclidian/Complete, Euclidian/Single, Euclidian/Average and Euclidian/Centroid dendrograms.

All dendrogram methods, with the exception of Euclidian/Ward, do not provide any significant contributions towards the compilation of the end states. However, when cross-referencing the outcomes with the groups the snapshot provides, the dendrograms do confirm of the grouping specific scenarios:

- Group 1: Leimbach – 400 ppm, Greenpeace – Energy [R]evolution, Greenpeace – Advanced Energy [R]evolution, WWF – 100% Renewable and IEA WEO 2011 – 450 Policies.
- Group 2: EC – Reference, EC – Hydrogen, EC – Carbon restraints, ExxonMobil, IPCC – A2-ASF, IPCC-B1-Image and EIA – Low oil price.
- Individual grouping of the Leimbach – Reference scenario.

Quantitative grouping of the scenarios according to the data dynamics analysis approach

The statistical clustering method (as explained above) uses a snapshot of the time-series data as input. As a consequence, the resulting clustering does not reflect any temporal dynamics of the energy mix that may be present. To compensate for this limitation, an alternative clustering approach is devised that incorporates as much of the temporal dynamics of energy use as possible without compromising the integrity of the data in the time-series or the objectivity of the analysis thereof beyond acceptable limits.

Only by plotting the (estimated, interpolated) lines between given data points, the general dynamics of a scenario's future energy mix prospects become visible. Still, the differences between various scenarios using these visualizations remain subtle at best. To better quantify and illustrate the dynamics of the presented future energy mixes, converting the given figures to annual growth rates proves elementary.

Growth rates capture the direction of trends and amplify subtle changes therein. Moreover, data for absolute and relative energy mixes alike can be recalculated into average annual growth rates. It thereby reduces different data bandwidths between and within scenarios to a single uniform standard, thus allowing for more reliable comparison. Visually analysing growth rates provides the additional advantage of not having to stick to a specific year for which the data density is best. Instead, all scenarios can be analysed together over their entire time span or any desired subset thereof. Nevertheless, only a handful of scenarios provide data beyond the year 2050 so the focus will be on the time frame between 2010 and 2050.

The data provided in the scenarios are recalculated to uniform growth rates using the compound annual growth rate (CAGR) method:

$$CAGR(t_1,t_2)=(V_{t2}/V_{t1})\hat{}(1/(t_2-t_1))-1$$

Where t_1=starting year of time frame

t_2=end year of time frame

V_{t1}=data value for the starting year of the time frame

V_{t2}=data value for the end year of the time frame

The compound annual growth rate method results in a growth percentage that is constant for every year in the time frame. Start and end years of a time frame are chosen such that the resulting time frame spans exactly the period between two available data points. For example, if the total absolute energy use data available for a certain scenario is limited to 500EJ in 2010, 600EJ in 2020 and 900 EJ in 2050, two growth rate figures remain after recalculation: one for the time frame between 2010 and 2020, and one for the time frame between 2020 and 2050. The compound annual growth rate between 2010 and 2020 would be (600/500)^(1/(2020-2010))-1=0.018, or 1.8%. Between 2020 and 2050, the compound annual growth rate would be (900/600)^(1/(2050-2020))-1=0.014, or 1.4%.

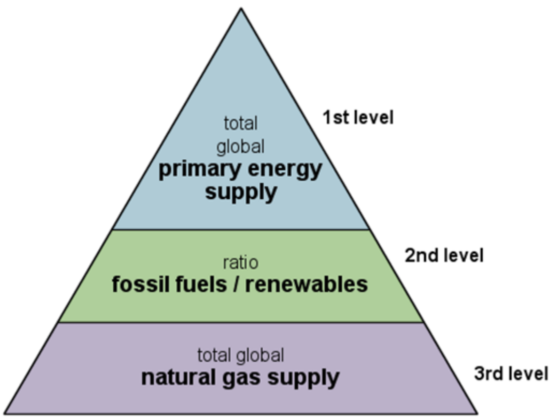

Figure 9: Three-level top-down clustering criteria

The method to cluster the scenarios based on similarity of behaviour of the compound annual growth rate over the time span of the scenario is designed as a three-level procedure, classifying the scenarios according to a different criterion on each level. As visualized in the image of Figure 9, with each level, the focus turns to more deeper lying aspects of the energy mix, so as to mimic a top-down approach. From the first to the third level, the procedure uses absolute total energy use, the ratio of energy from fossil and renewable sources and absolute gas supply, respectively, as the classification criteria. Total energy use represents the broadest and most general aspect of future energy scenarios. The ratio between energy from fossil and renewable sources adds a qualitative perspective, incorporating two types of energy sources in one quantifiable unit without explicitly singling out a specific primary energy source. Using absolute gas supply as the final criterion does single out a specific primary energy source, providing a meaningful qualitative approach to future energy mixes. These criteria and the sequential order thereof were chosen to reflect the intentions of the project, i.e. a broad perspective on energy futures while allowing special attention for the role of natural gas.

At each of the three levels (or, for each of the criteria), the complete group of scenarios is initially classified into three classes of similar behaviour: roughly low, medium and high depending on the most prominent general direction of a scenario's growth rate between the years 2010 and 2030/2050. Some scenario's growth rate behaviour would be erratic up to the point of potentially fitting in more than one class. As a solution to that problem, a scenario could also be labelled with a secondary and tertiary class. The weighted average of the three classification strengths would then deliver the final classification to be used in the remaining part of the procedure.

The final step in the data dynamics clustering approach is the integration of the three levels from the procedure as described above into a combined cluster structure. This integration is realized through aligning the weighted average classification of each of the three levels. As noted above, the classification into three distinct classes results in an uneven distribution of the scenarios over those classes at each of the three classification criteria. Combining the first two classes of each selection criterion resolves this problem and allows for a more straightforward integration of the three criteria. This leaves two classes for each selection criteria, "low" and "high". For the total energy use growth rate criterion the "low" and "high" classes refer to growth rates below 1% or above 1%, respectively. The "low" and "high" classes for the fossil-renewables ratio criterion are defined by growth rates below or above -2%. The total natural gas supply criterion's "low" and "high" classes are differentiated by growth rates below or above 1%.

Aligning the results of the consecutive operations and abstractions performed for each of the classification levels yields a 31x3-sized colour-coded matrix, as shown in Table 2. This matrix consists of one row for every scenario and one column for each of the classification levels. The columns from left to right represent the classification for the criteria total energy use, ratio of energy from fossil and renewable sources and gas supply, respectively. Added to the right of the matrix is the identification of the associated combined scenario cluster.

In Table 2, the list of scenarios is sorted by their associated three-level classification. Three similar-sized groups of scenarios can be identified: one group of scenarios (the first nine) in which all are classified with the "low" label for all three criteria, another group of scenarios (the middle 12) which show a combination of "low" and "high" classification for different criteria, and a third group of scenarios (the last ten) which are classified in the "high" category for all three criteria. In Table 2, dashed horizontal black separation lines help to identify the groups and thus the clustering within the set of scenarios resulting from the data dynamics approach.

The classification of the scenarios in the first cluster characterizes this group along the lines of advocates of energy from renewable sources, efficiency improvement, clean energy use etc. The scenarios in this cluster suggest small long-term growth of absolute energy use, if not even decline thereof. Also, energy from fossil sources is expected to lose ground in favour of energy from renewable sources relatively rapidly, and natural gas supply may see decline or only small to moderate growth. Such characteristics justify naming cluster 1 "High Renewables".

The composition of the second cluster is best described as heterogeneous, the combined picture of the included scenarios not displaying clear and distinct overarching themes or directions other than a continuation of the current situation. The scenarios in this cluster suggest a moderate to strong long-term increase of absolute energy use. There is no consensus about whether fossil fuels gradually make way for renewables or not and the pace with which that would happen. The expected growth of natural gas supply ranges from moderate to high. As such, it seems appropriate to name cluster 2 "Business as Usual".

The third cluster is composed of scenarios that are classified with "high" labels for all three criteria, and primarily distinguishes itself from the second cluster through consistent prediction of a growing role for natural gas. In this cluster, the scenarios are all on the same line expecting total primary energy supply to see high growth, renewables to gain ground on fossil fuels only comparatively slowly, and natural gas supply to enter a period of strong growth. On the basis of those characteristics, cluster 3 is named "High Gas".

Table 2: Overview of three-level classification of scenarios

Classification level // criterion

1 // total energy use — CAGR: 12 <1% 3 >1%

2 // fossil-renewables ratio — CAGR: 12 <-2% 3 >-2%

3 // total natural gas supply — CAGR: 12 <1% 3 >1%

1	2	3	Author // publication // scenario	cluster
1	1	1	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 2: "Energy [R]evolution"	B1: High Renewables
1	1	1	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 3: "Advanced Energy [R]evolution"	B1: High Renewables
1	2	1	WWF // 100% renewable	B1: High Renewables
1	2	1	Krewitt et al. // The 2°C scenario - A sustainable world energy perspective // Scenario 2: "2°C"	B1: High Renewables
2	1	1	Leimbach et al. // Technological Change and International Trade // Scenario 2: "400 ppm"	B1: High Renewables
2	2	2	Azar et al. // Global energy scenarios meeting stringent CO_2 constraints	B1: High Renewables
2	2	2	IEA // World Energy Outlook 2011 // Scenario 3: "450 policies"	B1: High Renewables
2	2	2	Leimbach et al. // Technological Change and International Trade // Scenario 1: "Reference"	B1: High Renewables
2	2	1	Shell // Energy Scenarios to 2050 // Scenario 3: "Blueprints"	B1: High Renewables
2	3	3	EIA // International Energy Outlook 2011 // Scenario 3: "Low Oil Price"	B2: Business as Usual
2	3	2	IPCC // Special Report on Emission Scenarios // Scenario 3: "B1-IMAGE"	B2: Business as Usual
2	3	3	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 1: "Reference"	B2: Business as Usual
3	2	1	Shell // Energy Scenarios to 2050 // Scenario 2: "Scramble"	B2: Business as Usual
3	2	3	BP // Energy outlook 2030 // Consumption	B2: Business as Usual
3	2	3	BP // Energy outlook 2030 // Production	B2: Business as Usual
3	2	3	IPCC // Special Report on Emission Scenarios // Scenario 1: "A1B-AIM"	B2: Business as Usual
3	2	3	IPCC // Special Report on Emission Scenarios // Scenario 2: "A2-ASF"	B2: Business as Usual
3	2	3	OPEC // World Oil Outlook 2035	B2: Business as Usual
3	3	2	EC // World Energy Technology Outlook - 2050 // Scenario 2: "Carbon constraints"	B2: Business as Usual
3	3	2	EC // World Energy Technology Outlook - 2050 // Scenario 3: "Hydrogen"	B2: Business as Usual
3	3	2	EC // World Energy Technology Outlook - 2050 // Scenario 1: "Reference"	B2: Business as Usual
3	3	3	IEA // World Energy Outlook 2011 // Scenario 1: "New policies"	B3: High Gas
3	3	3	Shell // Energy Scenarios to 2050 // Scenario 1: "Business-as-Usual"	B3: High Gas
3	3	3	ExxonMobil // The outlook for energy: a view to 2040	B3: High Gas
3	3	3	EIA // International Energy Outlook 2011 // Scenario 1: "Reference"	B3: High Gas
3	3	3	EIA // International Energy Outlook 2011 // Scenario 2: "High Oil Price"	B3: High Gas
3	3	3	IPCC // Special Report on Emission Scenarios // Scenario 4: "B2-MESSAGE"	B3: High Gas
3	3	3	IEA // WEO2011 - Golden Age of Gas? // Scenario 1: "New Policies Scenario WEO 2010"	B3: High Gas
3	3	3	IEA // WEO2011 - Golden Age of Gas? // Scenario 2: "Gas Scenario"	B3: High Gas
3	3	3	IEA // World Energy Outlook 2011 // Scenario 2: "Current policies"	B3: High Gas
3	3	3	Krewitt et al. // The 2°C scenario - A sustainable world energy perspective // Scenario 1: "Reference"	B3: High Gas

3.5.3 Analysis and integration of the obtained results into end states

Above, two different approaches to clustering the scenarios were outlined. The first method (A) involved clustering based on a statistical approach, using an agglomerative hierarchical clustering algorithm. The second method (B) aimed to cluster the scenarios on the basis of dynamics of the energy mix, using the strength of growth or decline of different aspects of the energy mix as clustering criteria. The next and last step is integrating the results from both methods to arrive at a final, combined clustering suitable as a foundation for the definition of potential long-term end-states.

The first step in integrating the clustering results from method A and B is assessing the degree of overlap that exists between the sets of clusters. This can work two ways: using the results from method A as the basis to compare the results of method B against, or vice versa. The overlap between the sets of clusters resulting from methods A and B changes significantly depending on the direction of comparison, or which set of clusters serves as the basis to compare the other set against. The final combined scenario clusters are the foundation of the definition of three distinct end-states – a rather semantic process. Therefore the dynamic characterization and qualitative nature of the clusters and scenarios therein outweigh the logic and correctness of a mathematical snapshot-based clustering. As such, the clustering suggestion resulting from method B is best suited to serve as the basis for further integration.

The first combined cluster of scenarios is rather well defined and easily distinguished from the rest: clusters A1 and A2 combined show an almost perfect match with cluster B1. Together, these clusters encompass scenarios that present revolutionary (some more than others) energy mix dynamics, involving increasing use of energy from renewable sources and improving energy efficiency. Of the nine scenarios that could potentially be included in the resulting combined cluster, only whether to include Shell's Blueprint scenario is open for discussion. Indeed, Shell's Blueprint scenario is the only scenario that changes position depending on the direction of assessing overlap between the clustering results from method A and B. However, the Blueprints scenario describes a world in which the role of energy from non-fossil sources gains importance. Therefore the scenario fits in the first combined cluster. Moreover, also the notion that a best-case final combined clustering output would yield three clusters of identical size dictates it to be included. As such, the first final, combined cluster C1 ("Renewables") is composed out of nine scenarios, as listed in Table 3.

Table 3: Composition of scenario-cluster C1 "Renewables"

Final cluster	Orig. clusters		Author // publication // scenario
C1: High Renewables	B1	A1	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 2: "Energy [R]evolution"
	B1	A1	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 3: "Advanced Energy [R]evolution"
	B1	A1	WWF // 100% renewable
	B1	A1	Krewitt et al. // The 2°C scenario - A sustainable world energy perspective // Scenario 2: "2°C"
	B1	A1	Leimbach et al. // Technological Change and International Trade – Insights from REMIND-R // Scenario 2: "400 ppm"
	B1	A1	Azar et al. // Global energy scenarios meeting stringent CO_2 constraints
	B1	A1	IEA // World Energy Outlook 2011 // Scenario 3: "450 policies"
	B1	A2	Leimbach et al. // Technological Change and International Trade – Insights from REMIND-R // Scenario 1: "Reference"
	B1	A3	Shell // Energy Scenarios to 2050 // Scenario 3: "Blueprints"

Combining the remainder of the sets of clusters poses a bit more of a challenge, resulting from the variation in the scenarios included in clustering suggestions resulting from method A and B. Clusters B2 and B3 were characterized along the lines of business as usual and gas advocacy, respectively. Extending along those lines the next step is to assess what changes and shifts may occur in the clustering composition based on the suggestion from method A.

The most obvious shift occurs for the gas-cluster: because of its characterization, cluster A4 ("Golden age of gas") should be included completely in C3. This effectively means shifting IPCC's A1B-AIM scenario. Another shifting scenario is EC's Reference scenario. Although initially included in the business-as-usual clusters A5 and B2, the trajectory of the role of gas in the energy mix allows it to be included in gas-cluster C3. Based on similar general characteristics of the dynamics of the energy mix, two other scenarios are shifted across the threshold in the opposite direction: ExxonMobil's Outlook and IEA's New Policies. As initially suggested in the clustering suggestion resulting from method A, both scenarios may belong in a business as usual cluster C2 rather than in gas cluster C3. With these shifts, the remaining two final combined clusters C2 ("Business as usual") and C3 ("Gas") are complete, the former encompassing 12 scenarios, the latter ten. The details of both scenarios' composition are outlined in Table 4 and Table 5 below.

Table 4: Composition of scenario-cluster C2 "Business As Usual"

Final cluster	Orig. clusters		Author // publication // scenario
C2: Business as Usual	B2	A3	Greenpeace // Energy [R]evolution - A sustainable world energy outlook // Scenario 1: "Reference"
	B2	A3	Shell // Energy Scenarios to 2050 // Scenario 2: "Scramble"
	B2	A3	BP // Energy outlook 2030 // Consumption
	B2	A3	BP // Energy outlook 2030 // Production
	B2	A5	EIA // International Energy Outlook 2011 // Scenario 3: "Low Oil Price"
	B2	A5	IPCC // Special Report on Emission Scenarios // Scenario 3: "B1-IMAGE"
	B2	A5	IPCC // Special Report on Emission Scenarios // Scenario 2: "A2-ASF"
	B2	A5	EC // World Energy Technology Outlook - 2050 // Scenario 2: "Carbon constraints"
	B2	A5	EC // World Energy Technology Outlook - 2050 // Scenario 3: "Hydrogen"
	B2	A1	OPEC // World Oil Outlook 2039 //
	B3	A5	IEA // World Energy Outlook 2011 // Scenario 1: "New policies"
	B3	A5	ExxonMobil // The outlook for energy: a view to 2040 //

Table 5: Composition of scenario-cluster C3 "Gas"

Final cluster	Orig. clusters		Author // publication // scenario
C3: High Gas	B2	A5	EC // World Energy Technology Outlook - 2050 // Scenario 1: "Reference"
	B2	A4	IPCC // Special Report on Emission Scenarios // Scenario 1: "A1B-AIM"
	B3	A3	Shell // Energy Scenarios to 2050 // Scenario 1: "Business-as-Usual"
	B3	A3	IEA // WEO2011 - Golden Age of Gas? // Scenario 1: "New Policies Scenario WEO 2010"
	B3	A3	IEA // WEO2011 - Golden Age of Gas? // Scenario 2: "Gas Scenario"
	B3	A5	EIA // International Energy Outlook 2011 // Scenario 1: "Reference"
	B3	A5	EIA // International Energy Outlook 2011 // Scenario 2: "High Oil Price"
	B3	A5	IPCC // Special Report on Emission Scenarios // Scenario 4: "B2-MESSAGE"
	B3	A5	IEA // World Energy Outlook 2011 // Scenario 2: "Current policies"
	B3	A4	Krewitt et al. // The 2°C scenario - A sustainable world energy perspective // Scenario 1: "Reference"

An interesting observation from the composition of the scenario clusters listed in Table 4 and Table 5 is that not all scenarios end up in the cluster one could expect them to end up in. Specifically, this applies to two scenarios published by the IEA: *Current Policies* and *New Policies*. The former ends up in cluster C3 ("gas") whereas one would expect that it would fit more in a business-as-usual-cluster. The latter appears in cluster C2 ("business-as-usual") although one would intuitively not characterize that scenario as fitting the business-as-usual description. This observation underlines the necessity of investigating a scenario's actual behaviour over time rather than assuming certain characteristics on the basis of just their title, narrative and/or description.

3.5.4 Quantitative analysis of the end states: energy mix data

Each of the three clusters of future energy scenarios defined in the previous sections has a different average energy mix resulting of the variety of scenarios the clusters are comprised of. Moreover, the type and characteristics of the scenarios included in a cluster by and large affect the shape of the average future energy mix development pathway represented by that cluster. The average future energy mix of each cluster was calculated by separately averaging the data reported for each element of the energy mix, using the original scenario data. The average energy mix composition for each timestamp is the cumulative of the averages of each element of the energy mix. The development of each cluster's average future energy mix is illustrated in Figure 10.

From the average energy mixes shown in Figure 10 it shows that the average energy mix of the 'Renewables' cluster looks markedly different from the average energy mixes of the 'Business-as-usual' and 'Gas' clusters. Moreover, the differences between the 'Business-as-usual' and 'Gas' clusters are subtle variations rather than distinct differences.

The distinct characteristic of the 'Renewables' cluster is that the absolute total average primary energy supply shows signs of gradually levelling out. By the year 2030, the most prominent increases have dwindled, leaving the total energy supply to increase only very moderately from about 550 EJ in 2030 to just under 600 EJ by 2050. This stabilization is largely the result of the combination between dwindling supplies of fossil energy and increasing supplies of energy from renewable sources. The reduction of fossil energy is strongest for oil and gas. From the year 2020 onwards, coal appears to provide a steady supply without showing strong signs of either growth or decline. From a relative perspective, the average energy mix of the 'Renewables' cluster clearly shows the substitution of non-renewables by energy from renewable sources. By 2050, the share of renewables is suggested to have increased to 40%, over double the share in the energy mix around the period 2010-2020. The loss of share in the energy mix is the strongest for oil, coming down from about 30% in the 2010-2020 period to less than 20% by 2050. The relative share of gas in the energy mix remains relatively stable at around 20% until about 2035, after which a slight decline is suggested.

The 'Business-as-usual' cluster shows a continuously increasing total energy supply, growing from around 500 EJ in 2010 to almost 900 EJ in 2050. This growth is reflected in growth for all elements in the energy mix. Growth for non-carbon based energy sources (renewables and nuclear) is remarkably strong, growth is moderate for coal and gas, and growth is least for oil. From a relative perspective, small absolute growth for oil combined with a growing total energy supply translates to a declining share of oil in the overall total energy mix. The shares of coal and gas remain largely constant at around 20% and 25%, respectively. The most prominent relative growth is for nuclear and renewable energy. Overall, the share of carbon-based energy sources decreases from about 80% in the 2010-2020 period to less than 70% in 2050, substituted by non-carbon based energy sources.

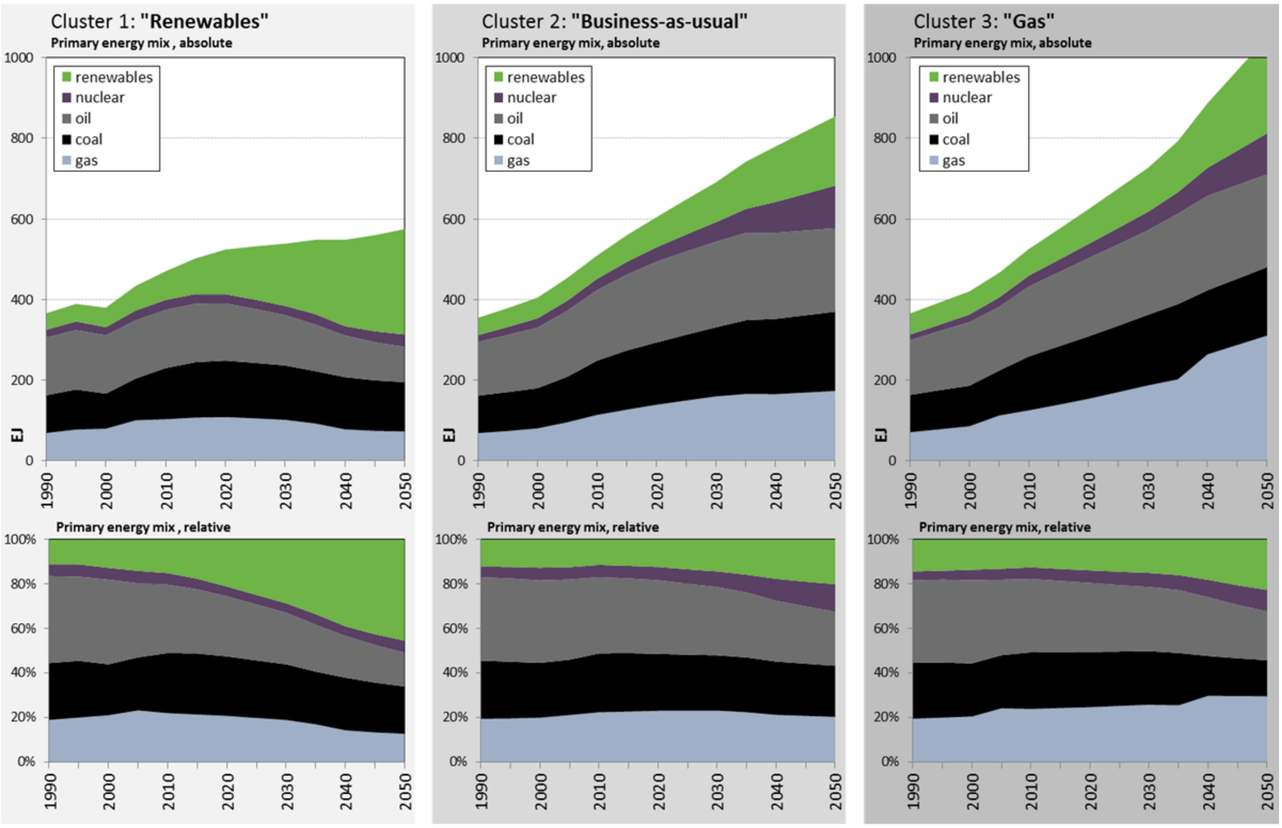

Figure 10: Average energy mixes of the three identified clusters of future energy scenarios.

In Figure 10 the upper graphs represent the average absolute contributions of the different energy sources to the energy mix. The lower graphs provide an impression of the average energy mix in relative terms.

The average energy mix of the 'Gas' cluster shows composition development that is only slightly different from the 'Business-as-usual' cluster. The most notable difference is the total energy supply increase that is even stronger than the increase in the 'Business-as-usual' cluster, and largely correlates to increasing gas supply. In absolute terms, the total energy supply increases to over 1000 EJ, about double the total global average energy supply in the period 2010-2020. All components of the energy mix increase, apart from coal. The most notable increase in this cluster is for gas, the supply of which doubles between 2010 and 2050 to over 300 EJ. The increase in gas supply is also clearly reflected in the relative composition of the average energy mix of this cluster. The shares of natural gas, renewables and nuclear all increase between 2010 and 2050, at the expense of coal and oil.

Renewables increase in all clusters, both in absolute and in relative terms, albeit more strongly in the 'Renewables' cluster than in the 'Business-as-usual' and 'Gas' clusters. Increasing shares of renewables imply declining shares of non-renewable energy sources, sometimes offset to some extent by developments for nuclear energy. The relative shares of oil and coal decline in the average energy mixes of all clusters. For gas, the relative share in the energy mix only increases in the cluster that encompasses scenarios that foresee a special role for gas. Despite absolute increases, the other clusters suggest a declining relative share of gas in the energy mix.

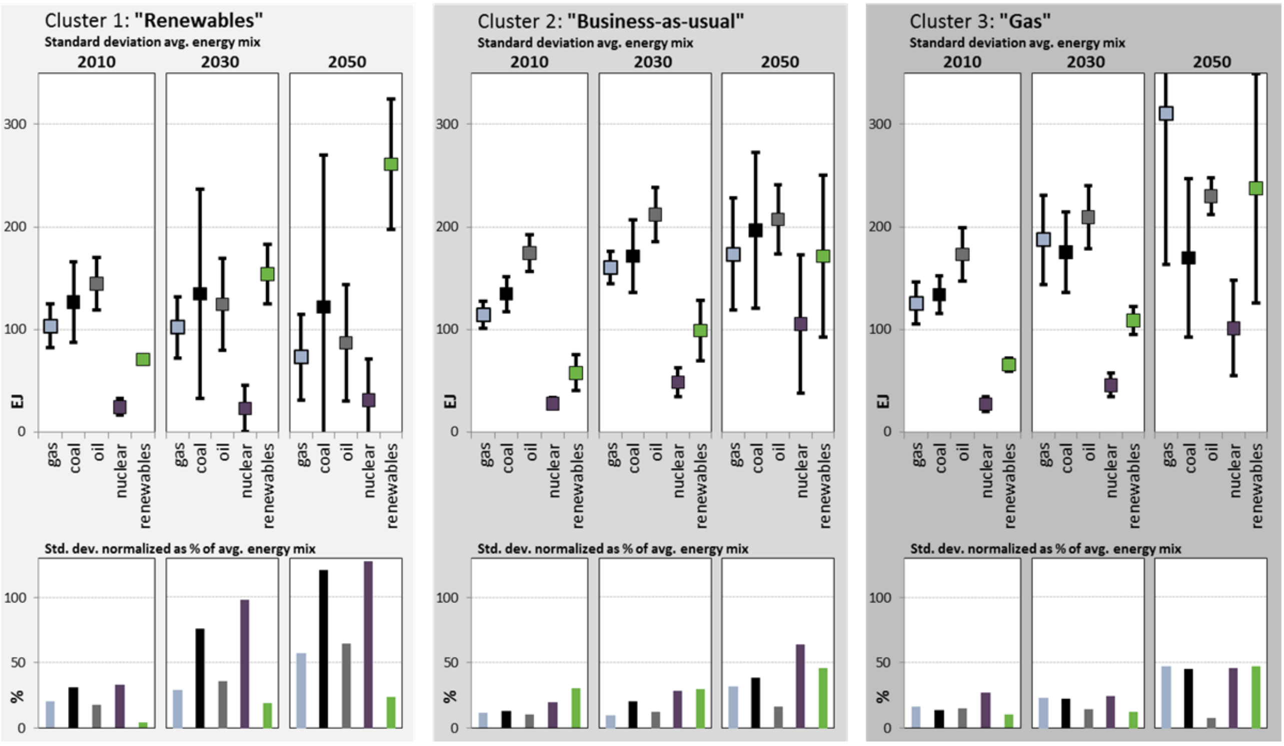

Figure 11: Standard deviations for the average energy mixes of the three identified clusters for the years 2010, 2030 and 2050.

In the figure above the upper graphs represent the absolute standard deviations calculated over the original scenario data. The lower graphs show the same standard deviations, but normalized to a percentage of the corresponding average.

Each cluster consists of a number of scenarios, each of which suggests different future energy development pathways. The average energy mixes discussed above represent certain quantitative ranges. We illustrate those ranges, or variance of possible energy system development pathways, by means of standard deviations calculated for every element of a cluster's energy mix. To facilitate comparisons within and between energy mixes of different clusters, we also normalized the absolute standard deviations as percentages of the corresponding averages. Figure 11 provides a visual representation of the absolute standard deviations associated with each cluster's energy mix, and the normalized standard deviations.

First and foremost, the variance for each energy mix element in each cluster increases substantially for longer time horizons. The variance in 2030 is larger than that of 2010, and the variance of 2050, in turn, is larger than that of 2030. The increasing variance reflects the long-term divergence of energy system development pathways suggested in the scenarios that are included in the clusters. Moreover, the increasing variance also reflects and confirms intrinsic energy system inertia: changes in the composition or behaviour of the system are obscured by the unchanged rest, and only over time may manifest themselves in high-level, abstract indicators. These notions are indicative of the difficulty and uncertainty associated with long-term future energy scenarios.

Between the three clusters, it can be seen that in terms of variance, the 'Renewables' cluster also stands apart from the other two clusters because of a markedly larger overall variance, both in absolute terms as in relative terms of normalized standard deviations. The variance indicators in the 'Business-as-usual' and 'Gas' clusters show similar fingerprints. These differences and similarities may be general indicators of uncertainty or agreement between future energy scenarios with different characteristics, backgrounds or themes. Apparently, scenarios suggesting somewhat substantial departures from existing energy trends, such as the scenarios typical to the 'Renewables' cluster, can be associated with much larger variance or uncertainty, and thus a wider bandwidth of future energy development pathways, than their more conservative counterparts as typically found in the 'Business-as-usual' cluster or, in a pinch, the 'Gas' cluster.

On a lower level, the contribution of energy from renewable sources seems to be associated with a reversed subdivision of larger and smaller variance. In the 'Renewables' cluster, the variance for renewable energy is smaller both in absolute as in normalized terms than it is for the other two clusters. Moreover, in the 'Business-as-usual' and 'Gas' clusters, the variance for renewable energy is among the largest of all elements of the energy mix, especially for longer time horizons. This may be indicative of a trade-off of variance and (un)certainty with regard to the energy sources that matter in the long term future, depending on the contexts of different scenarios. Renewable energy oriented scenarios appear to take a certain amount of renewables as guaranteed and vary the non-renewable energy padding necessary to meet energy demand. For scenarios not explicitly focused on renewable energy, it is the contribution of non-renewable energy that forms the foundation of the future energy mix, supplemented by varying amounts of renewable energy to complete the scenario's outlook on the future energy supply.

In the 'Renewables' cluster, the variance for coal and nuclear energy are the largest. This implies that scenarios with a focus on more sustainable future energy systems agree least on the roles of coal and nuclear energy. The variances, and implied agreement, on natural gas and oil increase moderately over time and on the long run occupy a position between the relative agreement of renewable energy and the large uncertainty associated with coal and oil. In the 'Business-as-usual' and 'Gas' clusters, the variance for oil remains notable small, indicative of certainty and agreement on the future role of oil in the energy mix. The other elements of the energy mix in both clusters all show similar variance growth patterns over time. The variance of natural gas is the exception: as much as the absolute contribution of natural gas in the average future energy mix of the 'Gas' cluster is highest, so is the associated variance. In fact, the variance of gas in the 'Gas' cluster is sufficiently large to partially overlap the bandwidth of pathways suggested in the 'Business-as-usual' cluster.

3.5.5 Quantitative analysis of the end states according to the PESTE categories

The three final clusters, identified on the basis of the quantitative analysis, are further analysed on the basis of the PESTE categories in order to identify commonalities and discrepancies. Since the numerical grouping already provided robust groups, the contextual grouping involves an analysis of the common variables within the groups. The qualitative analysis of the end states is performed on the basis of the storylines, as elaborated in the preliminary analysis phase (see Section 3.5.1).The storylines provide insight into the driving forces behind the energy mix and offer a structured approach in qualitatively analysing the scenario groups.

Preliminary comparison of the contextual aspects per group reveals a highly dispersed level of available information. Therefore seven contextual aspects have been identified, which are deemed important and generally available: GDP, Population, Carbon tax, applying CCS, Efficiency, Electrification and CO_2 emissions. The results can be seen in Table 6 below.

Table 6: Seven important driving factors of the end state C3: Gas

#	Author	Scenario name	GDP	Population growth	Carbon tax	CCS	Efficiency	Electrification	CO_2 emissions
1	EC	Scenario 1: "Reference"	Quadruple by 2050	8,9 billion by 2050	30 €/t in 2050	N/a	N/a	Yes	Double
2	IPCC	Scenario 1: "A1B-AIM"	2,9% p.a.	9 billion by 2050	N/a	N/a	Yes, Technology improvement and efficiency	N/a	N/a
3	Shell	Scenario 1: "Business-as-Usual"	N/a	9 billion by 2050	N/a	N/a	N/a	N/a	N/a
4	IEA	Scenario 1: "New Policies Scenario WEO 2010"	3,2% p.a.	8,5 billion by 2035	$50/t in 2035	Yes	Yes, Technology improvement and efficiency	N/a	35,4 Gt by 2035. 0,7% p.a.
5	IEA	Scenario 2: "Gas Scenario"	3,4% p.a.	8,5 billion by 2035	$50/t in 2035	Yes	Yes, Technology efficiency	N/a	35 Gt by 2035
6	EIA	Scenario 1: "Reference"	2,6%	8,4 billion by 2035	No	N/a	Capacity utilization nuclear, unconventional and conventional recovery.	Yes, moderately	1,3%/a
7	EIA	Scenario 2: "High Oil Price"	4,0%	8,4 billion by 2035	No	N/a	N/a	No	1,8%/a
8	IPCC	Scenario 4: "B2-MESSAGE"	2,2%	9,4 billion by 2050	n/a	N/a	Less than A1 & B1, higher than A2.	N/a	N/a
9	IEA	Scenario 2: "Current policies"	3,6%	8,6 billion by 2035	$45/t in 2035	Yes	End-use, energy production & supply. Supply more cost-efficient, leading to new & cleaner production/supply.	Yes	0,9%/a
10	Krewitt et al.	Scenario 1: "Reference"	N/a	N/a	N/a	N/a	N/a	N/a	N/a

Additionally, an overview of all scenarios per PESTE category is created, enabling comparison of other variables than addressed above. The observations of the contextual grouping are described per end state in the following chapter.

3.6 End states

Based on the quantitative analysis of the energy mix available in the scenarios, the scenarios are grouped into three end states. These end states are further analysed from a qualitative aspect, in order to identify the commonalities and discrepancies. The end states, as resulted from both quantitative and qualitative analysis, are described below.

3.6.1 End state: Renewables

The end state 'Renewables' (RES) is characterized by the following factors:

- *Political:* Most effective policies and measures to promote RES, long term perspective, stringent regulations and in increasing cost of CO_2.
- *Economic:* Global population and GDP increases, investment in infrastructure increases.
- *Social:* Climate change awareness shift, increasing tensions between rural and urban communities.
- *Technological:* Significant development and maturity of the existing technologies, efficiency increase, modal shift in transport, increased R&D expenditure and innovation.
- *Environmental:* Significant emissions reduction after 2020.

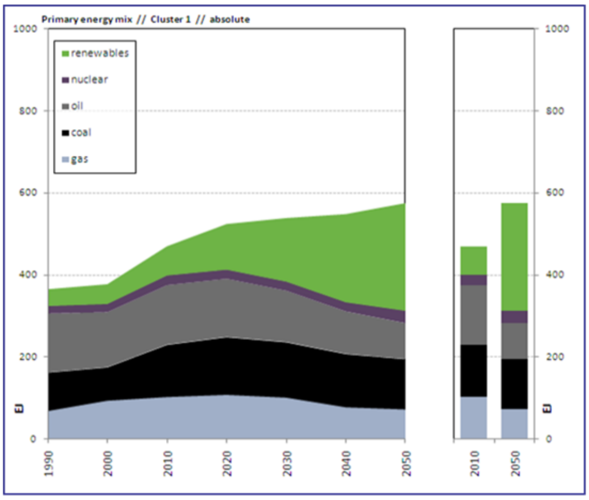

Figure 12: Evolution of the Energy Mix in End State C1: Renewables

The energy mix of the 'Renewables' end state is described in Figure 12 above. In this end state the world energy demand is presumed to be significantly lower than in other two end states. Renewables play an increasingly important part, becoming the major source in both absolute and relative terms by 2050.

In the 'Renewables' end state it is assumed that the level of political and/or policy intervention will be high. Governments take action to steer the energy system away from fossil fuels towards more renewables with a variety of policy measures. Especially the scenarios from environmental NGOs assume strong national and international policy actions, such as a forced phase-out of coal and an international framework for investing in climate change mitigation. It is assumed that governments invest heavily in infrastructure to facilitate renewables and in R&D to improve renewable technology. Most scenarios in this end state assume either a global or a regional CO_2 pricing system. The US loses its dominant position in the geopolitical system: it shares political dominance with China.

Most scenarios assume steady global economic growth, largely coming from developing countries. GDP growth is exogenous to the scenarios. More global economic integration with a decoupling of between economic growth and fossil fuels is assumed. It is expected that eventually economic growth will decouple from energy demand growth. An increasing price of CO_2 leaves no room for investments in fossil power generation.

All scenarios expect an increasing world population, reaching about 9 billion in 2050. The growth in population is mostly from the developing regions. Awareness shift by the public pushes for more political action to reduce emissions. Fear of climate change creates political turbulence with tensions between rural and urban communities, especially in countries with poor governance. Some scenarios assume a change in behaviour by the public in order to decrease energy consumption: such as reducing meat consumption or reducing mobility needs.

The environmental NGOs assume, besides a phase-out of fossil fuels, a phase-out of nuclear energy. Significant improvements in the efficiency and costs of renewable technologies are assumed due to heavy public R&D expenditures. The environmental NGOs assume almost a complete phase-out of fossil power generation. Other scenarios assume the implementation of CCS to reduce emissions. Some improvements are expected in utilizing hydrogen as an energy carrier, but no other fundamental breakthroughs are expected within the scope of the end state. Due to the increasing global integration, innovation spreads quickly between countries, increasing the use of more efficient technology and renewable technology. Information technologies stimulate the use of more demand side management solutions. Biomass plays a big role in most of the scenarios. Furthermore, wind and solar are mentioned as promising renewables.

Global carbon emissions peak around 2020 and begin to decline after that as an effect of international efforts to reduce emissions. One scenario assumes a growth in emissions because coal will increasingly be used when oil and gas reserves become depleted.

3.6.2 End state: Business as usual

The end state 'Business as usual' (BAU) is characterized by the following factors:

- *Political:* Focus on short term national security, developed countries assume more responsibility for climate change, RES support continues, increased CO_2 price.
- *Economic:* Global population and GDP increase and drive energy demand (especially in developing countries); energy efficiency grows in developed countries.
- *Social:* Income redistribution affects energy efficiency in developing countries, increased environmental consciousness.
- *Technological*: Increased energy efficiency, progress in CCS, hydrogen, and unconventional fossils.
- *Environmental*: Moderate emissions constraints.

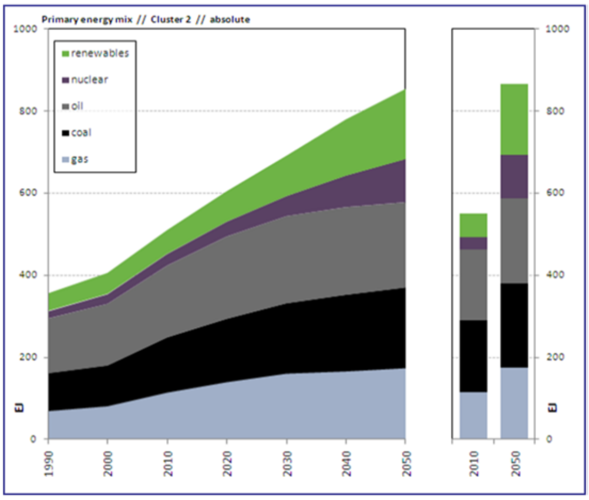

Figure 13: Evolution of the Energy Mix in End State C2: Business as Usual

The energy mix of the 'BAU' end state is described in Figure 13 above. In this end state the world energy demand is presumed to be significantly higher than in 'Renewables' end state, but still lower than in 'Gas' end state. Fossil fuels maintain their dominant position, regardless of both absolute and relative growth of renewables.

This end state is based on an extrapolation of current trends without major events that change the current path to increasing the use of all energy sources.

Developed countries assume a higher responsibility for preventing or mitigating climate change. There are policies in place to promote renewables (but on a smaller scale than in the renewables end state). In some regions in the world there is a CO_2 pricing system in place, but it is not assumed to be a global system. The political focus is more on short term national energy security. Major producers see their power increasing on the international arena. One scenario uses only policies that are already in place, another mentions a cautious implementation of recently announced commitments.

Global GDP increases around 3% per year, but energy intensity of GDP decreases gradually due to efficiency and high energy prices. GDP growth is assumed to be the main driver behind energy demand. Efficiency improvement is identified as a strong factor in reducing energy demand growth. The increase in demand for energy is due to the developing countries. OECD has a slightly lower demand due to efficiency.

World population is expected to rise to 9 billion in 2050. Income redistribution in developing countries could adversely affect energy efficiency and have a major impact on world markets.

The technological outlook in this end state varies between the scenarios. One scenario sees a large role for CCS in the future. Another explores the possibilities of hydrogen as energy carrier. Improved engine efficiency reduces energy demand in developing countries. Technologies in unconventional gas production help to increase supply. Due to less global economic integration as compared to the renewables end state, innovation spreads slower.

All scenarios assume an increase in carbon emissions. There are some efforts to reduce emissions, such as a carbon price or CCS in some regions. However, these do not off-set the increase in use of fossil fuels. On a local or regional level there is attention for pollution, environmental damage, however there is no international climate agreement.

3.6.3 End state: Gas

The end state 'Gas' is characterized by the following factors:

- *Political*: Focus on short term national security, RES support continues, increased CO_2 price.
- *Economic*: Global population and GDP increase, developing countries catch up in economic growth, high commodity prices.

- *Social*: Concerns about energy security.
- *Technological*: Progress in unconventional fossils' recovery, energy efficiency, CCS, no dominant technology.
- *Environmental*: Global emissions increase, no significant international agreements to reduce emissions in place.

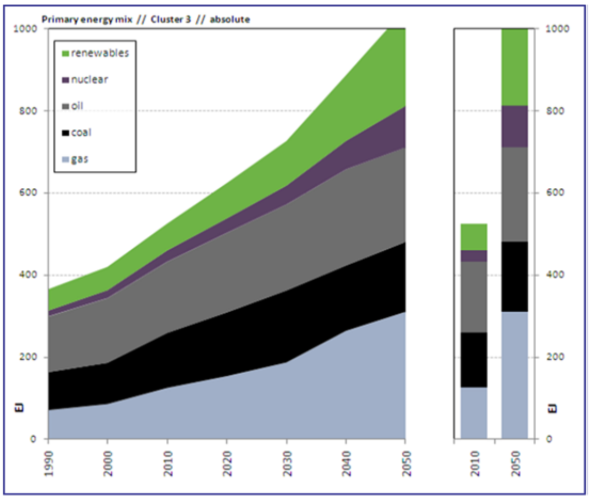

Figure 14: Evolution of the Energy Mix in End State C3: Gas

The energy mix of the 'Gas' end state is described in Figure 14 above. This end state has the largest increase in energy demand up to 2050 (compared to other end states). Comparable to the 'BAU' end state, fossil fuels maintain their dominant position, regardless of the growth of renewables. Notable for this state is the role played by gas: it becomes the main energy source in both absolute and relative terms by 2050.

Just as in the 'BAU' end state there is no international climate agreement in this end state. Some scenarios assume a CO_2 pricing system to be in place in OECD countries. Environmental policy is focused on the national or local level. The scenarios diverge on the political support for nuclear energy: some assume an extension of the lifetime of current nuclear power generation, and other scenarios assume a gradual phase-out.

Most of the scenarios assume a global GDP growth of over 3% per year. Europe experiences the slowest economic growth of all regions. Non-OECD countries have the highest GDP growth rates and also the highest increase in demand for energy. Due to the increasing demand for energy, energy prices are also gradually increasing. Oil prices are expected to increase faster than gas prices, therefore contributing to the competitiveness of gas. Lower gas prices are a result of growth in unconventional gas production.

World population increases to around 9 billion in 2050, with most growth coming from non-OECD countries. One scenario mentions the possibility of local social unrest due to resource scarcity and/or environmental damage.

Technological improvements increase the lifetime of fossil fuels. Oil and gas reserves and their recovery rates are increased. Improvements are realized in shale gas, coal bed methane, tight gas, underground coal gasification, CCS technologies and further developments of LNG markets. Some scenarios mention the adoption of electric vehicles, while another scenario assumes near-zero advances in transport technology. Most scenarios do assume some level of efficiency gains in energy use. The global share of gas in the energy mix increases with 33% in 2050, while the share of coal and oil declines. Furthermore, because some scenarios explicitly mention developments in gas technologies this end state is labelled the 'Gas' end state.

Global emissions increase significantly, however the increase is not equal between the regions. Emissions increase mostly in non-OECD countries. In Europe they decrease due to efficiency and the use of cleaner technologies.

3.7 Conclusions

This chapter identified three post-energy transition end states representing dominant views on energy futures in published literature. The end states are the result of analysis and grouping of various energy development scenarios, and are used as reference futures in subsequent chapters of this report. The end states are:

- *Renewables:* The Renewables end state is characterized by a high share of renewable energy sources in the world-wide energy mix alongside a sharp decline in energy demand growth towards the future.
- *Business As Usual (BAU):* In the BAU end states, the future (relative) energy mix is roughly the same as the present energy mix. However, a higher absolute energy demand is envisaged.
- *Gas:* The Gas end state assumes a significant portion of the energy demand to be fulfilled by natural gas. Furthermore, energy demand is expected to rise steeply towards the future.

The end states are based on an analysis and subsequent grouping of pre-existing scenarios describing various energy futures. These scenarios were aggregated through an extensive literature research and subsequent selection process. To compensate for the apparent unavailability of suitable pre-existing methodologies, an explorative approach was used to devise a methodology to analyse and group the relevant scenarios as per the intentions of this research. This approach was presented and explained in this chapter.

During this explorative process, several ways for comparing and grouping scenarios were investigated, both qualitative and quantitative. The two most promising means, a hierarchical clustering method and grouping method based on analysing and comparing growth rates, resulted in a fairly similar grouping whereby only a few scenarios were grouped differently. This process led to the eventual identification of the three aforementioned end states.

For each of the three identified end states, the average energy mix and the variability therein were assessed. From the average energy mixes it appears that the quantitative difference in future energy development between the 'Business-as-usual' end state and the 'Gas' end state is somewhat subtle, and mainly found in the role of natural gas in the future energy mix. Between these end states and the 'Renewables" end state, the difference is more substantial. There, differences include a stabilizing overall energy demand in the long-term for the 'Renewables' end state, and a marked decline in the role of non-renewable energy sources relative to a strong increase in the role of renewable energy. The variability is highest in the 'Renewables' end state. This higher variability may indicate that there are various ways to achieve an end state based on renewable energy sources and as such no clear or single pathway exists. As a consequence these different pathways may introduce more uncertainty about the way to reach such an end state. Also, this may imply that the lack of a clear vision and direction, and decisions may result in a more 'middle of the road' outcome instead of the envisaged or desired end states based on renewable energy sources.

Key findings:

- Using a tailor-made methodology, a large number of previously published future energy scenarios from a wide variety of backgrounds has been reviewed, analysed and grouped according to similarities in suggested energy futures to form three clusters: 'Renewables', 'Business-as-usual' and 'Gas'. Each of these clusters represents a differently characterized potential energy future, and post-energy transition end-state. Moreover, the three end states represent the dominant views on energy futures in recent future energy scenario literature.
- All three end states suggest a more important role for renewable energy in the energy mix, albeit in the 'Renewables' end state the suggested growth of renewable energy is stronger than in the other two end states. Conversely, the relative share of non-renewable energy in the energy mix declines in all three end-states.
- The contribution of natural gas in the future energy mix only increases in the 'Gas' end state. In the 'Business-as-usual' end state, the role of natural gas stabilizes in the long-term. Natural gas sees a decline in both the absolute and relative contribution to the energy mix in the 'renewables' cluster.
- Variance and uncertainty with respect to the average energy mixes are distinguishing characteristics between the 'Renewables' end state and the other two end states. The larger general variance associated with the 'Renewables' end state may be indicative of greater uncertainty and disagreement on the precise details of future energy pathways that involve a larger share of renewable energy.

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4 BOTTOM-UP IMPLICATIONS OF ENERGY END STATES IN EU IN 2050

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4.1 Introduction

The methodology to determine the 3 end states as described in Section 3.5 can be classified as top down. The consequences as a result of the choices made, are hard to see with this approach. However, it is of crucial importance to get a better idea of the impact of this top down scenario. The following aspects are deemed important:

- The impact on the system as a whole
- The impact on the inter-relations between sectors and energy conversion (e.g. micro CHP)
- A view on a more detailed level in the defined sectors
- A check on the validity and/or the bottlenecks like land use for biomass production, which may arise

To realize this reality check, an energy flow model was developed which will be discussed briefly in this section (see Appendix A for a more detailed discussion). The model is referred to as the 'Big Picture' model.

Figure 15 shows how calculations are carried out in the Big Picture model. First, the energy demand per sector in a certain year is given as a starting point of the calculations. Per sector the demand for energy carriers is determined by the ratio of used technologies (Agriculture, Transport, Households, and Commercial & Services) or simply by sub-sectors and energy demand (Industry). The format of these data is mainly obtained from the IEA Energy balances. All calculations are done on an hourly basis.

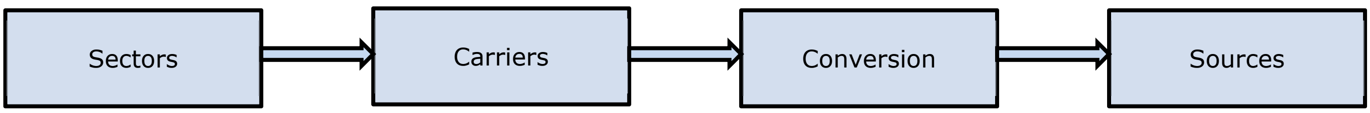


Figure 15: Calculation sequence Big Picture energy flow model

To convert carriers out of sources several conversion options are available. Besides the power sector, in which multiple conversion technologies exist, other energy carriers can also have multiple sources. For example:

- Methane can be produced by gasification of biomass and fossil sources or by digestion of biomass.
- Motor fuel can be produced from oil and biomass.
- Hydrogen can be produced by steam reforming or electrolysis.

In addition, storage of electricity is also regarded as a conversion. The final outcome of the model is the amount of resources needed to fulfil demand. In case of electricity, the production from intermittent sources are handled is a special way. When there is a surplus of electricity, the electricity is stored first if possible and otherwise if allowed converted to hydrogen using Power-to-Gas technology. This hydrogen can be used directly in for example fuel cell cars, as feedstock or for the production of methane. If, after all these options, still a surplus exists, the remaining electricity will be dumped. In case an extra amount of hydrogen (e.g. more methane from renewable sources) is needed, extra intermittent renewable sources can be placed to produce the needed electricity.

4.2 End states description

In this section, three end states are described that are derived in Section 3.5. These end states are worked out in more detail here and are used to do an infrastructure analysis in Chapter 5.

4.2.1 General assumptions

The end states described here cover all EU-27 countries (thus, without Norway and Switzerland). As described in Appendix A, the format of the IEA balances is used as a basis. This means that there are five sectors: (1) industry, (2) agriculture/forestry, (3) transport, (4) residential and (5) commercial & public services. Fishing is added to the agricultural sector. Moreover, the industrial sector is divided into 13 sub-sectors. The relative contribution of these sub-sectors and their fuel use are kept mainly constant. Therefore, all increase or decreases (in terms of percentage) are compared with 2010 data. Since the RES and BAU end states, as based on the EU Road Map 2050, only differentiate the sectors industry, transport, and residential & tertiary, the agricultural sector is added to the industrial sector. The commercial & public services sector from the IEA tables is similar to the tertiary sector as in the EU road map.

A surplus of intermittent electricity can be stored in Pump Hydro Storage (PHS) plants. The installed capacity is obtained from Gutiérrez et al.[1].

4.2.2 RES end state 2050

This end state is characterized by high penetration of Renewable Energy Sources (RES) and based on the High RES scenario in the EC roadmap for 2050[2]. Energy reduction strategies lead to a decrease in final energy demand of 31%. The primary energy savings are even a bit higher: 38% (see Figure 16). Nuclear and fossil sources are all reduced strongly, respectively by 81% and 70%. These energy sources are mainly replaced by electricity from wind, solar and biomass (see Figure 17). Biomass is either used directly or to produce biofuels and bio-methane. The share of renewable sources in the primary consumption increases from 9% to 60%.

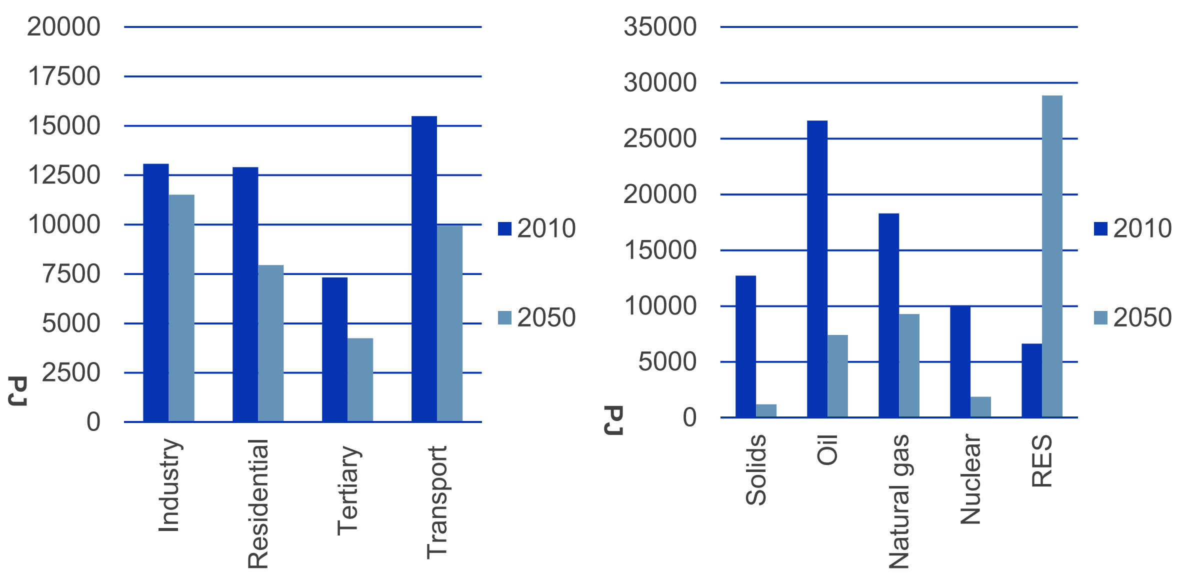


Figure 16: Final energy demand per sector (left) and primary consumption by fuel (right) for the RES end state.

Comparing the different sectors shows that mainly the residential and the tertiary sector show a large decrease, respectively 38% and 42%. This is predominantly due to insulation programs and the introduction of heat pumps and micro-CHP. Final demand in the transport sector is strongly reduced as well by 36%. This is mainly caused by efficiency programs and the introduction of electric vehicles (EV).

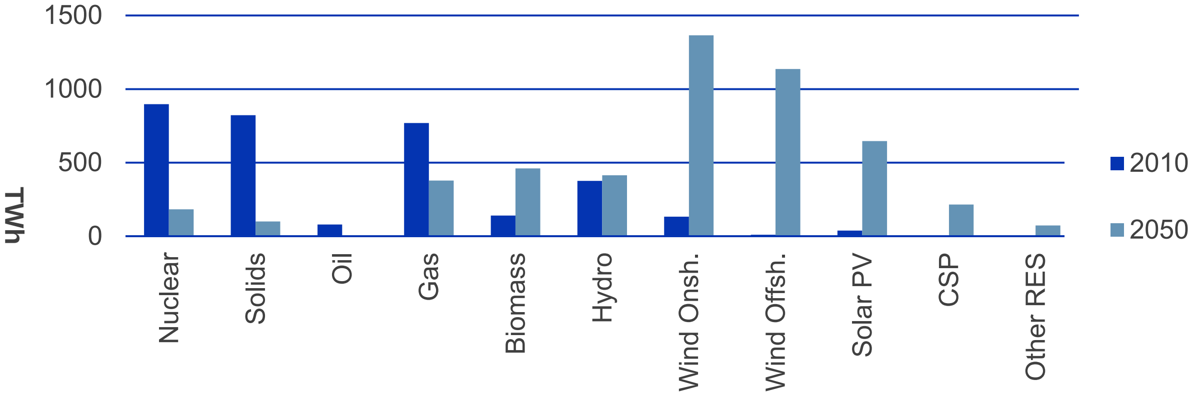


Figure 17: Electricity production by source for the RES end state.

Since the RES end state has the largest impact on the energy system some additional analyses are made. All three end states are calculated for the EU-27 as a whole, but for the RES end state all 27 countries are calculated separately. This gives some results worthwhile to elaborate on in the context of this research.

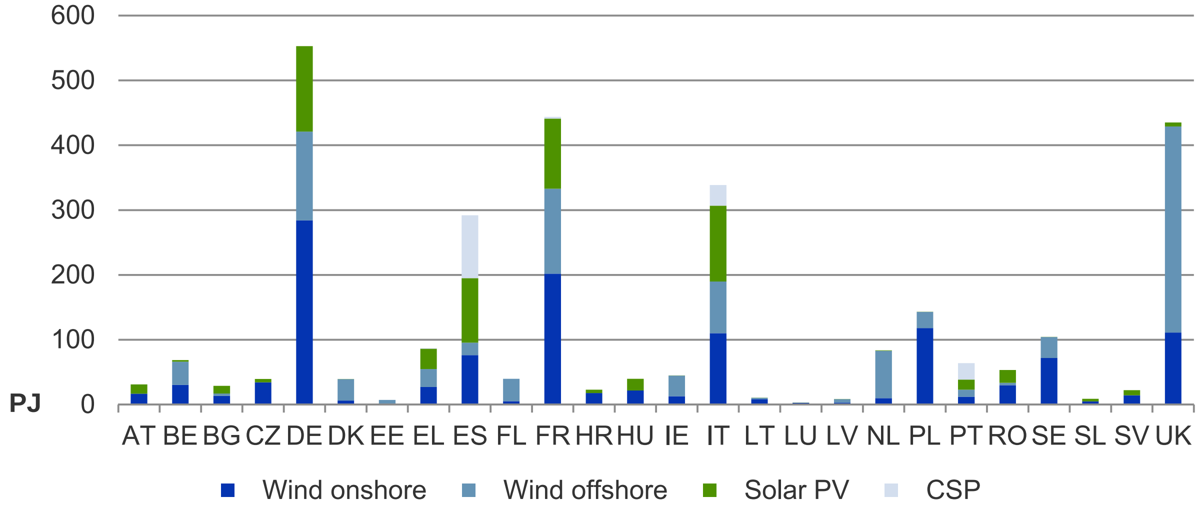


Figure 18: Intermittent sources for electricity production. CSP is assumed to be intermittent which is not necessarily the case.

Figure 18 shows the absolute generated electricity by intermittent sources per country. In percentage terms, the share of intermittent sources in the total electricity production varies between 15.5 % for Luxembourg and 81.0% for Greece.

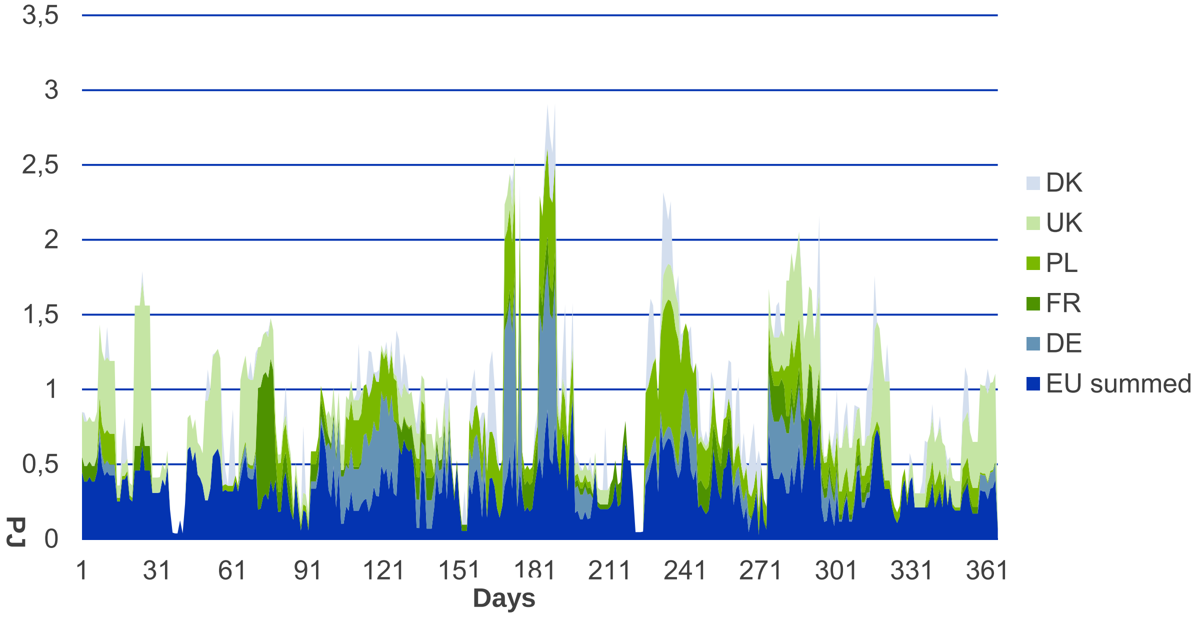


Figure 19: Surplus of electricity for five EU countries with the highest surplus. 'EU summed' is the surplus of the other 22 EU countries. 'EU total' is the surplus if the EU is calculated as one region.

Figure 19 shows the difference between the effect of calculating the surplus of electricity for the EU as a whole or for the separate countries. The surplus for the EU as a whole is negligible (0.14 PJ, only for the days 273..279), while the cumulative surplus for all separate countries it is about 340 PJ. The absolute values in Figure 19 are not automatically an indication of an unbalanced grid. Therefore, the relative surplus is more important (surplus/total electricity). The values differ between 0 (e.g. Austria and Spain) and 1.05 for Estonia. The countries with a low surplus/total electricity ratio are countries with a low and/or balanced set of intermittent sources. The best example here is Spain which has 66% fraction of intermittent sources in the total electricity generation but has still no surplus. The large amount of PHS capacity available in Spain was not used. The intermittent sources in Spain are about one-third wind energy, one-third solar PV and one-third CSP. Countries like Estonia rely fully on wind and have no PHS for buffering.

4.2.3 BAU end state 2050

This end state is based on the reference scenario in the EC roadmap for 2050[2]. It is characterized by a small growth (4.7%) of the final energy demand, while a small decrease (1.0%) in primary energy consumption is projected. Only the demand in the residential sector decreases while the others increase (see Figure 20). The increase in electricity generation is much larger: 44.6%. To match this increase, nuclear power increases with 40.7%, thermal power generation with only 1.5% and renewables sources (excl. biomass) more than triples. The share of renewable sources in the primary consumption increases from 9% to 20% as shown in Figure 21. In the left graph, the final demand per sector for the BAU end state is given. The primary consumption by fuel is shown in the right graph

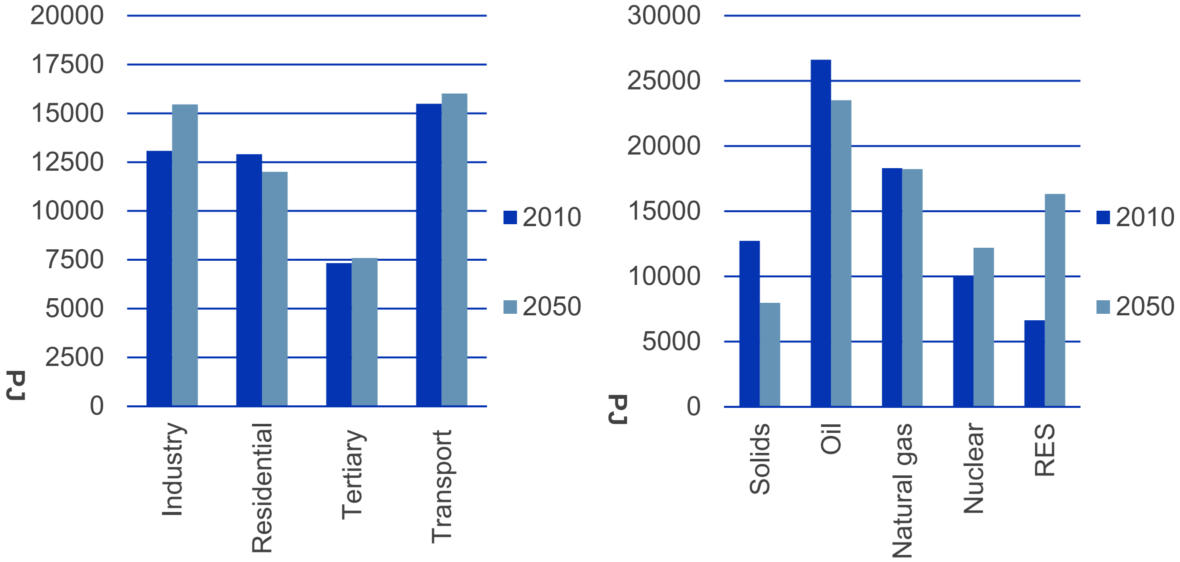


Figure 20: BAU end state primary consumption by fuel and the final demand per sector

A more detailed look to some sectors shows that the transport sector does not change significantly and thus stays mainly oil-based. The built environment (i.e. households and the tertiary sector) made a switch to more district heating, micro-CHP and heat pumps. However, the reduction in the demand for space-heating in households is limited to 17%, while the reduction in the tertiary sector is fully compensated by growth in this sector. Figure 21 shows the electricity production by source. In this end state, an increase of nuclear energy and wind energy is expected.

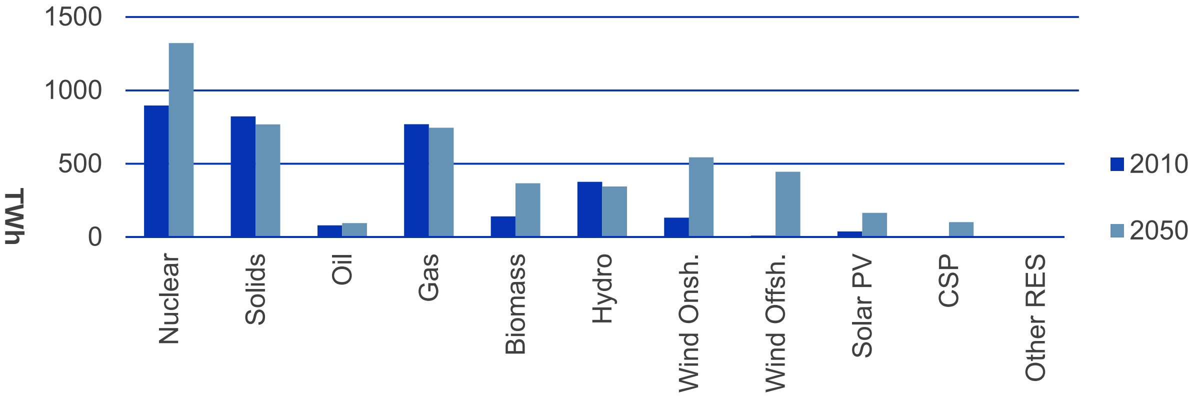


Figure 21: Electricity production by source for the BAU end state.

4.2.1 GAS end state 2050

The GAS end state is based on the Long-term outlook for gas to 2035[3]. Data for the year 2050 are obtained by linear extrapolation of the 2010 to 2035 data. This end state intensifies gas use in the residential and tertiary sector at the expense of coal, oil, wood, and electric stoves. On the other hand, buildings will be insulated and gas-fired heating equipment will become more efficient. This results in a stabilisation of the gas demand in this sector. The same goes for the industrial sector (see Figure 22). The power sector shows an absolute increase in gas demand. These gas-fired power plants are used to balance the electricity grid in countries with high percentage of intermittent sources. In addition, these plants reduce the CO_2 emissions since they replace coal-fired power plants (see Figure 23).

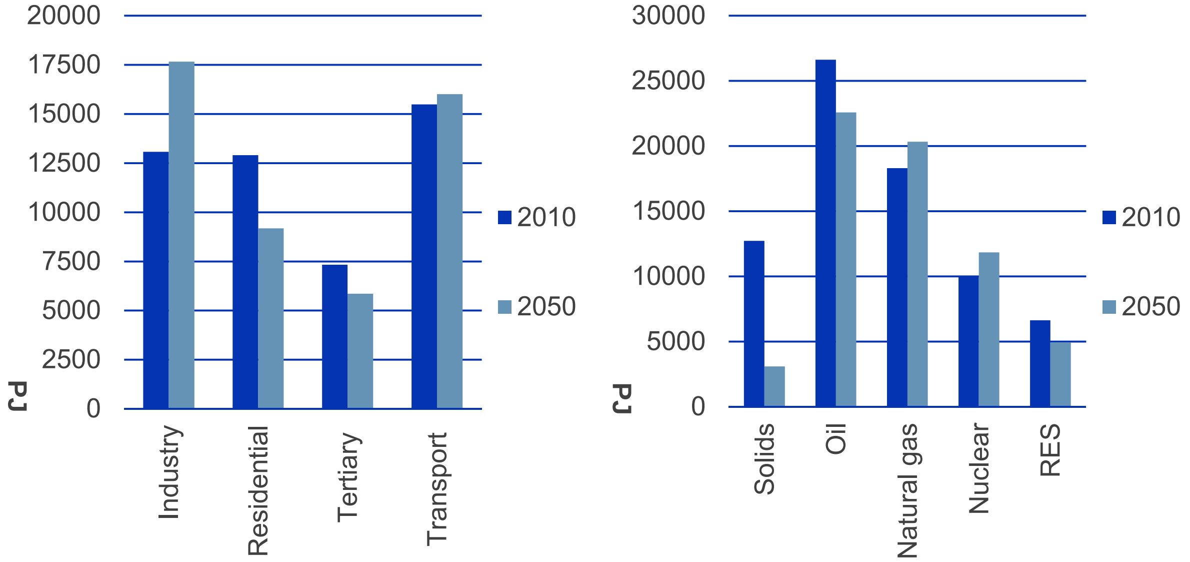


Figure 22: Final consumption by sector (left) and primary consumption by fuel (right) for the GAS end state.

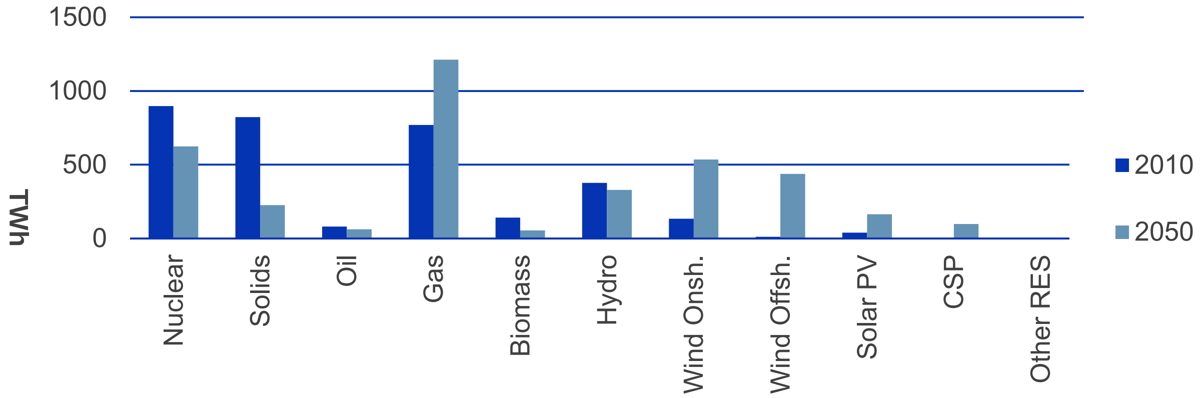


Figure 23: Electricity production by source for the GAS end state.

4.2.1 Three end states compared

When the three end states are compared, the differences become clear. The energy reduction strategies in the RES end state and the high penetration of renewable results in a substantial lower CO_2 emission of 909 Mton compared with 2574 Mton in the BAU end state (see Figure 24).

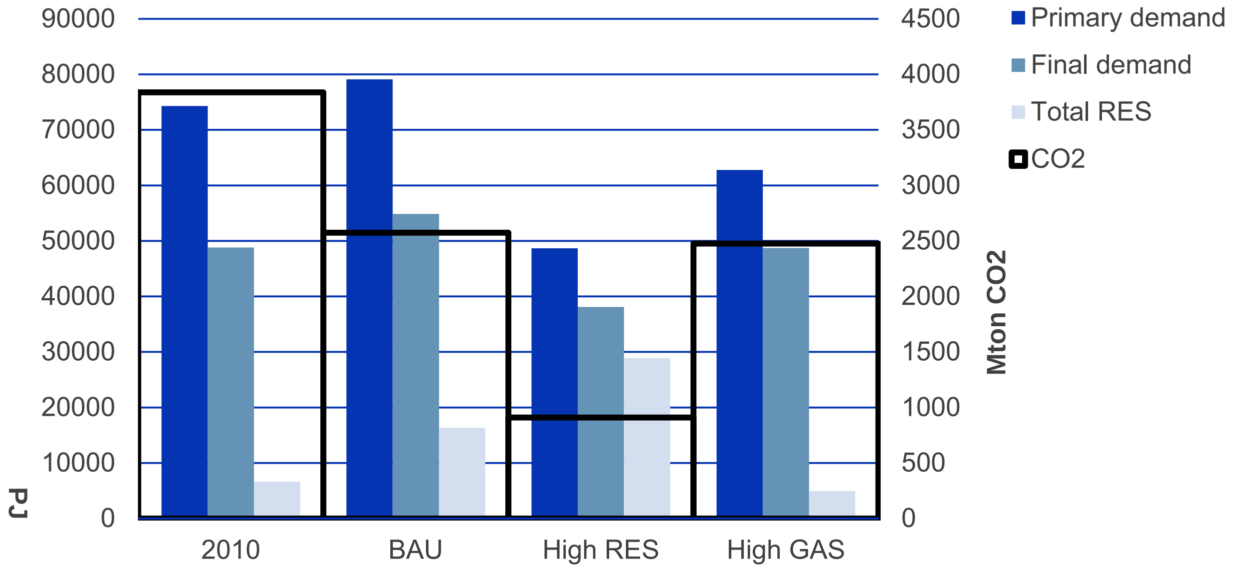


Figure 24: Comparison between the 2010 situation, the BAU, the RES, and the GAS end states on four indicators. The CO_2 emission is linked to the right axis.

Figure 25 shows the surface (on land or sea) needed for the renewable energy sources. Some remarks have to be made here. Solar PVs are for a large part installed on roofs. In the RES scenario however suitable roofs become scarcer so part of this land use is additional and cannot be used for other purposes. Wind onshore land use is the surface of the land that will be covered by wind turbines. The land beyond these turbines however can be used for other purposes like agriculture or solar PV farms. The land use for biomass is more complex. For first generation energy crops, like rape seed and sugar beets, average yields are used. For co-digestion, only 50% of the land use is attributed since often a part of the co-digestion materials come from agricultural residues. For energy crops used for gasification and as co-combustion in electric power plants, it is assumed that these crops are produced in an extensive way. This means that artificial fertilizer and pesticides are not used. The GAS scenario uses almost exclusively natural gas which explains the lowest land use for biomass.

From Figure 25 it becomes clear that biomass has by far the largest impact on land use. The land use of onshore wind is about 200 times smaller. The total land use for biomass is about 50% of the agricultural area in the EU-27 countries. Thus, from an energy security point of view, this is not a desirable solution.

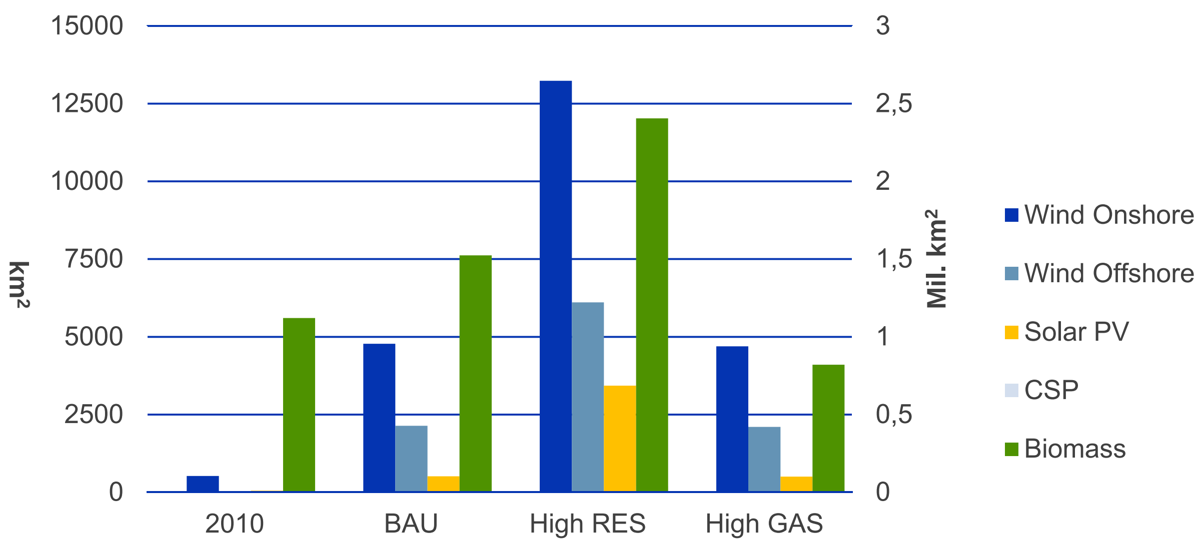


Figure 25: Land and sea surface use for five renewable energy sources. The biomass land use is linked to the right axis.

Key findings

- Shifting energy use to land use is a consequence of the implementation of large amounts of renewable sources. This especially the case for biomass (see also Chapter 6)
- The RES end state has the largest impact on end users. Electrification, as a result of the choices made in this end state, is reflected mainly in the transport (EV's) and the residential and tertiary sectors (space heating).
- On the RES and GAS end state, the industrial sector does not change much compared with the BAU end state. There are no major changes in the production structure and activities (which is a limitation).

4.3 References

[1] Gutiérrez, M.G. and R.L. Arántegui (2013). Assessment of the European potential for pumped hydropower energy storage. JRC scientific and policy reports, report EUR 25940 EN

[2] EC (2011). Energy roadmap 2050 Annex 1 Scenarios – assumptions and results. SES(2011) 1565, Brussels

[3] Eurogas (2013). The long-term outlook for gas to 2035. Brussels.

5 IMPLICATIONS ANALSYSIS GAS INFRASTRUCTURE

Authors: Maurice Vos, Ivan Wapstra, Huub Roeterink – DNV GL

5.1 Introduction

In this chapter the results of analysis on the suitability of the existing European gas infrastructure to support the gas supply and demand situation under each of the three end states are presented. The analysis is conducted by means of a European gas infrastructure model. This model is explained in the next section. Afterwards, the assumptions regarding gas demand and supply are presented. The chapter ends by presenting and discussing the results of the analysis.

5.2 The ENIGMA model

5.2.1 Modelling approach

For this project, the DNV GL gas model ENIGMA[1] is used. The model is an aggregated representation of the existing European gas value chain. The model optimizes the dispatch of each infrastructure element in the gas value chain on a daily basis by minimizing the total cost while assuring that supply and demand are matched. The model can be used to test whether existing cross-border capacities and storage capacities are sufficient. Therefore, it includes actual cross-border capacities to represent the current pipeline system and all relevant European gas storages and LNG terminals. For the analysis of the end states, it also includes those projects, pipeline, LNG terminals and storages for which a final investment decision (FID) has been taken. Figure 26 illustrates the modelling approach used.

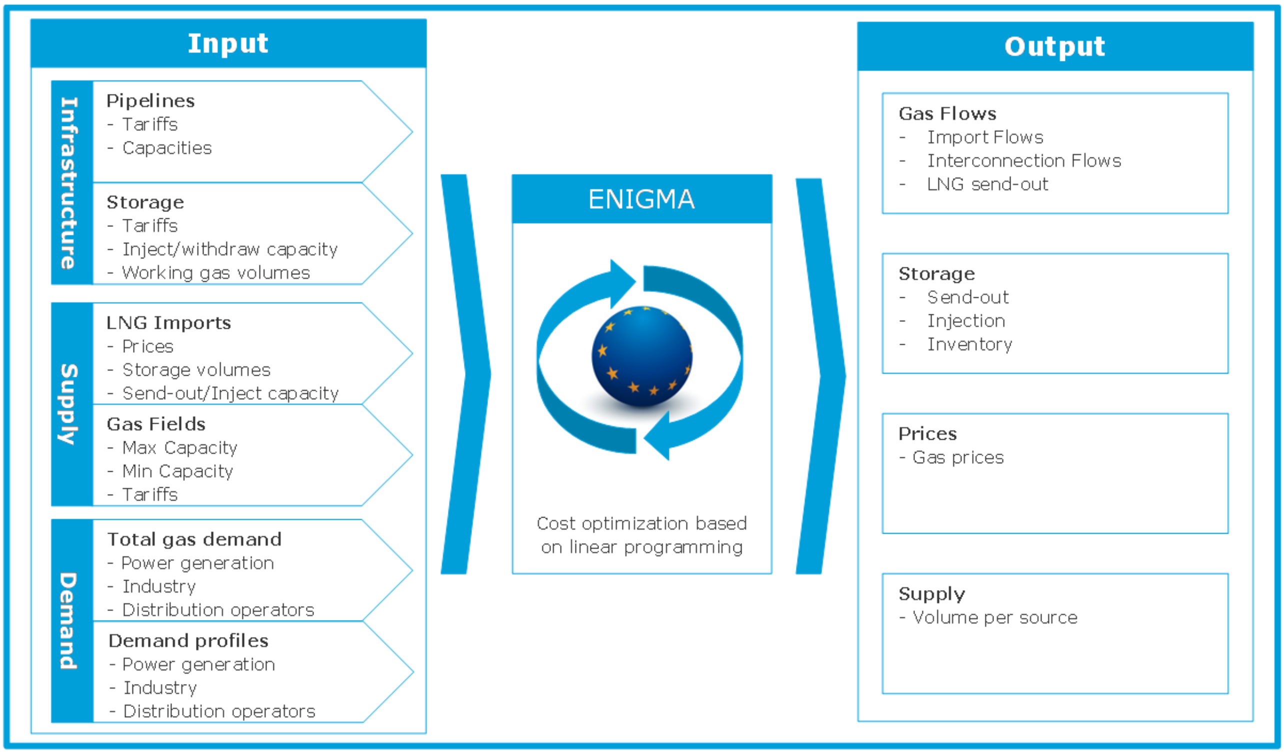


Figure 26: Modelling approach

Input for the model is gas demand and supply at a given year. By combining both the total demand per country and the actual profile per day for three consumer segments, gas flows can be assessed on a daily basis and bottlenecks in the European gas infrastructure system identified. Below the selected

[1] ENIGMA stands for the European Network Infrastructure and Gas Market Analysis Model.

consumer segments and profiles are discussed as well as the way they have been used as input for the analysis.

5.2.2 Model topology

The European gas infrastructure network is represented by an aggregated structure as it is too complex to fully include all details. The chosen structure aligns with the way the EU gas market is commercially set up: all market areas, i.e. the so-called entry-exit systems, have been included in the model. In each market area, gas storages, production facilities, LNG regasification terminals and interconnection capacities are aggregated into single elements. This topology is used for both years, i.e. 2012 and 2050, although in the latter additional gas infrastructure is included.

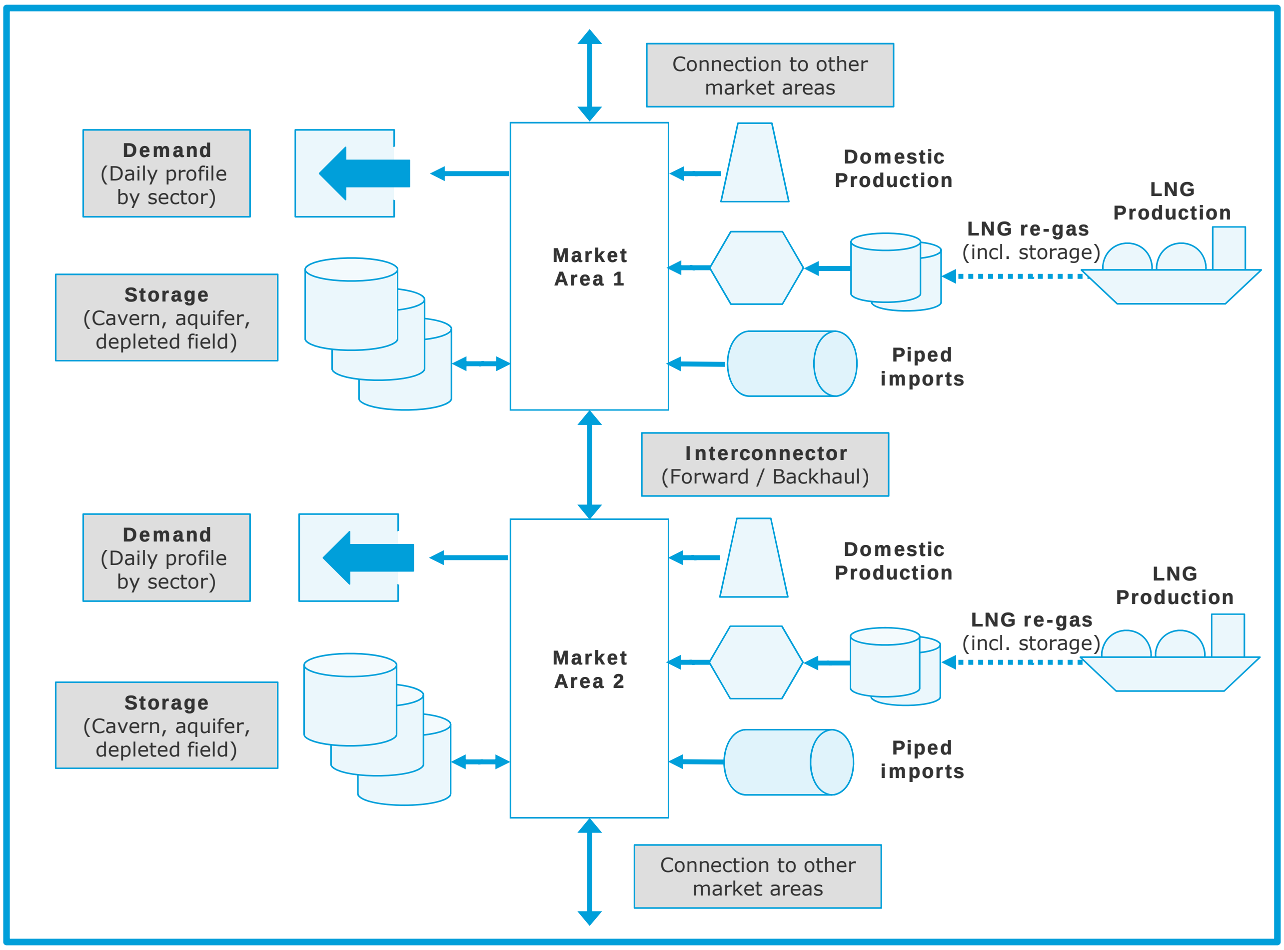


Figure 27: Model Topology

Figure 27 shows an example of the different elements included in the model for two market areas: domestic production, LNG production and regasification, piped imports, demand and storage. It also shows the interconnection capacity between the two market areas. All these elements are discussed in more detail in the next section.

Each individual country is represented by a region. In total, the model spans 31 European countries which have gas demand. Also, major natural gas producing countries (e.g. Russia and Norway) are included but without demand (i.e. net exporters). In addition, the model contains a single LNG production region representing global LNG supply as an additional supply source.

In most cases a region corresponds directly to a market area. This is the area where natural gas can be traded; market areas can include gas production, storage, LNG terminals and pipeline capacities to other market areas. In the model, market areas are represented by a single node in which gas is demand is centred and to which all gas infrastructure elements are connected. This representation is in line with the commercial set-up of (most) gas markets in the EU which usually have a single market area. Exceptions are France and Germany, which consists of more market areas (2 and 3 respectively) as shown in Figure 28 below.

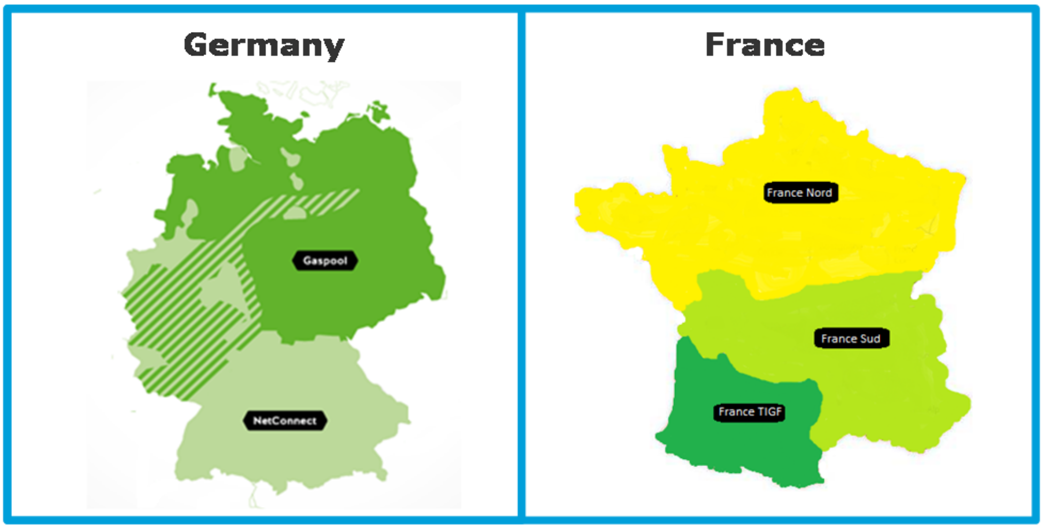


Figure 28: Market areas per country – Germany & France

5.2.3 Gas infrastructure

ENIGMA contains the gas infrastructure as was in place in 2012. Furthermore, for the year 2050, it contains the gas infrastructure likely to be in place in 2050. Those projects for which an FID has already been taken are included. As discussed above, not all European pipelines are included in the model; the model is limited to interconnection capacities between market areas only. Below the included infrastructure elements are discussed.

Gas transmission pipelines: Gas transmission pipelines are represented by interconnection points between market areas. Virtually all separate entry and exit points are included. In the model a distinction is made between three types:

- *Inter-region (Cross Border Lines)*: The inter-region pipelines reflect the capacities between regions. This type of pipeline is mostly used.
- *Intra-region*: For those regions with more than one market area, the intra-region line connects the internal market areas.
- *Imports*: Import pipelines represent the interconnection lines from major producing countries to a market area, are unidirectional and in general have a large capacity.

Gas fields: In each region, all gas fields are aggregated to a single element with natural gas production. However, gas production in the Netherlands was split into two gas fields: the Groningen gas field and other smaller fields. This was done due to the fact that the Netherlands is an important European natural gas producer and the clear distinctive properties of the Groningen field compared to other gas fields (i.e. highly flexible).

Underground gas storages: Underground gas storages are also aggregated in each market area. Each storage facility in the model is modelled with injection, withdrawal and volume capacities that match the sum of the individual storages in the respective market areas. For Germany and France, gas storage facilities are first assigned to market areas and then aggregated into a single facility.

LNG Terminals: Also, in case of multiple LNG regasification terminals, LNG terminals are aggregated into a single element for each market area. Further, LNG terminals are positioned on a separate node to clearly distinguish between liquefied natural gas and natural gas in gaseous state. This dedicated LNG node contains the LNG regasification terminal, its storage tanks and the interconnection with the market area node. Furthermore, this node is also connected to the global LNG market by means of an 'import pipeline'.

5.3 Model input

This section discusses the input to the model. First, assumptions regarding gas supply are discussed. Secondly, gas demand is discussed.

5.3.1 Gas supply

With respect to gas supply, a distinction is made between pipeline imports and LNG imports. Under pipeline imports, gas from major producing countries and gas produced domestically in the EU is meant. LNG imports refer to gas imported by LNG terminals.

Pipeline imports

For all relevant gas producing countries connected by pipeline to or in Europe, the total maximum annual gas supply in the reference year 2012 and for the scenarios in 2050 are established. Each gas field receives the following four properties to take into account the physical/technical properties and the typical arrangements in gas production:

1. *Maximum annual volume*: the maximum amount of natural gas that can be produced by the country
2. *Minimum daily volume*: the minimum daily volume of natural gas that needs to be produced by the country
3. *Maximum daily volume*: the upper limited of the daily volume that can be produced by the country
4. *Gas price*: estimation of the price for gas

LNG imports

For LNG production a separate 'gas field' is modelled. This field is connected to all LNG terminals in the model. The LNG gas field has the similar properties as the gas fields mentioned above. In Table 7 below, the gas supply sources which are included are shown.

Table 7: Gas supply sources

Major Gas Producing Countries	Domestic European Production
Azerbaijan	Austria

Major Gas Producing Countries	Domestic European Production
Algeria	Bulgaria
Libya	Czech Republic
Norway	Germany
Russia	Denmark
	Croatia
Global LNG	Ireland
	Italy
	Netherlands
	Poland
	Romania
	Slovakia
	United Kingdom

5.3.2 Gas Demand

The analysis of the European gas demand covers 31 countries, summarized in the table below.

Table 8: Countries in the model with gas demand

Country and Country code							
AT	Austria	EL	Greece	LT	Lithuania	RO	Romania
BE	Belgium	ES	Spain	LU	Luxembourg	SB	Serbia
BG	Bulgaria	FI	Finland	LV	Latvia	SE	Sweden
CH	Switzerland	FR	France	MK	Macedonia	SI	Slovenia
CZ	Czech Republic	HR	Croatia	NL	Netherlands	SK	Slovakia
DE	Germany	HU	Hungary	NO	Norway	TR	Turkey
DK	Denmark	IE	Ireland	PL	Poland	UK	United Kingdom
EE	Estonia	IT	Italy	PT	Portugal		

A country's total gas demand is split across three end-user segments:

1. *Gas distribution networks*: These include the residential – commercial/tertiary customers.
2. *Industry*: High energy intensive industry, with a direct connection to the gas transmission network.
3. *Power generation*: Gas-fired power generation stations, with a direct connection to the gas transmission network.

For 2012 this is based on the actual division of gas demand between the segments, for 2050 this is based on the scenario data.

The daily demand profiles for each of these segments are combined to create an aggregated daily gas demand profile per market area. In this way, infrastructure utilization and gas flows behaviour can be analysed on a daily basis.

5.4 Validation

In order to validate the ENIGMA model, the model is run for the reference year 2012. The resulting gas flows are compared with the actual 2012 gas flows. The analysis is based on the total gas demand figures in 2012 (Eurostat) and a thorough analysis of gas profiles per segment, as described above. The reference year 2012 has been chosen on the basis of the availability of data. In the input side gas demand, supply and infrastructure are taken, while on the output side information on gas flows, prices and usage of LNG and storages are examined. In order to validate the model, the output of the model should show a realistic behaviour of gas flows, prices, storages and LNG use.

5.4.1 Gas demand 2012

As described above, the total gas demand serves as one of the inputs to the model to assess the sufficiency of the existing capacities of the European gas infrastructure and resulting flows under different scenarios. Figure 29 below shows the total gas demand and its division across the various segments for the year 2012. Later in the report the results of the simulation of the year 2012 are compared with the results of the simulations as done for the three end states in the year 2050.

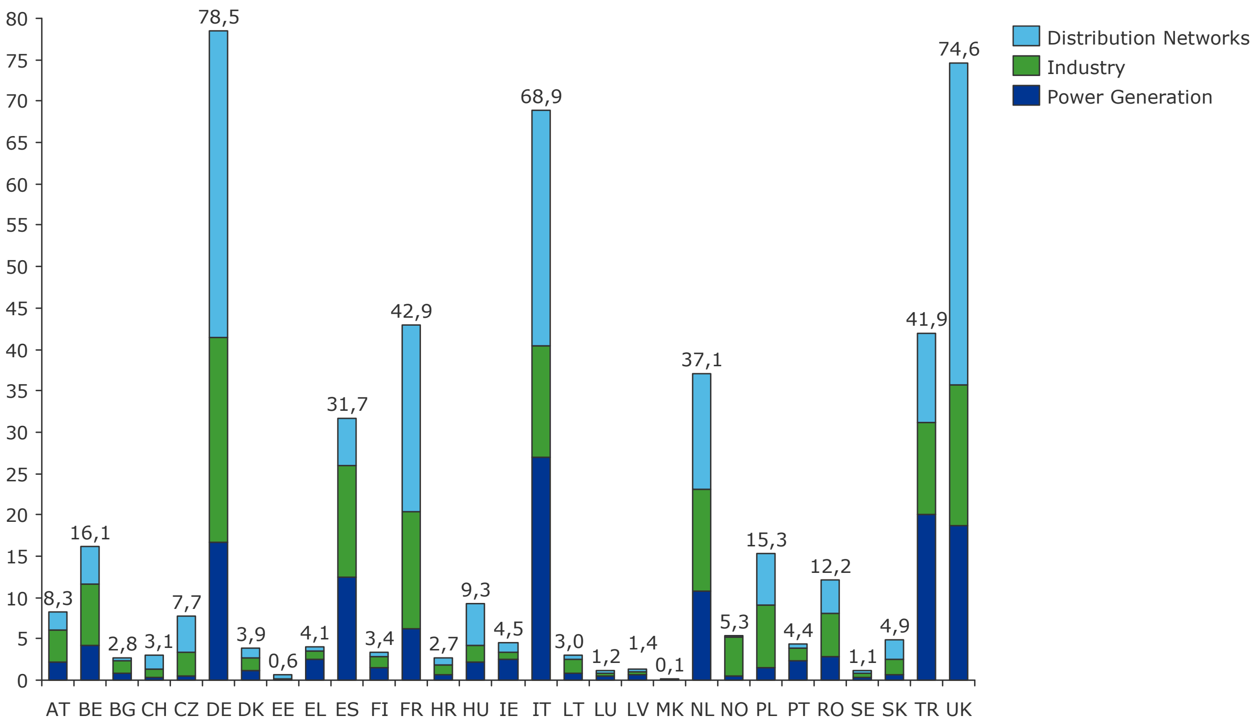


Figure 29: Gas demand 2012 – gross inland consumption per country – in TWh

It becomes instantly apparent that a few countries are responsible for the majority of the gas demand in Europe. These countries are Germany, Spain, France, Italy, Netherlands, Turkey and the United Kingdom. In order to gain a better understanding of the relative difference in demand by end-user segment the following figure is presented.

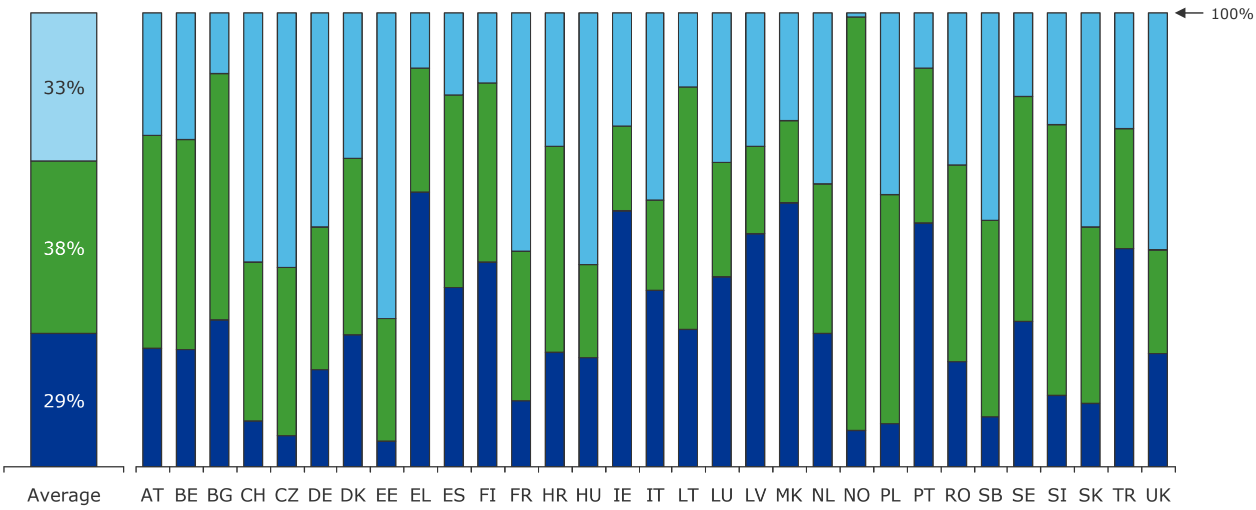


Figure 30: Gas Consumption 2012, per end-user segment – in %

Gas demand profiles for each segment are input to the model. Therefore the actual daily gas profiles of several countries in 2012 have been reviewed and used to calibrate the way these profiles are derived in the model. This has been done in order to mimic the actual gas profiles of 2012. Furthermore, the gas profiles of 2012 form the foundation for those used for the year 2050. Below, the three different segments and their profiles are discussed in more detail.

Gas Distribution Networks: Gas demand for distribution networks (residential & commercial customers) is predominantly based on the demand for heating. In order to describe the relationship between the gas demand for heating and the outside temperature, input data is based on a temperature formula as derived by the University of Munich[1]. This formula describes the relationship between residential & commercial gas demand and temperature. The analysis of historical gas demand for five European countries (in relation to actual temperatures) shows that the formula is applicable for all countries. Actual gas profiles (provided on the websites of several TSOs) have been compared with the temperature formula in order to determine the accuracy and applicability across regions in Europe. The formula's parameters have been adjusted to better reflect the actual gas demand as observed in each country.

Industry: The industry profiles for Italy, France and the Netherlands are examined. These three countries are chosen because of data availability from the national transmission operators regarding exit volumes to the industry. Gas demand between week and weekend days range between 20% less in Italy and 7.5% less during the weekend in France. An example of the average profile for the industry for is shown below for a 14 days period. For the industry segment an 85 – 15% week – weekend profile for all European countries is chosen.

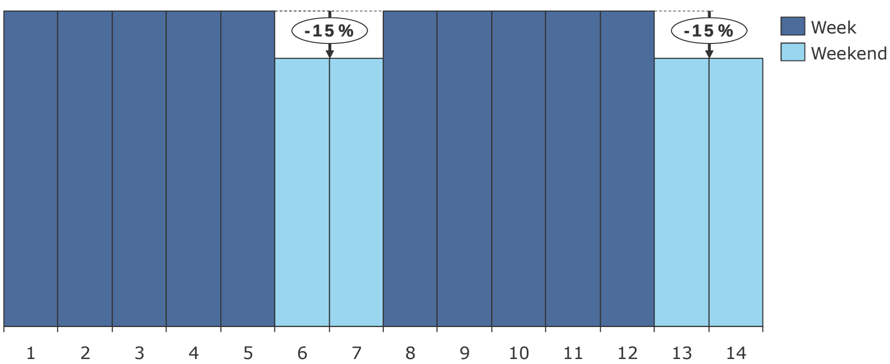


Figure 31: Example week-weekend industry profile – period 2 weeks

Power Generation: Gas demand for power generation is seen as quite influential on the required capacities of gas infrastructure. Gas fired power generation is viewed as the flexibility fuel to balance the increasing supply of renewable electricity generation. Based on the data from several national gas transmission operators a general profile for the year 2012 is deducted and several analyses on the generation profile are performed. It has been assumed that the power generation profile is directly correlated with temperature and that it might differ per region in Europe (North and South). For example, demand spikes are expected during winter in northern Europe and during summer in Southern European countries due to the use of air conditioning. A week-weekend profile is, just like the industry segment, could reasonably capture the overall profile for the power generation sector in 2012. This simplified profile is only used for the 2012 situation and is shown in the figure below. For the analysis of the end states, the results of simulations conducted with an electricity market model are used as input.

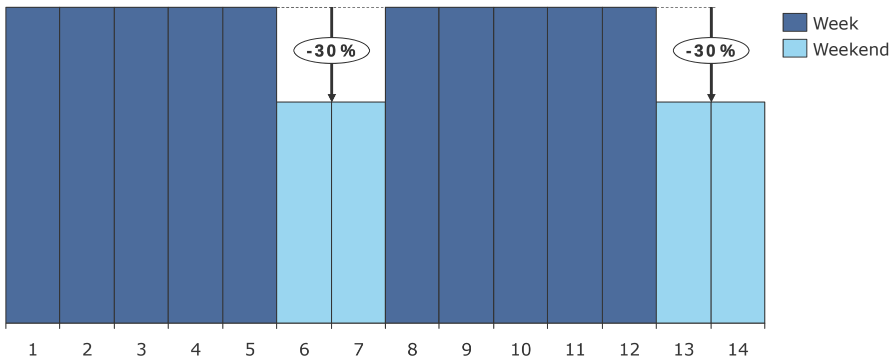


Figure 32: Example week-weekend Power Generation Profile – period 2 weeks

5.4.2 Model 2012 outputs

The model provides a number of outcomes. For the validation of the base year, the behaviour of the gas flows and storages are analysed specifically.

Gas flows: Gas flow behaviour can be represented in graphs showing the gas flow through a pipeline for one year. This so called 'flow profile' is characterized by two indicators: (1) the load factor and (2) the transported volume. The load factor is a utilization indicator and expresses the use of the pipeline compared to the maximum flow. The transported volume indicates the amount of gas that is actually transported through the pipeline during the year under consideration.

In the graph below the results of the simulations for the year 2012 are shown using the two indicators. The colour of the arrow corresponds to the load factor whereas the thickness correspondents to the transported volume. Although there are deviations in the individual pipeline gas flow indicators compared to the actual situation of 2012, the European gas network flow pattern is perceived as logical and representative by the researchers.

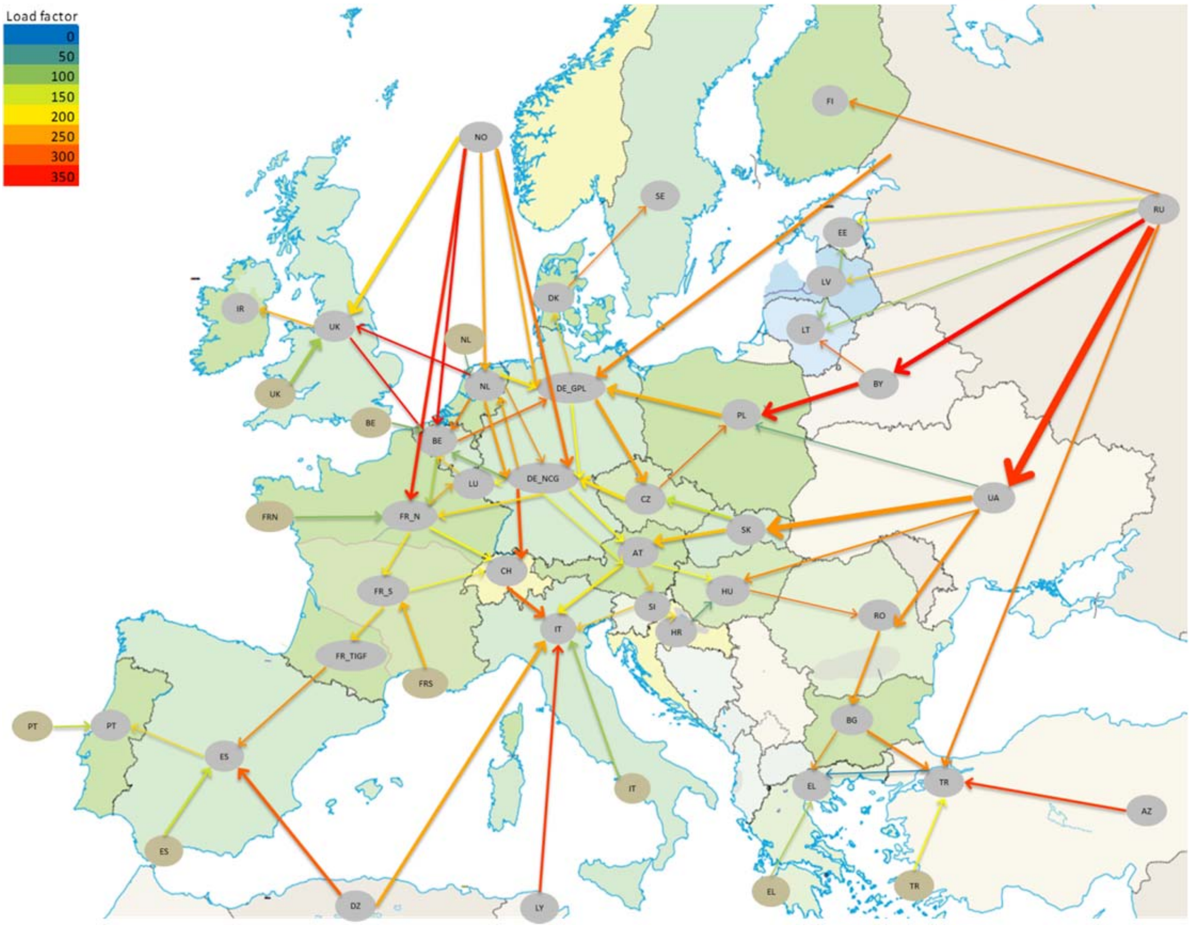


Figure 33: Model results for gas flows for the year 2012

Storage: Use of gas storage can be represented in graphs showing the storage level over a certain period. The ENIGMA model provides the daily storage level over a period of one year. This so called 'storage profile' is characterized by two indicators providing quantitative information on the utilization level:

- *Buffer capacity use:* The buffer capacity use indicates which part of the maximum buffer volume is actually used during a certain period.
- *Buffer frequency use:* The buffer frequency use indicates how many times an equal amount to the maximum buffer volume is sent out during the same period.

Formulas and examples of these two indicators are provided in the box below.

<u>Formulas for 'buffer capacity use' and 'buffer frequency use'</u>

$$buffer\ capacity\ use = \frac{V_{buffer} - V_{min}}{V_{buffer}} x100\%$$

$$buffer\ frequency\ use = \frac{V_{sent\ out}}{V_{buffer}} x \frac{1}{\Delta t}$$

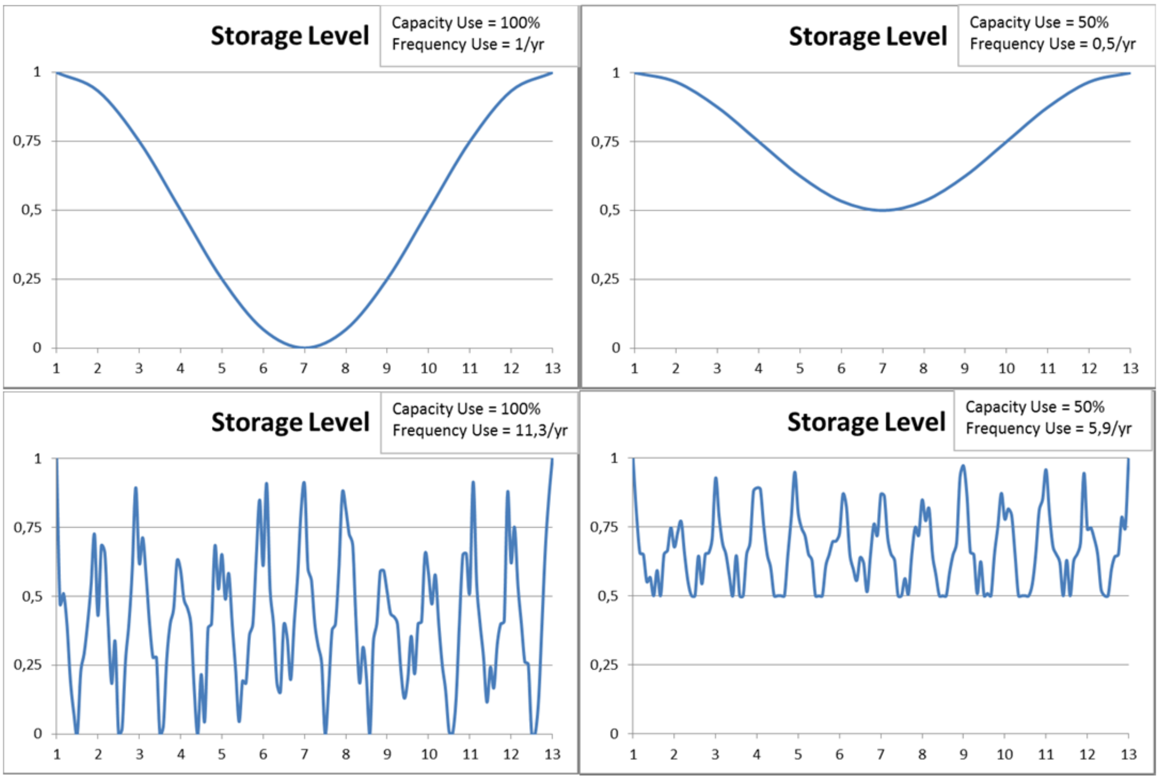
$$V_{buffer} = buffer\ capacity\ [mcm]$$

$$V_{min} = minimum\ buffer\ volume\ [mcm]$$

$$V_{sent\ out} = total\ sent\ out\ volume\ over\ a\ time\ period\ \Delta t\ [mcm]$$

$$\Delta t = time\ period\ [yr]$$

To illustrate the gas storage behaviour with these indicators, four examples are provided.



In the graph below, the resulting storage behaviour according to ENIGMA for the year 2012 is shown. The colour of the doughnut corresponds to buffer frequency use (blue = low, red = high) whereas the number correspondents to buffer capacity use. Storage behaviour could not be validated for the majority of storages in 2012 due to the lack of data. However, the resulting behaviour of gas storages is perceived by the researches as typical.

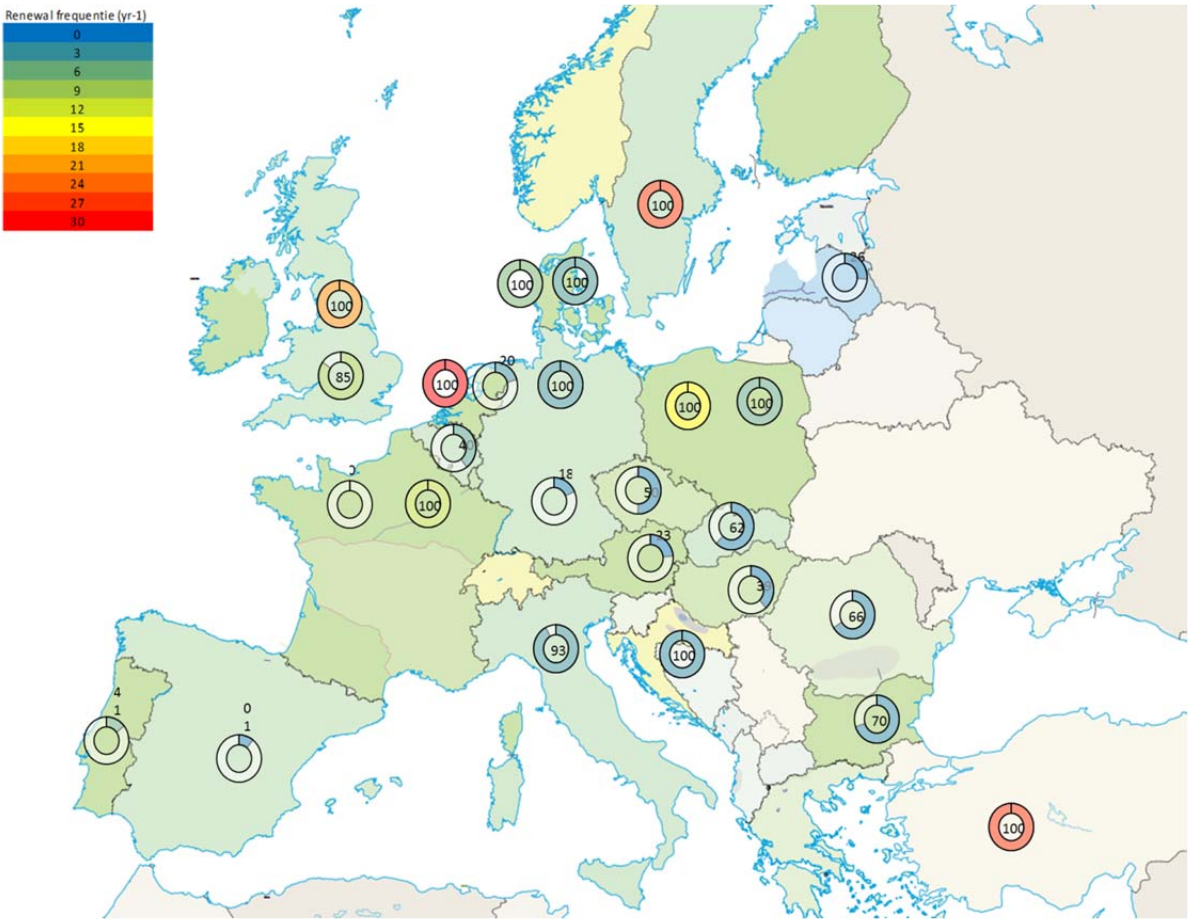


Figure 34: Model results for storage use for the year 2012

5.5 Description of three end states as input to ENIGMA

In this section, the conversion of the thee end states such that they can be used as input for the ENIGMA model is treated. First, the scenarios that are used as a basis for quantifying the end states are discussed. Secondly, each end state is discussed in more detail separately.

5.5.1 Selection of scenarios

In order to demonstrate the 'big picture of the European gas infrastructure in 2050' three energy scenarios for 2050 are chosen to assess the impact on the European gas infrastructure in 2050. The scenarios are a practical implementation of each of the three identified end states. The results of model runs for these three scenarios offer insights into the possible gas flows and capacities matching supply and demand in 2050 under the identified end states. As the scenarios correspond to the end states, they have been named in a similar way:

- (high) renewable energy scenario (RES)
- business as usual scenario (BAU)
- (high) gas scenario (GAS)

The first two scenarios are based on the energy scenarios developed for the European Commission by the University of Athens. They have used their PRIMES (Price-Induced Market Equilibrium System) model[2] to develop a range of scenarios; of these scenarios the ones most typical for the RES and BAU end states are selected for the purposes of this study.

The third scenario is chosen to represent a situation in which gas demand is higher than present levels as is the case in the GAS end state. Such a scenario is not part of the scenarios that have been developed for the EC. However, Eurogas has created a gas favourite scenario for Europe and this scenario is used to represent the GAS end state.

Table 9: Scenario selection

Scenario	Gas demand compared to 2012	Expected impact on infrastructure and utilization	Source
High Renewable	Significantly Lower	High	EC – PRIMES
Business as Usual	Comparable	Low	EC – PRIMES
High Gas	Significantly Higher	High	Eurogas

5.5.2 Basics characteristics demand 2050

For each of the three scenarios, the total gas demand and its division over the three end-user segments are shown in the graph below. Furthermore, total gas demand and its division for the year 2012 are shown as well to offer a comparison between each scenario and the 2012 situation.

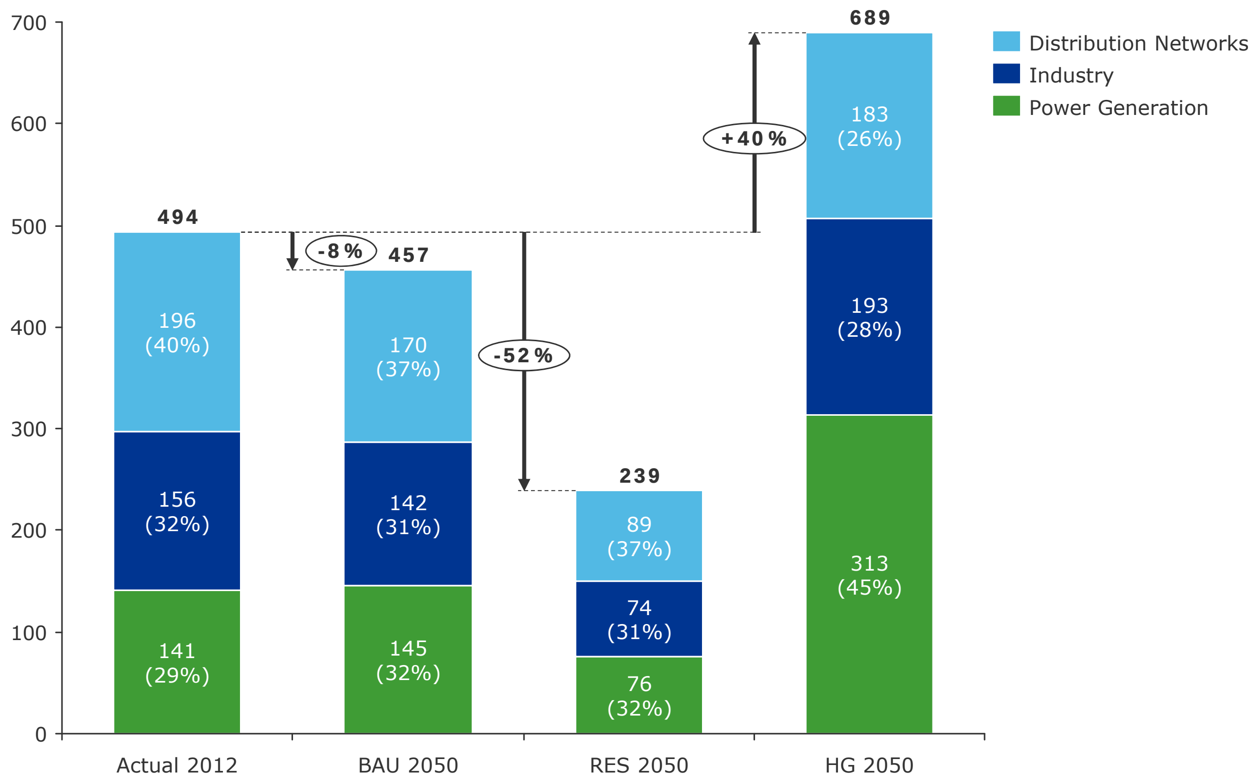


Figure 35: Total Gas Demand 2012 – 2050 scenarios comparison - Bcm

The total gas demand for each of the 31 countries under the three scenarios and the 2012 situation is provided in the next figure.

2 PRIMES provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions for each individual European country and for Europe-wide trade of energy commodities.

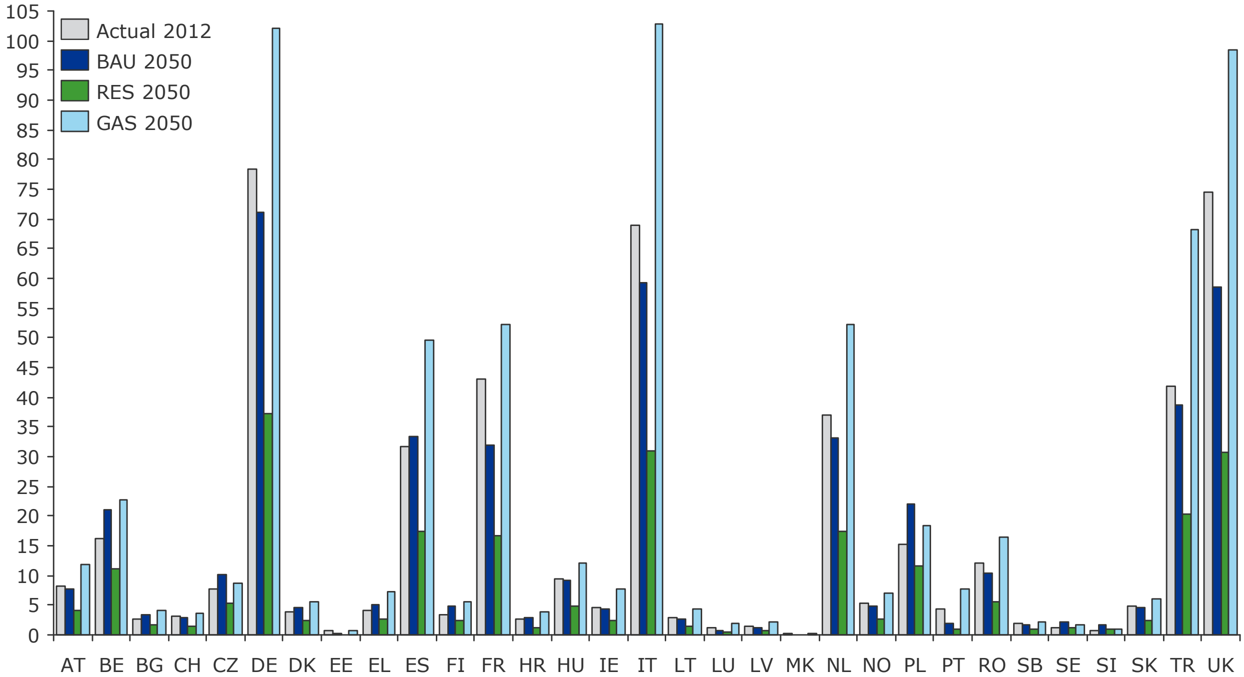


Figure 36: Total Gas Demand 2012 – 2050 scenarios country comparison – Bcm

5.5.3 Gas supply 2050

For each of the scenarios considered, gas supply needs to align with gas demand. For 2050, it is assumed that most indigenous resources in the EU have been depleted and that the majority of gas supplies should be imported. Imports from Norway, Algeria, Libya, Azerbaijan and Iran are capped. Therefore, the combination of Russian gas and LNG is pivotal. The following has been assumed for each end state.

- *RES*

  Under the RES end state, LNG supplies are pegged at the presently (low) levels. It is assumed that gas demand will drop over the years and that volumes supplied by LNG will increase nor drop as compared to present levels, where present levels are at an historic low. This assumption aligns with the observation made in Chapter 2, where it was noted that Europe might be heading towards an RES end state whereas the rest of the world is more inclined to move to a BAU or GAS end state. As a consequence, it was assumed that LNG is not available for, nor required by, Europe to satisfy its declining gas demand. Russian gas supplies are assumed to fill the gap.

- *BAU*

  For this end state, it is assumed that Russian supplies match Russian export capacity (by pipeline) to Europe as it currently exists. This means that there are no Russian gas volumes available for TurkStream. Also, no additional export infrastructure needs to be built in order to ship these volumes to Europe. Consequently, the remaining volumes are supplied by LNG. The share of LNG compared to the share of Russian gas is significantly larger as compared to that under RES.

- *GAS*

  For GAS end state, supplies from LNG and Russia are balanced in such a way that the existing infrastructure and projects for which an FID has been taken (i.e. LNG regasification terminals and Russian pipelines to Europe) are optimally used. This also means that, for example, no additional LNG terminals are needed when there would be still export potential by pipeline from Russia. It is noted though, that the gas demand in 2050 is higher than the combined annual throughput of the regasification terminals and existing Russian export pipelines together. Therefore, the assumption is made that NordStream 3 and 4 will be built. These are included in the model – for this particular end state – as well.

This results in a break down per supply source as shown in the following figure.

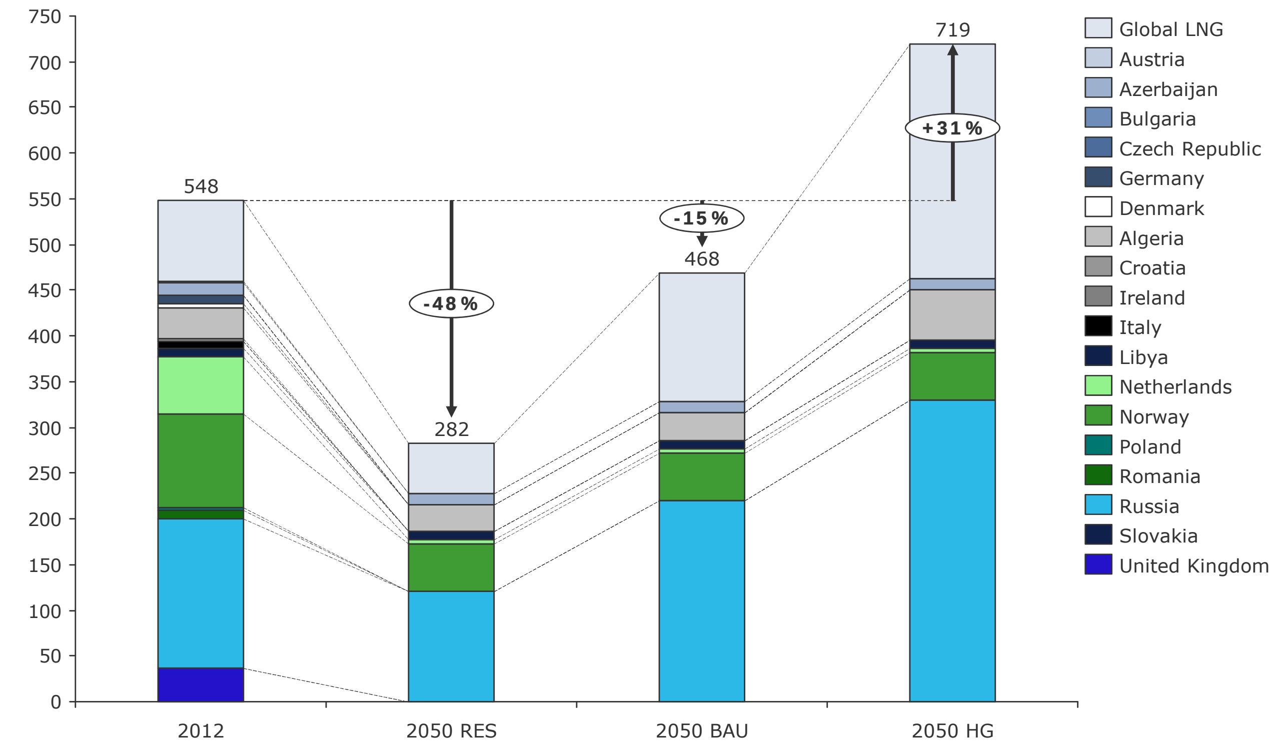


Figure 37: Gas supply 2012 – 2050 scenarios comparison – Bcm

5.5.4 Gas infrastructure 2050

The changes in the gas infrastructure for 2050 compared to 2012 are based on the Ten Year Network Development Plan 2013 from ENTSOG[2]. Only projects for which an FID has been taken are included.

- *Pipelines:*

  South Stream II (Turkey), Trans Adriatic Pipeline (TAP), Ostsee Pipeline AnbindungsLeitung (OPAL).

- *Other interconnection capacities between market areas:*

  GRT GAZ-Sud and TIGF (VTP), Belgium and GRT GAZ-Nord (Blaregnies), Belgium and Netherlands (Zelzate), Bulgaria and Greece (Kula), Germany and Denmark (Ellund), Denmark and Sweden (Dragor), France TIGF and Spain (Larrau and Biriatou), Italia and Switzerland (Griespass), Italia and Slovenia (Gorizia), Netherlands and Germany NCG (Oude Statenzijl), Romania and Bulgaria (Negru Voda and Ruse), Hungaria and Slovakia (Balassagyarmat).

- *LNG regasification terminals:*

  Spain (Bilbao), France (Dunkirk), Lithuania (Klaipeda), Poland (Swinoujscie), Italia (offshore Tuscany), Greece (Revythoussa)

- *Storage:*

  The Netherlands (Bergermeer), 3x Italy (Bordolano, San Potito e Cotignola, enhancement of existing storages), Portugal (Carriço), France (Hauterives), 2x UK (Holford, Stublach), 5x Poland (Kosakowo, Mogilno, Brzeznica, Husow, Wierzchowice).

5.5.5 High Renewable Energy Scenario (RES)

Energy mix: A main source for the description of RES is the report titled "Impact assessment part 2/2 2011" accompanying the Energy Roadmap 2050[3]. RES is a scenario which strives to fulfil the objective of the European Council to attain at least 80% decarbonisation in 2050 compared to 1990. It implicates 85% energy related CO_2 reductions and 80% reduction of GHG emissions in 2050 (1990 = 100).

RES incorporates substantial reduction of final energy demand by using energy efficient technologies and a high penetration of renewable primary energy sources. In the figure below the projected energy mix for RES is shown.

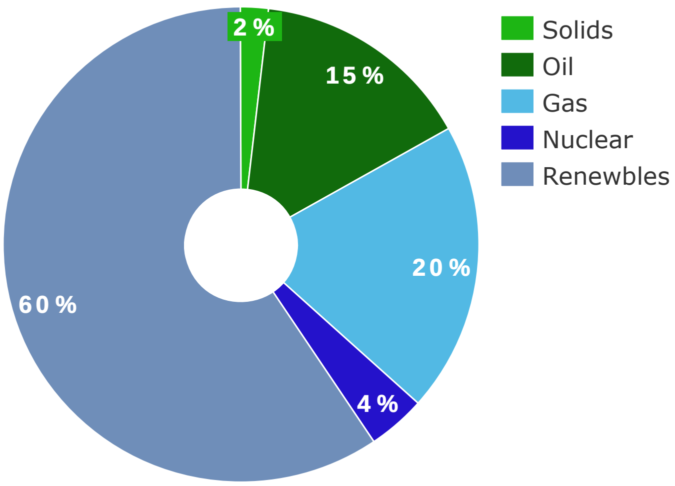


Figure 38: Energy Mix in 2050 for RES

Gas demand: The next figure shows the gas demand for the three sectors for each of the 31 European countries. It has been derived as follows:

- The total gas demand for EU27 is based on "Impact assessment part 2/2 2011" report on page 72.
- The gas demand in each EU27 country is assumed to have the same share (%) in the EU27 total gas demand as in the BAU.
- The gas demand for the other countries is adjusted with an average EU27 demand growing factor compared to 2012.
- The gas demand for each of the three sectors is assumed to have the same sector share (%) as in the BAU.

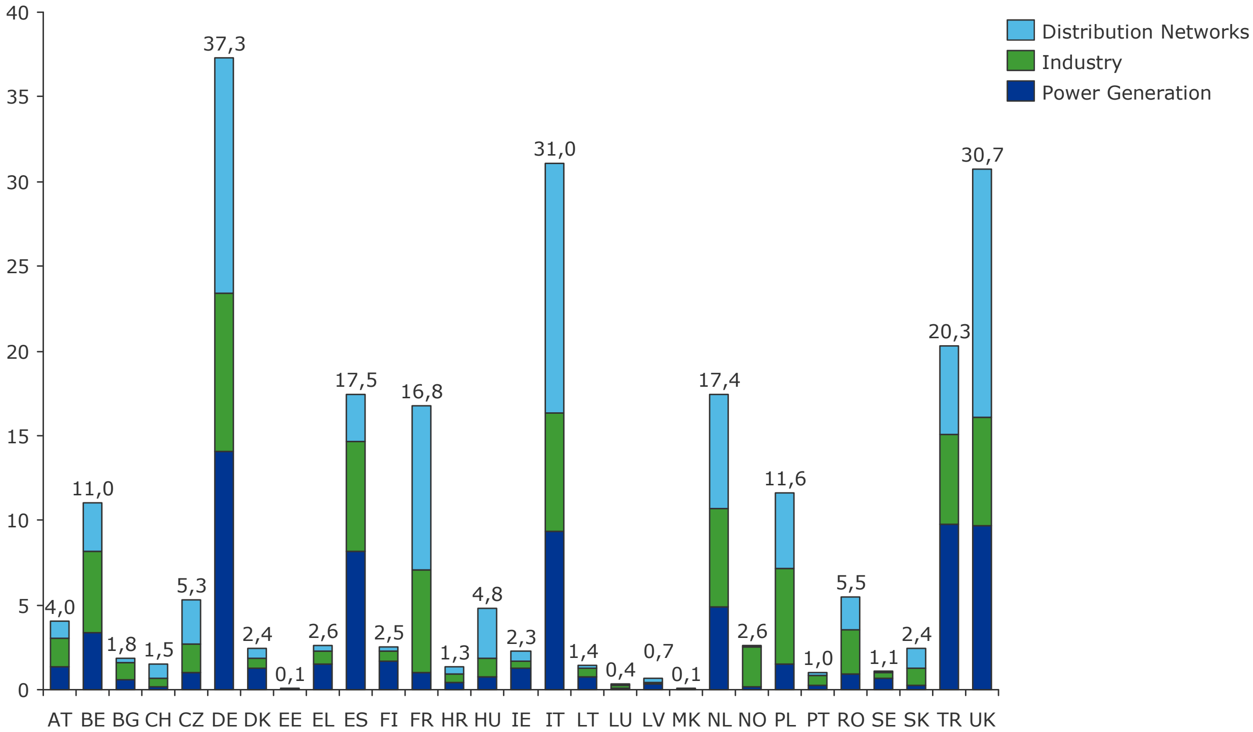


Figure 39: Gas Demand 2050 - RES – Gross inland demand per country – in Bcm

It becomes again instantly apparent that still a few countries are responsible for the majority of the gas demand in Europe. These countries are the same as in 2012: Germany, Spain, France, Italy, Netherlands, Turkey and the United Kingdom. In order to gain a better understanding of the relative difference in demand by end-user segment the following figure is presented.

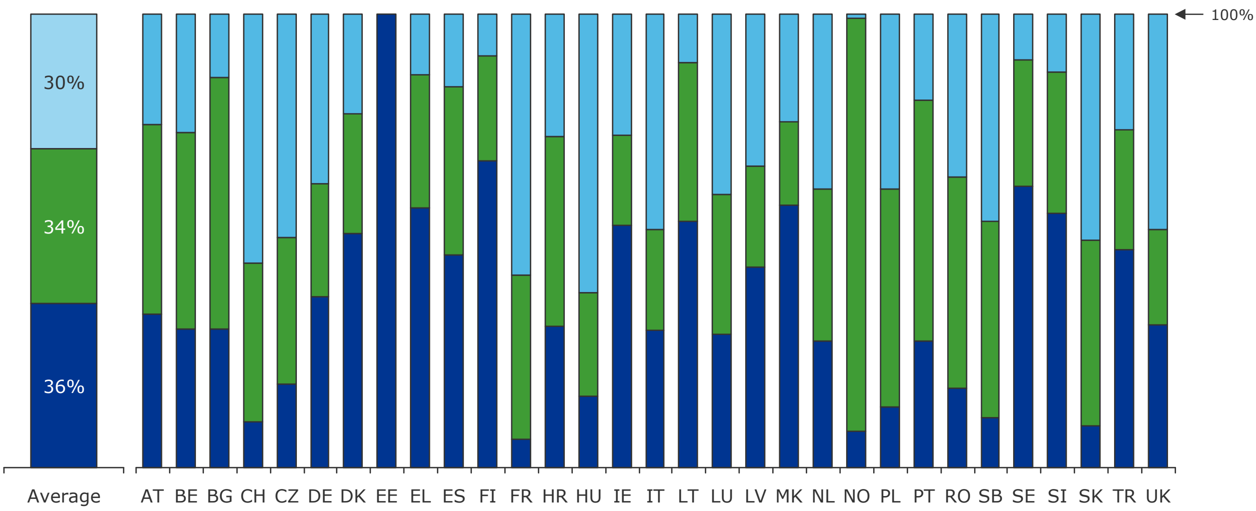


Figure 40: Gas Consumption 2050 – RES - per end-user segment – in %

Gas demand profiles 2050

- *Distribution Networks:* For the end-user profile of users connected to the distribution networks, the same temperature formula as in 2012 was applied. The estimated volumes are based on the scenario itself.
- *Industry:* For the gas profile for industrial gas demand, it is also decided to use the week-weekend profile which was derived on the basis of the actual demand profile in 2012. Again the

volumes are based on the scenario and as such only the profile has been kept the same. No evidence is found that the industry profile would change in our PESTE analysis.

- *Power Generation:* The end-user profiles for gas demand for power generation are based on an internal DNV GL technical report 'Electrifying the future' (2014)[4] for the European countries. Based on the expected electricity demand for the selected scenarios and the assumed installed gas-fired power stations, a country power generation profile for electricity has been developed, with corresponding gas demand.

5.5.6 Business As Usual Scenario (BAU)

Energy mix: A main source for the description of BAU is the report titled "Trends to 2050, reference scenario 2013". It is a scenario which simulates the energy balances and GHG emissions trends under the trends and policies as adopted by the Member States by spring 2012.

In 2050, perspective emissions continue to decrease primarily driven by developments in power generation. This implies 46% energy related CO_2 reductions and 44% reduction of GHG emissions in 2050 (1990 = 100).

The BAU scenario takes into account the highly volatile energy import prices. The scenario includes the 2012 legislation promoting energy efficiency. The reduction in final energy demand is marginal compared to the 2005 situation.

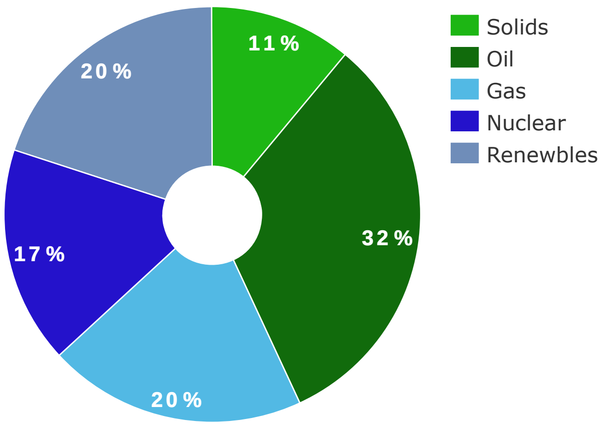


Figure 41: Energy Mix – BAU -2050

Gas demand: In the next figure, gas demand per segment for each country under the BAU scenarios is presented. These figures have been derived as follows:

- The total gas demand and the gas demand in the power sector for each of the EU28 countries are based on "Trends to 2050, reference scenario 2013", pages 85-146.
- The gas demand in the other two sectors for each EU-28 country is assumed to have the same ratio as in 2012.
- The gas demand for the other countries is adjusted with an average EU28 demand growing factor compared to 2012.
- Gas demand in the sectors for the other countries follows the same pattern as in 2012.

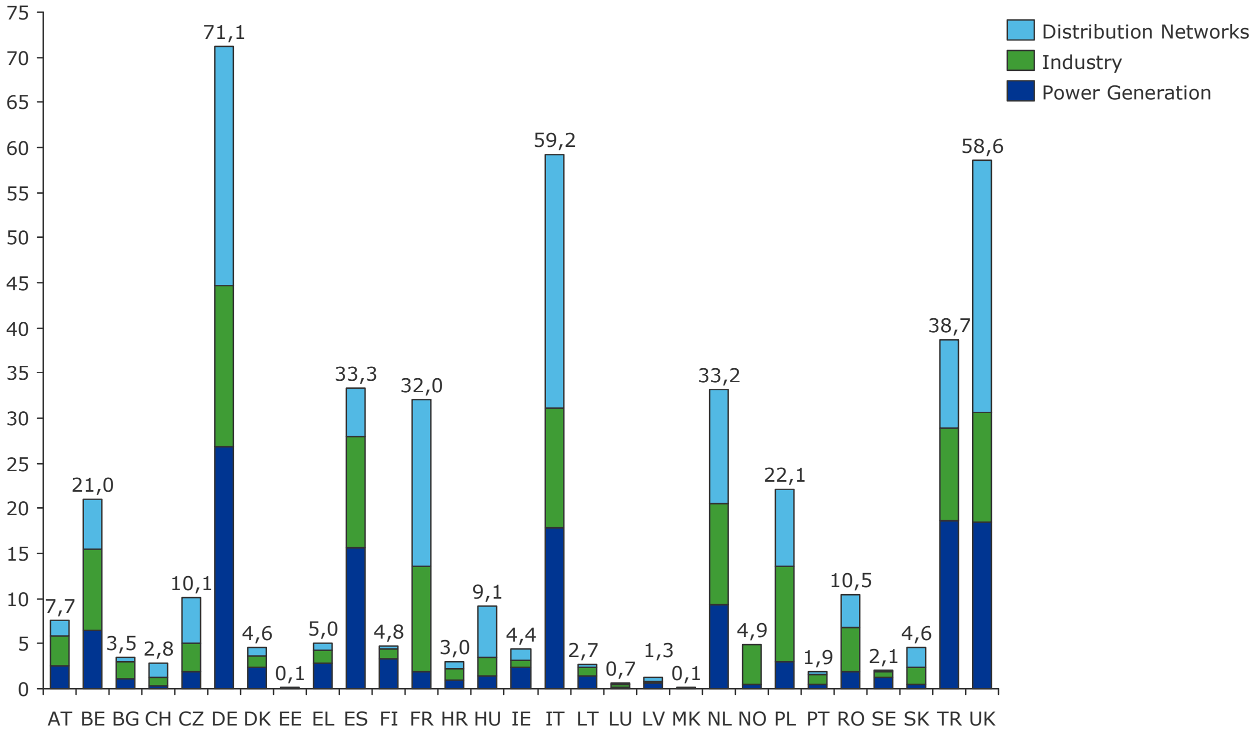


Figure 42: Gas Demand 2050 - BAU – Gross inland demand per country – in Bcm

In order to gain a better comparison of the relative difference in demand by end-user segment the following figure is presented.

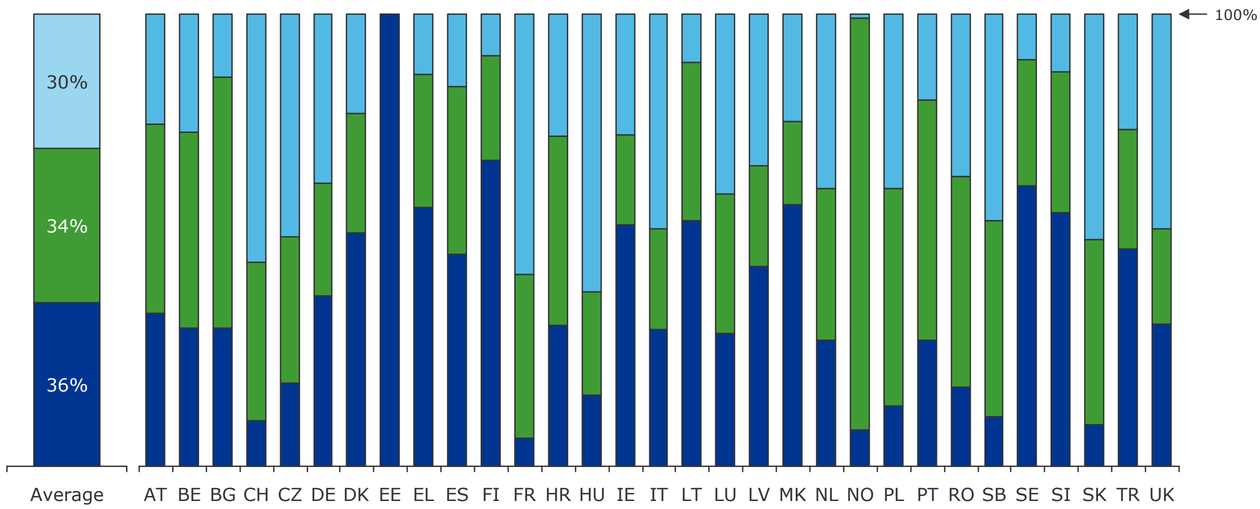


Figure 43: Gas Consumption 2050 – RES - per end-user segment – in %

5.5.7 High Gas Scenario (GAS)

Energy mix: A main source for the description of the GAS end state is the report titled "Long-Term outlook for gas to 2035" from Eurogas 2013[5]. It is a gas markets driven scenario which anticipates a rebalancing of the energy mix towards more renewable and slightly less nuclear electricity, together with restored economic growth and a high rate of innovation in energy-efficient equipment (rapid development of efficient gas appliances in home and office heating).

The scenario assumes that the qualities of gas will still lead customers in all sectors to want to keep using it. The cleanliness, controllability, low carbon dioxide content and flexibility in use of gas will continue to create demand in both difficult and favourable market and policy conditions.

The contribution of gas in the energy mix in 2050 is assumed by the authors of the report to be the same as in 2035. This implies a 30% share of gas in the energy mix.

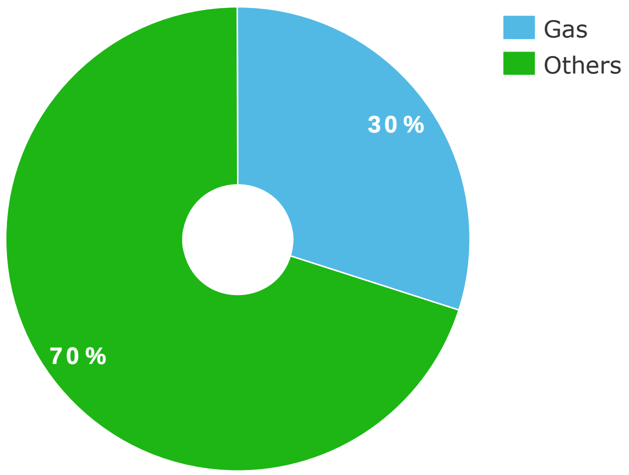


Figure 44: Energy Mix in 2050 for GAS

Gas demand: The next figure shows the gas demand for the three sectors for each of the 31 countries. It has been derived as follows:

- The total gas demand and the gas demand in the three sectors for the EU27 countries together are based on extrapolation of the gas demand in the three sectors from 2035 to 2050.
- The gas demand for the other countries is adjusted with an average EU27 demand grow factor compared to 2012.
- The gas sector demand per country is adjusted with the grow factor of the total sector demand for the 31 countries in 2050.

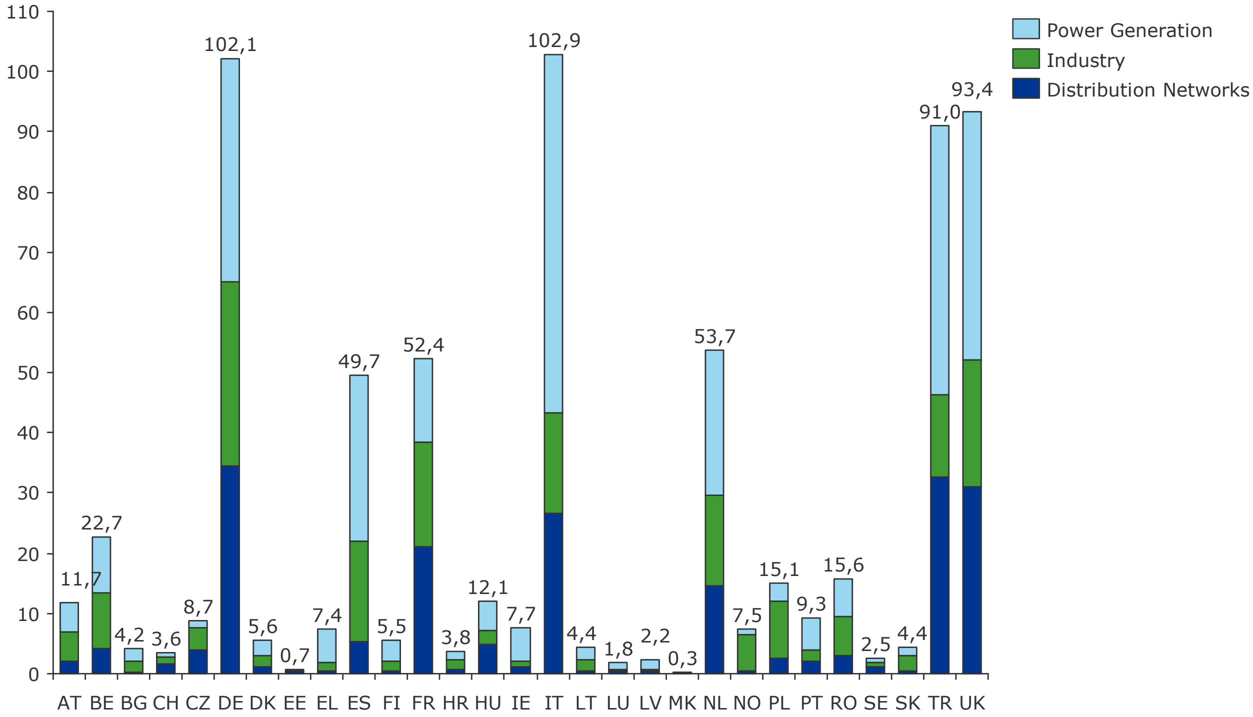


Figure 45: Gas Demand 2050 – Gas – Gross inland demand per country – in Bcm

In order to gain a better comparison of the relative difference in demand by end-user segment the following figure is presented.

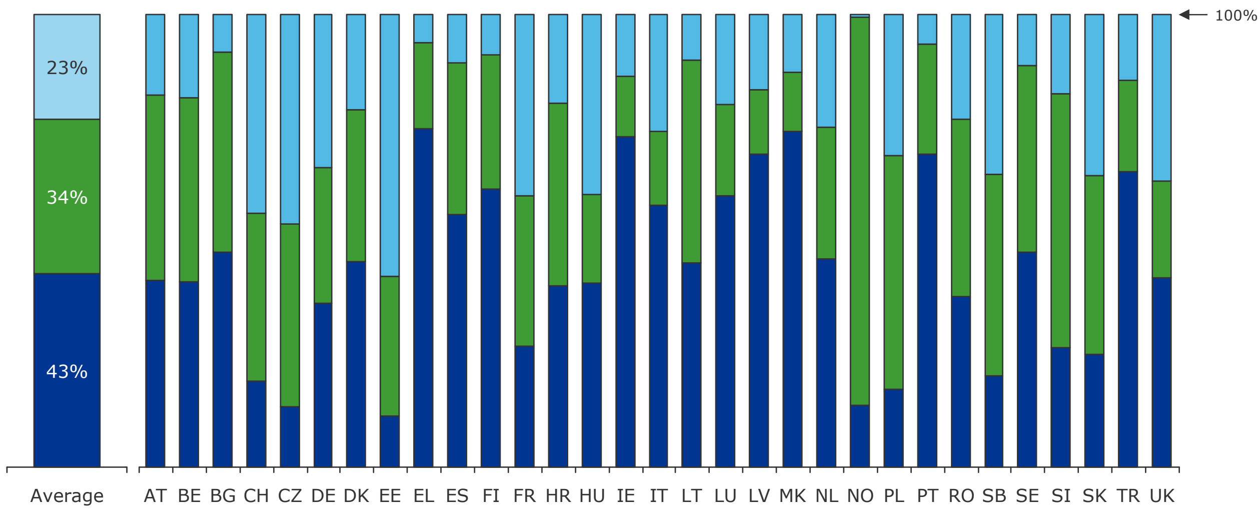


Figure 46: Gas Consumption 2050 – Gas - per end-user segment – in %

5.6 Scenario results

The results from the analysis will be captured with two main output categories: flows and storages. For each scenario the main observations and implications for the European gas infrastructure and its utilization is briefly discussed.

5.6.1 Gas Flows

In order to show the results of the model, a graphic representation of the European network is used. The figure below shows the direction of flows, volumes and the load factor of the interconnectors between the defined market areas in Europe. The market areas are represented by grey circles. The brown circles indicate LNG regasification terminals. The arrows show the origin and direction of the gas flows. The colour of the arrows denotes the load factor. The thickness of the arrow represents the transported yearly volume.

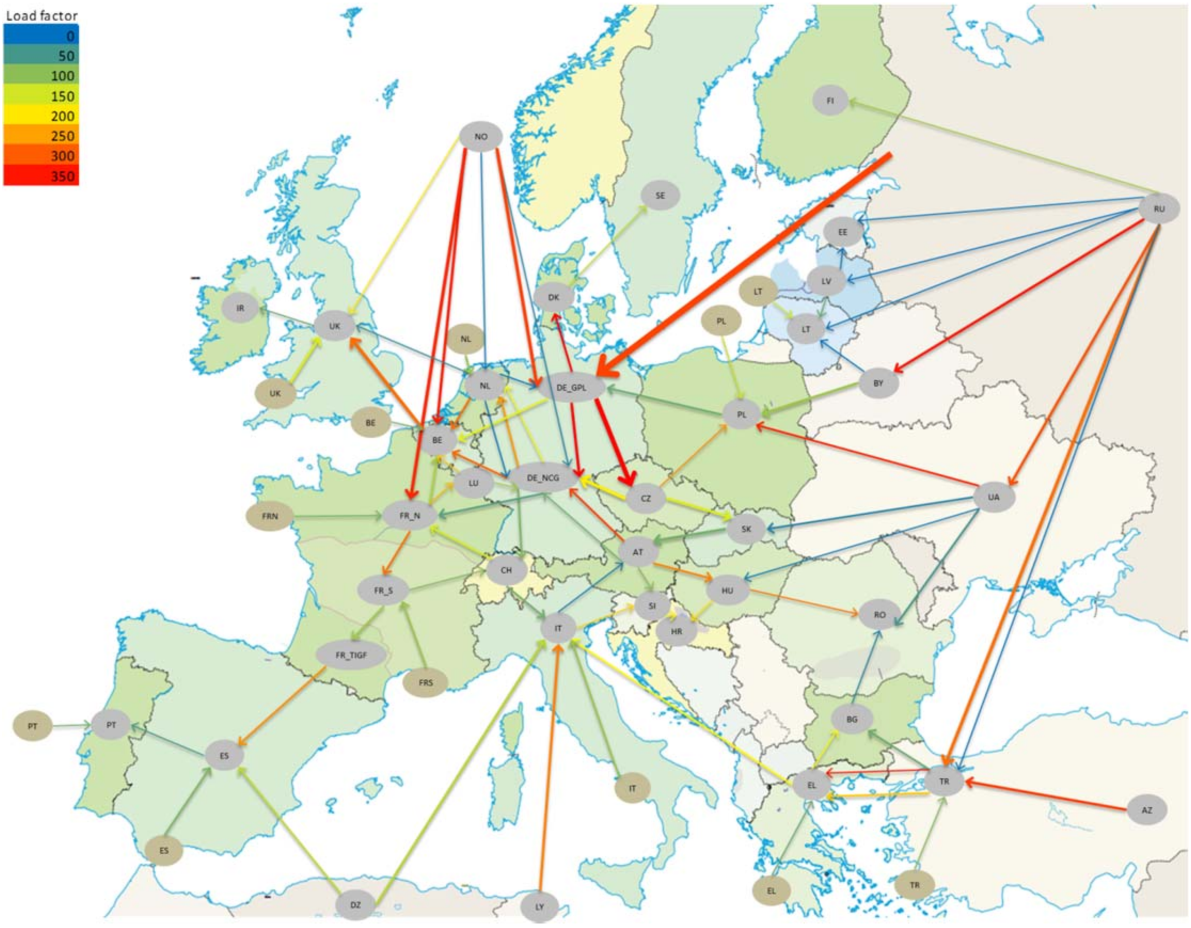


Figure 47: Model results for gas flows for RES

From the above figure several conclusions can be drawn regarding the gas flows and utilization of pipelines in Europe. Below the most noteworthy changes, compared with the modelled 2012 situation, are listed:

1. The most eye catching change is the switch of Russian gas transported to Europe through the Ukrainian transmission system and the Yamal pipeline to the North Stream and OPAL pipelines.
2. This also shows Russian gas being transmitted through Ukraine, Romania and Bulgaria to Turkey. In 2050, gas flows in the opposite direction (sourced from Azerbaijan) to Bulgaria and Romania.
3. A third effect of the smaller volumes through the Ukraine transmission grid is the reverse flow that occurs on the TAG pipeline. In 2012, there was a large flow from Austria to Italy; however in 2050 under the RES scenario the model predicts a much smaller flow in the opposite direction.
4. The two new infrastructure projects that have been included for 2050, namely TurkStream and TAP, are only limitedly used, although flows through the Ukraine have been drastically lowered. This is partly due to the low demand in general compared with 2012 and the alternative large capacities to transport Russian gas into Europe. Although volumes imported from Azerbaijan are

increasing, most of these volumes are consumed in Turkey, and therefore not transported further into Europe by using for example the TAP.

5. With respect to the situation in North-West Europe the most notable change is the decrease of Norwegian gas supplied to Germany and the Netherlands through the Emden receiving terminal. Furthermore a decrease in the volume and load factor of the BBL is observed as well as a reverse flow compared to 2012 of the IUK.
6. Looking at the situation in Southern Europe the most notable change is the decrease in load factor of the pipeline infrastructure in Iberia.

In the figure below, the gas flows for BAU are provided.

Figure 48: Model results for gas flows for BAU

Compared to RES scenario, the switch back from the gas flows though the Ukrainian gas transmission system instead of North Stream is most striking. In general, the utilization of infrastructure is higher than in RES because of the higher gas demand and therefore gas supply.

As a consequence of the declined indigenous gas resources, LNG and Russian gas supply to Europe is expected to increase substantially compared to the 2012 situation.

There is no need identified to build additional infrastructure on top of the infrastructure already in place and planned in the BAU scenario.

In the figure below, the gas flows for the GAS end state are provided.

Figure 49: Model results for gas flows for HG

In a similar fashion as the two other end states – RES en BAU – the implications for the European gas infrastructure under the GAS end state are assessed. In contrast to the previous two end states, the GAS end state has far fetching implications for today's existing and planned gas infrastructure. This is attributed to two main factors:

1. Strong growth in European gas demand
2. Declining indigenous gas production leaving the majority of gas supply (>80%) restricted to two main sources, namely LNG and Russia

In order to match demand with supply, several large infrastructure projects need to be developed. Most notably are the doubling of Nord Stream to four parallel pipelines, the completion of TurkStream and the TAP. As the major gas markets are expected to (still) be in North West Europe, reverse flow possibilities in the Italian grid towards Switzerland and even into the Netherlands at the start of the TENP pipeline are required. Besides these larger projects, the need for additional interconnection capacity between Germany and two neighbouring, smaller gas markets is required as well: both cross-border capacity between Germany and Denmark, and Germany and Luxembourg need to be increased. Apart from these projects, the analysis shows that no further increase in the European gas infrastructure is required.

Besides an increase in pipeline capacity, there seems a need for additional LNG import capacity in the UK (doubling of present import capacity), the Netherlands (about 1.5 times current capacity) and the south of France (about twice as much).

5.6.2 Storage

In this section, the result with respect to storage utilization are presented. Similar to the section on gas pipelines, the RES end state is discussed first. After the results of the RES end state are presented, the BAU and GAS end states are discussed.

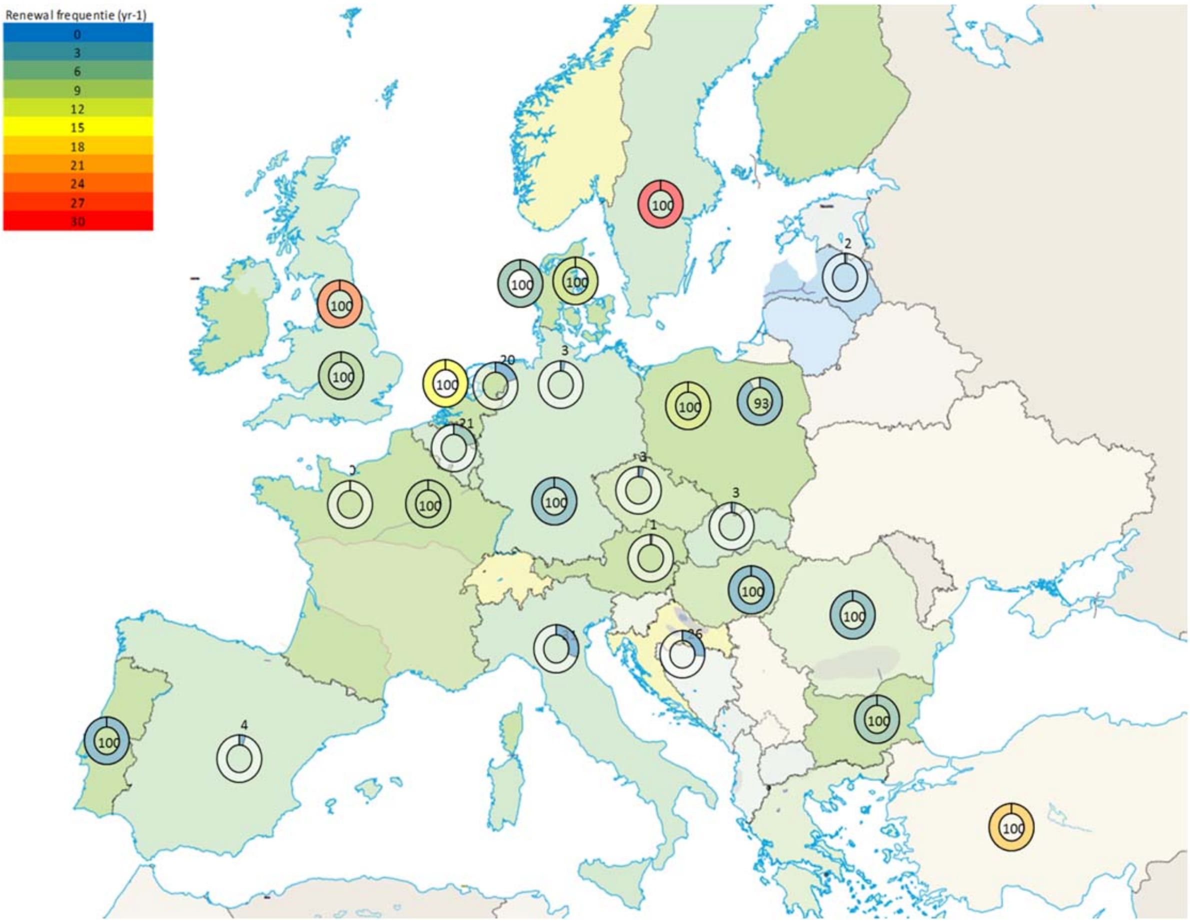


Figure 50: Model results for storage for RES

From Figure 50 above it is clear that the storage infrastructure in 2050 is sufficient to cover the supply-demand fluctuations. The gas storage capacity use is highest in North-Western Europe, Scandinavia, Poland, Portugal and South-East Europe. The frequency use is by far the highest in Sweden, followed by UK, The Netherlands and Turkey. It is striking that the storage use in South and Central Europe is relatively low.

Compared to the 2012 situation, the gas storage use in UK and Portugal is more intensive under the RES end state. The storage use in Netherlands, Italy and Balkan is less intensive, whereas the use in South-East Europe is more intensive, except for Turkey.

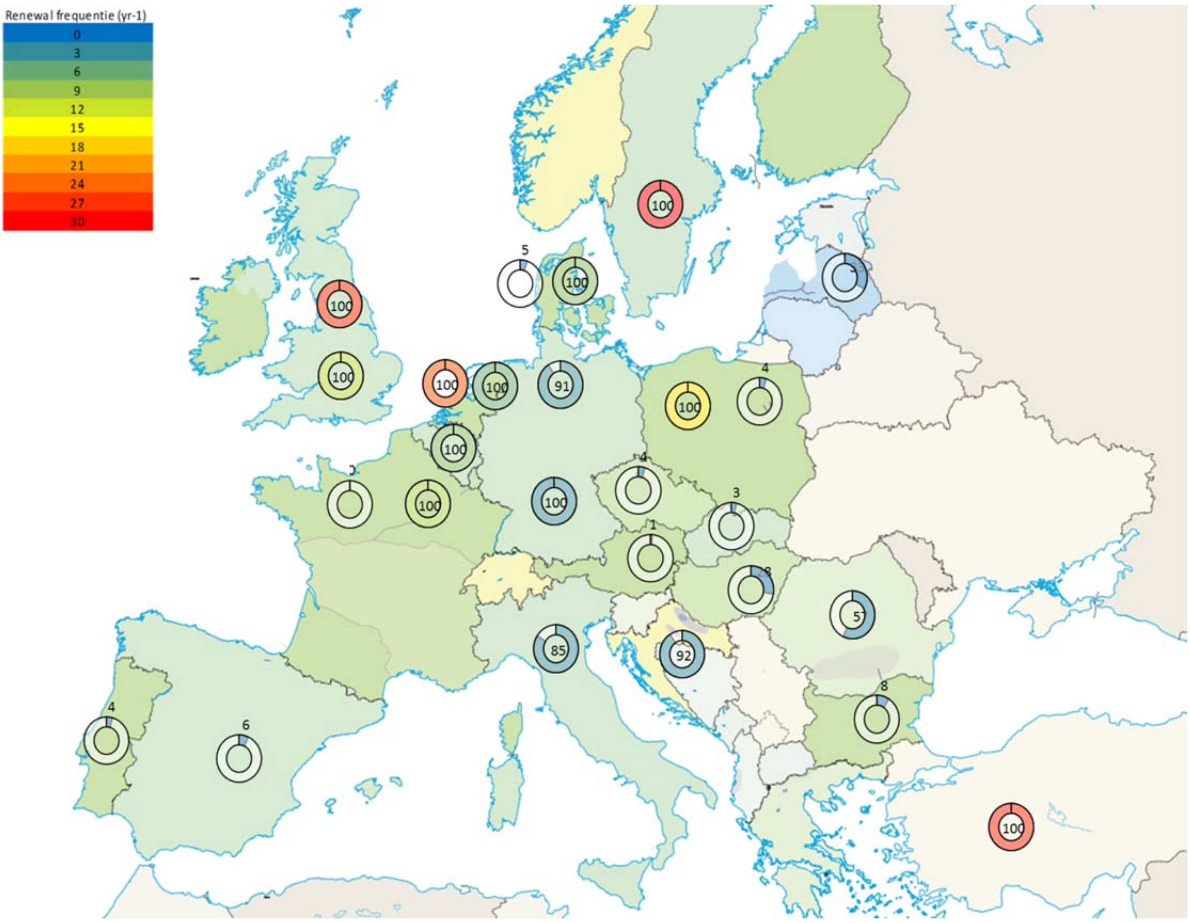


Figure 51: Model results for storage for BAU

The storage infrastructure in 2050 is expected to be sufficient to cover the supply-demand fluctuations in the BAU scenario. The gas storage capacity use is highest in North-Western Europe, Scandinavia, and South-East Europe (Balkan). The frequency use is by far the highest in Sweden, followed by UK, The Netherlands and Turkey.

In general, storage capacity use in BAU is higher than in the RES end state. It is striking that the storage use in Portugal, Hungary, Bulgaria and Romania is low compared to the RES scenario.

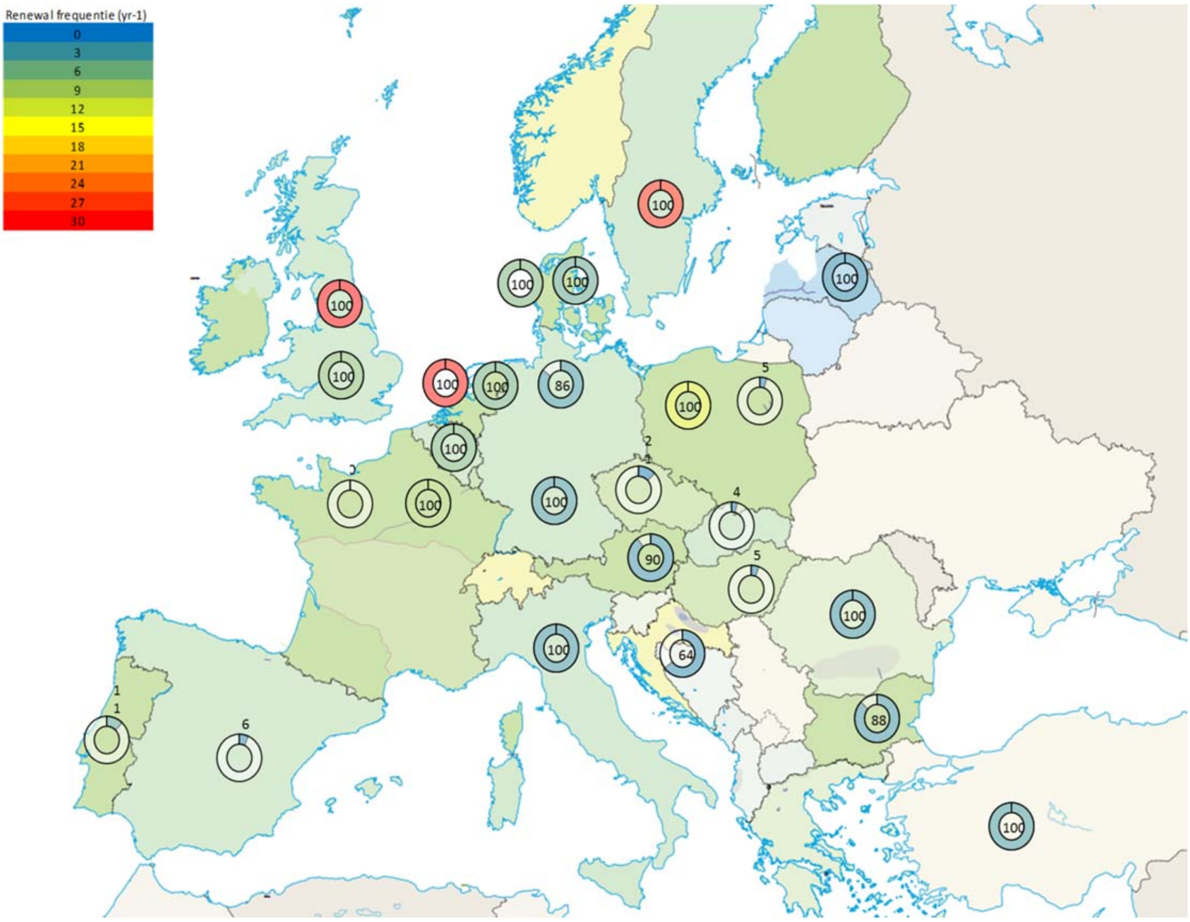


Figure 52: Model results for storage HG

Storage capacity in the GAS end state is expected to be required to increase in the following countries:

- Austria will see the need to a slight increase in storage capacity, just as in Bulgaria. The additionally required capacity is however fairly limited compared to current storage capacities and to the European situation as a whole.
- In Croatia, the required storage capacity is expected to triple in order to match supply with demand.
- In the UK, storage capacity is expected to double.
- In Romania and Italy, storage capacity needs to be increased as well, but by far less as in the UK. In both countries, the need for storage is expected to be around 40% and 20% higher respectively.

5.7 Conclusions

The conclusions of the research are presented in this section. Three end states have been selected to capture the Big Picture for gas in 2050: Business As Usual (BAU), High Renewable Energy (RES) and High Gas (GAS).

To operationalize the three scenarios, a dedicated model was built. The model has been validated against actual 2012 data.

Below, the main conclusions for the effects on gas infrastructure for the three scenarios are provided.

RES

- The gas infrastructure currently in place and planned is sufficient to match gas demand and supply in Europe. Although the gas demand fluctuations in the power generation sector tend to increase, the pipeline capacities and the storages are adequate to accommodate these fluctuations.
- The utilization of both gas pipelines and gas storages will decrease in general compared to the modelled 2012 situation. However, the utilization of Nord Stream and OPAL are expected to increase substantially at the expense of gas transported through Ukraine.
- Compared to the 2012 modelled situation, gas storage use in UK and Portugal is in RES 2050 more intensive. The storage use in Netherlands, Italy and Balkan is less intensive, whereas the use in South-East Europe is more intensive, except for Turkey.

BAU

- The gas infrastructure currently in place and planned is sufficient to match gas demand and supply in Europe for this scenario. As a consequence of the declined indigenous gas resources, LNG and Russian gas supply to Europe is expected to increase substantially compared to the 2012 situation.
- Compared to RES scenario, the switch back from the gas flows though the Ukrainian gas transmission system instead of North Stream is most striking.
- Gas storage use is highest in North-Western Europe, Scandinavia, and South-East Europe (Balkan). In general, storage use in BAU is higher than in the RES end state. It is striking that the storage use in Portugal, Hungary, Bulgaria and Romania is low compared to the RES.

GAS

- In the GAS end state, gas demand is substantially higher than in the other scenarios. The gas infrastructure currently in place and planned is not sufficient to match gas demand and supply in Europe. LNG and Russian gas supply are by far the dominant gas sources for Europe.
- In order to match demand with supply, several large infrastructure projects need to be developed. Most notably are the doubling of Nord Stream to four parallel pipelines, the completion of TurkStream and the TAP.
- Storage capacity in the GAS end state is expected to be required to substantially increase in the UK, moderately increase in Romania and Italy, and slightly increase in Austria, Bulgaria, and Croatia.

5.8 References

[1] Entwicklung und Anwendung parametrisierter Standard-Lastprofile, Mark Hellwig (05-2003)

[2] European Network of Transmission System Operators for Gas (ENTSOG), “Ten Year Network Development Plan”, 2013

[3] European Commission, “EU Energy, Transport and GHG Emission Trends to 2050”, 2013

[4] DNV GL, “Electrifying the future”, 2014 (internal report)

[5] Eurogas, ""Long-Term outlook for gas to 2035", 2013
http://www.eurogas.org/uploads/media/Eurogas_Brochure_Long-Term_Outlook_for_gas_to_2035.pdf

6 CASE STUDY: BIOMASS AVAILABILITY AND BIO CNG AS A TRANSPORT FUEL IN EUROPE

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6.1 Introduction

In order for Europe to end up in a sustainable energy system the dependency on carbon should be reduced and cycles should be closed. Biomass is thought to have large potential to contribute to a sustainable energy system. This potential is clearly visible in the end states described in Chapter 3. This large potential for biomass is also visible in the renewable energy statistics provided by Eurostat (2014a)[1], which show that about two-thirds of the current renewable energy supply in Europe originates from biomass. This chapter is used to focus on the limitations and implications when it comes to the production and use of biomass in Europe. First the shares of biomass are derived from the three energy mix end states and converted to a European geographical scale, after which the required domestic (i.e., within European borders) production is estimated. A case study was done in order to generate insights in the economic and some environmental implications of the production of these biomass quantities. The economic part is assessed with a bottom-up approach; the environmental impact is assessed with a top-down approach. The chapter is finalised with a conclusion and discussion in which the results are put into perspective and the limitations and implications for biomass applied for energetic purposes are elaborated upon. The discussion is partly used to analyse the economic incentive for farmers and to also include biomass originating from other sectors than agriculture.

6.2 Biomass availability

Based on the energy mix end states described in Chapter 3 the contribution of biomass over time was estimated. This research assumes that 10% of the globally available biomass can be available for energetic purposes in Europe, since this is roughly Europe's share in the global consumption. From the three end states the upper and lower boundaries were taken for energy carriers with an organic origin; together with the average, this data is displayed in Figure 54 which shows the estimated availability of biomass for the EU28 until 2050. Remarkable is that the highest biomass contribution is in the High Gas end state. This is due to the assumptions made in Chapter 3 regarding the clustering of the end states and the higher estimated energy demand in the gas end state. It does however, match with the idea of natural gas as an enabler of the energy transition with a large role for biomass.

Eurostat (2014b)[2] shows that on average, the import dependency of the EU28 as a whole is in the order of 55%. Therefore this research assumes that 45% of the biomass should be produced domestically. This value is arbitrary, but seems to be the obvious choice, since arguments to increase or decrease the assumed value are hard to quantify. For 2020 this assumption would mean an annual production of 2.6 EJ, when looking at the High Res end state. Assuming an average biomass yield of 8 ton dry matter ha^{-1} with an energy density of 18 MJ kg^{-1}, the required area within the EU would be over 18 Mha. This is over 10% of the agricultural and grassland area currently in use in the EU27. Figure 53 gives an overview of the land use in the EU27 in Mha as an illustration. When looking at the data provided by Eurostat it appears that the actual consumption of bioenergy was 3.6 EJ in 2012 (Eurostat, 2014c)[3]. This is 0.4 EJ more than the average as estimated in the BAU end state (see figure 39); it is 2.2 EJ and 2.6 EJ less than respectively estimated in the RES and GAS end state. It therefore appears that the BAU scenario is currently the most realistic one.

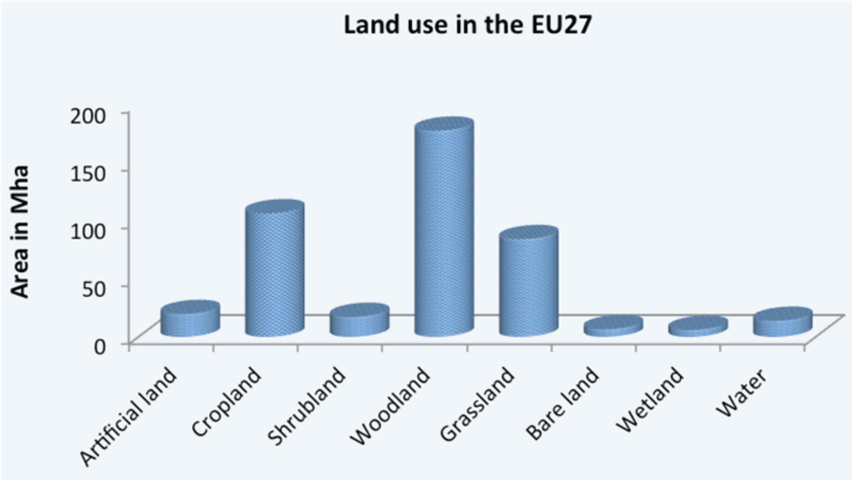

Figure 53: Land use in the EU27 in Mha

(Source: Eurostat, 2014d)[4]

Case study bioCNG

When looking at the carbon dependency of different energy consuming sectors, it seems that the largest challenge to overcome is the shift to clean transport. Hence, transport fuels require a high energy density, which gives the advantage to liquid fuels. Battery driven transport appears to have opportunities, but battery weight, cost kWh^{-1} and charging time are still limiting factors. Liquid biofuels, when produced sustainable, therefore offer possibilities to reduce carbon emissions from transport during a transitional period towards a sustainable supply system. Therefore, this research zooms in on transport, since the economic value of one unit of energy in the form of a liquid transport fuel has more economic value than electric power or a natural gas substitute. This challenge is dependent on the design of a biomass supply system that is seen as sustainable and on the economic feasibility of such a system. A methane based fuel might have opportunities during a transition phase from fossil transport fuels to a carbon neutral transport sector. When the methane based fuel has a renewable origin there seems to be an even larger opportunity as a transition fuel, since it is part of the short carbon cycle. This chapter therefore aims to find the limitations and possibilities for compressed natural gas (CNG) derived from synthetic natural gas (SNG) produced through biomass gasification. A chain analysis focussing on energy efficiency is undertaken and it is tried to pinpoint the sensitive parts of the supply chain. Subsequently, the availability of the required quantities of biomass is assessed.

6.3 Methodology

Based on the model displayed in Figure 55 the energy efficiency and energy ratio of two chains are determined. Subsequently, the designed model is discussed, followed by the performance indicators, scenarios and the boundaries. The difference in these two chains is determined by the biomass production system, which can be intensive (scenario 1) or extensive (scenario 2). An intensive system requires substantial fossil inputs, mainly from artificial fertiliser and crop protection agents; an extensive system does not require such inputs. The result is that an intensive system requires less agricultural area and less transport for forwarding the harvested biomass to a central point, but generally has a larger environmental impact due to the extra fossil inputs in the system.

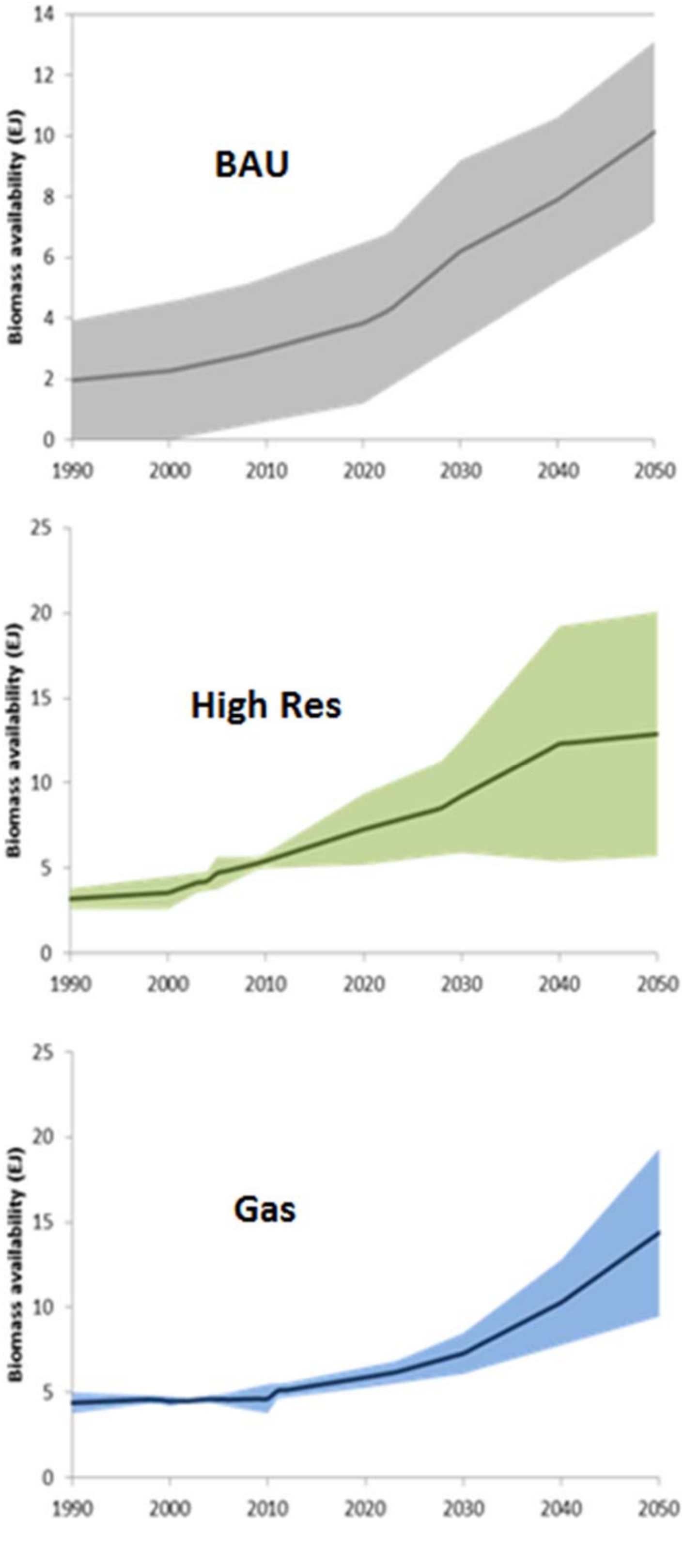

Figure 54: The estimated biomass availability in the EU28

6.4 Model

In order to find the sensitive parts of the chain a model is used as displayed in Figure 55. This chapter focuses on the sensitivity of the biomass production system. This image and the applied method are taken from Miedema et al., (2014). In the model applied for this chapter an extra conversion step is added to the model where SNG is compressed, before it is further transported to the end user as CNG. For compression of SNG an efficiency of 96.6% is applied based on Wang and Huang (2000)[5].

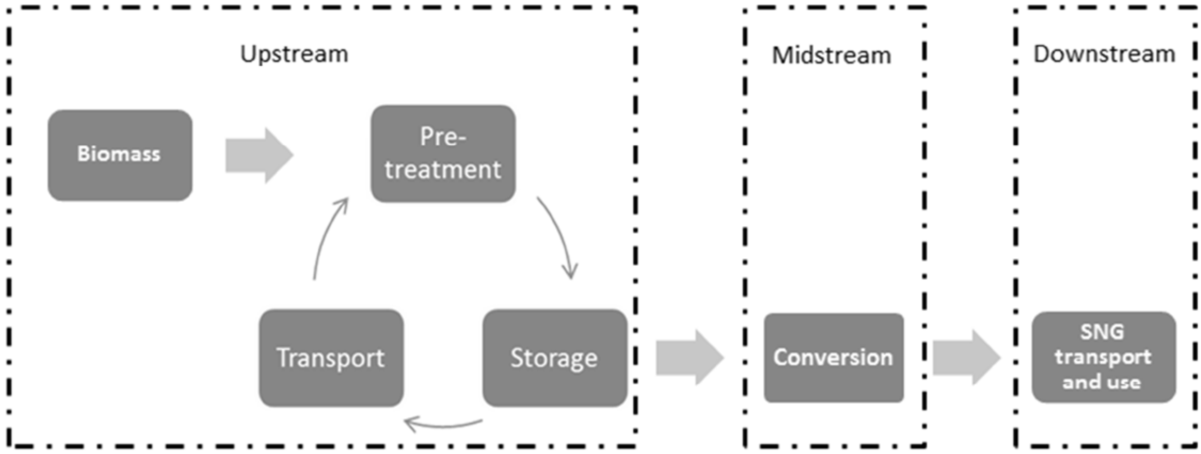

Figure 55: Model overview containing the most important steps in the biomass-to-end use-chain.

The model calculates the energy used in biomass production, harvesting, forwarding, pre-treatment and storage in the upstream part of the chain. The midstream part of the chain takes into account the conversion efficiency from biomass to CNG after which the distance that can be driven by the end user on one hectare is determined, in the downstream part of the chain. A brief assessment of the availability in the EU28 is elaborated upon in the discussion section.

6.4.1 Scenarios and performance indicators

In this case study the capacity of the gasification plant is assumed to be constant throughout the scenarios at 800 MW. This is a high capacity and therefore the value of 800 MW should be interpreted as 8 plants of 100 MW. This value is applied in order to make it easily comparable with existing fossil power plants. The biomass produced for CNG is poplar.

This chapter estimates the effect of two biomass production systems; this can be an extensive (scenario 1) or intensive (scenario 2) system. The choice for the analysis of two production systems is required, since literature discussing biomass production efficiency such as Nonhebel (2002)[6], does not continue after the harvest. Based on these boundaries, she concludes that intensive systems have the highest energetic efficiency and therefore have a preference over extensive systems. When considering a system with broader boundaries than Nonhebel (2002), as this chapter does the results might change. When including the forwarding distance of biomass to a central point and conversion of the biomass, these insights might differ. With forwarding this research specifically means the required transport distance to a central point where pre-treatment such as drying can take place before the biomass is transported over longer distances towards a conversion plant. Hence, an extensive system requires more land due to lower yields, resulting in larger forwarding distances compared to an intensive system. Therefore the optimal (from an energetic and environmental viewpoint) production system is also dependent on whether the supply chain uses centralised or decentralised conversion and the assumed transport distance required for forwarding.

The energetic performance of the systems is measured by determining the energetic efficiency and the energy ratio (see equation 1 and 2).

$$EE = \frac{E\ cng - E\ fossil\ input}{E\ biomass} \quad (1)$$

$$ER = \frac{E\ cng}{E\ fossil\ input} \quad (2)$$

E_{cng} = The energy contained in the SNG delivered to the grid (MJ)

$E_{fossil\ input}$ = The amount of fossil energy used in the upstream process (MJ)

$E_{biomass}$ = The energy contained in the biomass at harvest (MJ)

A third indicator is the distance that can be travelled with the net energy produced on one hectare (km ha^{-1}) in the two analysed supply systems. The net energy produced is calculated by taking the gross energy produced in the biomass and subtracting the fossil inputs and losses due to conversion from it. The fossil input for the forwarding distance of biomass is dependent on the area and given by equation 3 and based on a biomass production system displayed in Figure 56. The distance travelled per hectare is further discussed in Section 6.5.1.

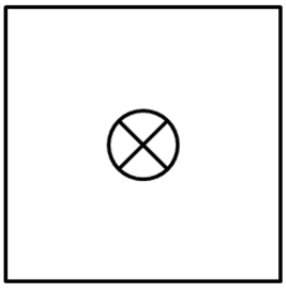

Figure 56: Biomass production system with conversion technology in the centre

$$Dmax = \frac{1}{2}\sqrt{Area} \quad (3)$$

Half of the value of *Dmax* is the average transport distance; return trips are included and therefore *Dmax* represents the total transport distance. For the extensive system (scenario 2) this chapter assumes that the forwarding distance quadruples compared to the intensive system, since return trips are included.

6.4.2 Boundaries

Both scenarios have the same chain trajectories. They differ in the use of artificial fertilizer and the use of pesticides for crop protection. Furthermore, the difference in yield affects the required area for poplar production. Poplar is chosen since it has a high energy yield compared to other energy crops. This chapter does not take into account the energy used for consumption of water for irrigation, which can be a substantial amount (Nonhebel, 2002). Nonhebel (2002) shows that irrigated systems can have a four times higher yield, but require six times the input resulting in a lower efficiency. Therefore irrigation is not taken into account. When it comes to storage and pre-treatment and conversion, the indirect energy for the construction of the facilities is not taken into account. The indirect energy required for construction of facilities is assumed to be negligible when taking the total lifetime of storage and conversion facilities into account. Therefore storage only includes loading and unloading movements. When it comes to pre-treatment, only direct energy consumed for chipping is taken into account; drying is assumed to be done passive in an ambient environment. The midstream part of the chain calculates the conversion to SNG and subsequently to CNG. The downstream part of the chain is the same for both scenarios, and therefore only the end use (i.e., combustion in a natural gas driven vehicle) is taken into account. Therefore the possible difference in local distribution of biogas compared to transmission over longer distances for natural gas is not taken into account. The basic line of reasoning is that a gasification plant should be located near a natural gas injection point, resulting in a similar downstream supply system. Hence, in the end it is of little interest whether a methane molecule with an organic origin is actually combusted in a CNG driven vehicle or in another sector, as long as it is allocated to transport fuel in statistics.

6.5 Results

6.5.1 Land use and forwarding distance

The required area for biomass production is dependent on the biomass demand and the average poplar yield. The demand for biomass is dependent on the capacity of the gasification plant which is in this case 800 MW. This requires 914 MW of biomass when applying a conversion efficiency from biomass to SNG of 70% and an uptime of 80%. The energy density of poplar on a wet basis is taken as 12 MJ kg^{-1}. The energy density is 17 MJ kg^{-1} after drying towards a moisture content of 20%. This results in a demand of 28.9 10^6 GJ a^{-1} with a gasification uptime of 80%. For scenario 1 and 2 this results in the requirement of 0.1 Mha and 0.48 Mha respectively. This results in a forwarding distance for scenario 1 and 2 of 15.8 km and 69.3 km respectively.

This results in a new insight compared to previous literature in which the importance of the energy consumed by the use of artificial fertiliser is often emphasized (Nonhebel, 2002). This is visible in Table 10, which shows that the EE is roughly the same for both scenarios. This case study shows that the increased energy use for forwarding in the extensive (scenario 2) system has such a large effect that the extensive system performs worse than the intensive system. The assumed installed capacity determines the demand for biomass, resulting in a substantial increase in land requirements in the extensive scenario 2. The increase in land requirements results in increased energy consumption for ploughing, forwarding, and harvesting, which compensates for the absence of crop protection and artificial fertiliser. Indirect energy for harvesting is related to maintenance of the harvesting equipment which is expressed in energy input per distance. This means that in an extensive (scenario 2) system, the indirect energy for harvesting is larger, since the land requirements also increase. When choosing one hectare as a starting point for reasoning, the results might be interpreted differently.

Table 10: Results of the model simulations

		Fossil input		
		Scenario 1	Scenario 2	
Ploughing and preparation	Direct	6.65E+06	3.19E+07	MJ a^{-1}
Crop protection	Direct	2.15E+07	0	MJ a^{-1}
	Indirect	2.00E+07	0	MJ a^{-1}
Forwarding	Direct	1.29E+08	5.67E+08	MJ a^{-1}
	Indirect	3.50E+07	1.53E+08	MJ a^{-1}
Harvesting	Direct	2.13E+08	2.13E+08	MJ a^{-1}
	Indirect	2.81E+06	1.35E+07	MJ a^{-1}
Artificial fertiliser	Direct	1.80E+07	0	MJ a^{-1}
	Indirect (application)	2.80E+06	0	MJ a^{-1}
	Indirect (production)	2.48E+08	0	MJ a^{-1}
Chipping	Direct	3.36E+08	3.36E+08	MJ a^{-1}
Loading / unloading	Direct	5.00E+08	5.00E+08	MJ a^{-1}
Total fossil input		1.53E+09	1.81E+09	MJ a^{-1}
Energy in biomass		2.89E+10	2.89E+10	MJ a^{-1}
Energy in SNG		2.02E+10	2.02E+10	MJ a^{-1}
Energy in CNG		1.95E+10	1.95E+10	MJ a^{-1}
Performance indicators				
EE		62.3	61.3	%
ER		12.7	10.8	-

Results in Table 10 are expressed in total energy input per annum for both systems.

6.5.2 Performance indicators

The results from the simulation of the model are given in Table 10. Based on this data the EE and ER for both scenarios are estimated. The results show that when the whole supply system is taken into account the EE and ER do not represent the difference in land use very well. Despite the fossil input from artificial fertilizer being almost 18% of the total fossil input in scenario 1 this gets more than compensated for by amongst others, the increase in forwarding distance in scenario 2.

In order to estimate the distance covered per hectare by a passenger vehicle, this research uses the Maruti Suzuki Ertiga as an example. The mileage for CNG is given as 22.8 km kg^{-1} (Carblogindia, 2013)[7]. Considering CNG consists out of pure methane, the energy density is 55.6 MJ kg^{-1}. Given the net CNG yields of 179 and 36.8 GJ ha^{-1} for scenario 1 and 2 respectively, the Maruti Suzuki Ertiga could cover 1.6 – 7.6 10^4 km ha^{-1}. Roughly, 46 10^7 GJ is consumed in road transport in the Netherlands. The contribution from CNG based on 800 MW production capacity would therefore be 4.2% of the annual transport fuel consumption. When including the fossil input and therefore calculating the net energy, the contribution is 3.9% and 3.8% for the intensive and the extensive system respectively.

The estimated transport distance per hectare is in the same range as the distances calculated by Dijkman and Benders (2010)[8]. The values are not directly comparable due to different system boundaries, but it seems that an intensive biomass production system results in a distance driven on CNG which is about 4 times higher than the system from Dijkman and Benders (2010)[8] for electric driving based on wood. The difference is due to their choice for the average scenario, whilst this research analyses a scenario with high intensity. Furthermore, the conversion from wood to electricity is less efficient than the conversion of wood to CNG. An electric vehicle is more efficient when it comes to fuel use, but the difference in system boundaries combined with the previous arguments seem to be a decent explanation for the difference in outcome.

The results show that an intensive system is favourable, since the EE gives no clear indication; land use is the most important constraint.

6.5.3 Implications for the end states

Considering that the consumption of transport fuels is in the order of 30% of the total energy consumed in the EU, this research assumes that about 30% of the available biomass is used for the production of transport fuels. Based on the high estimates in the renewables end state this would be around 1.5 EJ in 2020 corresponding to almost 80 gasification plants with 800 MW capacity and a minimum land requirement of 8.0 Mha, assuming high yields can be achieved. These land requirements correspond to 4.5% of the total utilised agricultural area (Eurostat, 2013)[9]. This suggests that the availability of agricultural land is not the main issue. However, this research assumes high yields, which might result in the requirement of more land than estimated here. Furthermore, a contribution of 1.5 EJ from 8.0 Mha is approximately 10% % of the energy consumed in European transport in 2012. This shows that the contribution of 3.8 Mha is required to broadly foresee in the targets set by the European Commission for blending of biofuels. Substantial reduction of carbon emissions is however not obvious, since the existing biofuel supply chains are not carbon neutral. This means that a 10% reduction in carbon emissions is not feasible for the EU by the system described here.

6.6 Discussion

To illustrate the limitations and implications of intensive biomass production, the discussion section is partly used to describe the trade-offs a farmer has to determine before deciding on which crop he will grow. As an example, the province of Flevoland is used, since the soil in Flevoland has the highest fertility and thus yields in the Netherlands. CBS Statline (2014)[10] shows that 98500 ha are used as agricultural land, which is a combination of crop- and grassland. An 800 MW gasifier would therefore 102% of this acreage in an intensive system, suggesting that all grassland should be converted. A farmer has an economic point of view when it comes to deciding which crop is most suitable to produce. Currently, potatoes are mostly grown in this region. According to KWIN-AGV (2012)[11], the net profit per hectare is in the order of €4,500. In order for a farmer to start producing poplar the profit should be similar. When using a high yield of 12 ton ha^{-1} the farmer should make €0.38 kg^{-1} dry matter. This means that, without taking the inputs into the biomass production system into account and also the cost for biomass conversion, let alone added taxes, the cost for SNG would be in the order of €0.8 m^{-3}. This is already higher than the current average consumer price for natural gas in the Netherlands.

The results show that an intensive system is favourable, since land availability is a limiting factor, especially within the Netherlands. However, applying the most fertile soils in the Netherlands does not appear to be economically feasible as emphasised by the previous paragraph. Hence, the estimated SNG price is too high. Therefore a similar analysis is done for sugar beets in the Groningen area where lower profits per hectare are observed. The net profit is in the order of €1600 ha^{-1} for sugar beets on clay soils in the Northern part of the Netherlands. A reduction of 20% in yield is assumed based on the difference in potato yield for both regions (i.e., Groningen and Flevoland). The price for poplar should then be €0.17 kg^{-1} dry matter, resulting in a price of €0.35 m^{-3} SNG. This number has, however, the same limitations as the €0.8 m^{-3} estimated before.

The current price for imported gas is $9.24 MMBtu^{-1}; this corresponds to roughly €0.27 m^{-3} natural gas. This corresponds to roughly €120 per ton dry matter produced. However, the actual turnover will probably be half or less, since the fossil inputs and conversion to SNG should also be taken into account. This underlines that it is currently economically unfeasible to produce poplar in the Netherlands. It is probable that this line of reasoning also holds for other regions in Europe. The Ukraine is often argued to be a country with large potential for biomass production. The crops produced there also end up on the world food market where they earn a similar amount of money per unit of mass produced.

This chapter shows that at least 0.1 Mha is required to foresee in the demand for an 800 MW biomass gasification plant. The average field crop producing farm in the EU27 has a size of roughly 43 ha, requiring over 2,300 field crop farmers to cooperate in such a project with all their arable land. Miedema et al., (2014)[12] emphasize the impact of biomass transport on the system performance. These distances should be reduced as much as possible, resulting in an organisational challenge when a large group of farmers is needed to cooperate in a local setting.

Panoutsou et al., (2009)[13] provide an overview of the biomass supply in the EU27. Besides agriculture, they discuss three other sectors namely; forest, industry and waste as biomass resources. The results of the extensive review of literature by Panoutsou et al., (2009)[13] are presented here in Table 11.

Table 11: Biomass supply in the EU27, derived from Panoutsou et al., (2009)[13]

The data are converted from ktoe to EJ.

	2000	2010	2020
Forest	1.8	1.9	2.2 EJ
Industry	1.1	1.2	1.3
Waste	0.8	1.3	1.8

When the sum of these figures is taken it roughly corresponds to the total demand in 2020 based on the biomass contribution displayed in Figure 54. The data in Table 10 is expressed as primary energy. This means that about 30% to 50% of the energy is lost due to conversion. Furthermore, the actual availability of biomass from these sectors is disputable. More than half of the forest in Europe is privately owned (Schmithüsen et al., 2008)[14]. According to Eurostat (2011)[15] this is about 60%. When focusing on size classes of forest ownership there are data available for nine countries (Schmithüsen et al., 2008)[14]; only 1% of the privately owned forest has a size over 50 hectare. This 1% however, owns 41% of the private forest area. It is probable that the forests below 50 hectare are not suitable for harvesting equipment and therefore, the technical feasibility of harvesting the increment rate from these private forests is expected to be rather low. Furthermore, the harvested quantities are often used in the paper, pulp and timber industry and therefore not directly available for energetic purposes.

The value for industry consists for 40% out of black liquor (energy basis), which is a by-product from the paper and pulp industry. This black liquor is largely produced, but also consumed in the paper and pulp industry. That means it is already applied for energy and thus not freely available. Besides this, the wood used for paper and pulp comes from the agricultural or forestry sector, which might result in double counting of biomass. Furthermore, industry is focussing more and more on closing cycles. Hence, the European Commission emphasises the need for a bio-economy, in which waste is not seen as waste, but as a co-product with potential value. Therefore, waste streams are not always seen as waste streams anymore, but whenever possible applied as feedstock in other industrial processes. If this becomes a trend, one cannot argue that biomass supply equals availability for bioenergy.

The increase in availability of biodegradable municipal waste suitable for incineration is due to the assumption by Panoutsou et al., (2009)[13] that "the resource is expected to quadruple in 20 years". This is justified to some extent, since the Landfill directive aims to decrease the amount of landfills. Therefore they assume that waste that was available for production of landfill gas becomes available for incineration with energy recovery. The decrease in energy from landfills is however, nothing compared to the increase in energy from incineration. When arguing that the European population is rather stable or increasing slowly and thus waste constituted by the population is not obviously increasing that much.

6.7 Conclusions

This chapter shows that a gasification plant with a large capacity of 800 MW, requires over 0.1 Mha for the production of short rotation forestry in an intensive system. On a Dutch scale this contributes with four percent to the current quantities of energy consumed in road transport. Furthermore, 0.1 Mha is about 5% of the Dutch agricultural area.

The difference between an extensive and intensive production system is only visible in the land requirements and not in the EE or ER. Therefore, in the scenarios analysed in this chapter, it seems that the energy consumed by the use of artificial fertiliser in the intensive system is largely compensated by increased forwarding distances in the extensive system.

Even though the developed end states show a relatively large use of biomass for energetic purposes in the coming decades, the choice for the produced crop is at the farm. Besides this, the chemical industry is probably prepared to pay more for a bio-based product than the energy industry. This underlines that a significant increase in price is necessary in order to persuade farmers to start producing energy crops by converting grassland or at the cost of food or other valuable crops. Therefore, the biomass has to be supplied from other sectors such as: forestry, industry and waste. In a renewable or gas focused energy system where the demand for biomass is twice as high as in the business as usual end state (Figure 54) the supply from aforementioned sectors is not sufficient.

The limitations of the use of biomass for energy are therefore in the availability of land, combined with the economic feasibility for farmers to produce energy crops. The primary supply from other sectors could be sufficient, but the technical and organisational feasibility of harvesting from forests remains critical. Industrial streams are often already used and waste streams are not expected to increase as much as thought by Panoutsou et al., (2009)[13]. This underlines why the BAU end state is the closest to reality, instead of the more optimistic High Res and Gas end state, when it comes to biomass use for energetic purposes.

Key findings

When looking at the BAU end state, which seems to be the most obvious when it comes to biomass consumption one needs 4.5% of land available in the EU in order to fully supply the transport sector with biogas. This could theoretically be accommodated within the BAU end state. However, this would be more complicated for the RES and GAS end state with higher demands. This is a clear limitation. There will be competition with land use for production of food, when substantial quantities of dedicated biomass are required for energetic purposes.

For a high density populated country (such as the Netherlands) it is impossible to produce the biomass fuels to their supply their own system. This is further complicated by the competition between food and energy. Not only the food and fuel discussion, but also due to competition between feedstock for other applications (e.g. bio plastics). This will trigger increased competition between the use of biomass as feedstock.

Looking at a possible business case for biomass, it is more obvious to work with economic cascading. This means that organic streams available for energetic purposes have a degraded quality compared to the use of dedicated energy crops. This will result in a challenge when aiming to include substantial amounts of green gas in the existing natural gas supply system.

6.8 References

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7 GRID IMPLICATIONS OF DECENTRALIZED RENEWABLE ENERGY GENERATION AT VARIOUS DEMAND SCALES

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7.1 Introduction

This chapter presents an analysis of decentralized renewable energy generation: self-consumption characteristics of power from solar-photovoltaics (solar-pv), wind and biogas at various demand scales.

Renewable energy is an essential element in the transition towards a more sustainable energy system. Most future energy scenarios suggest significant growth of renewable energy in the energy mix. Large shares of renewable energy in the energy mix are often associated with requirements to adapt existing energy grids to decentralized generation and potential supply and demand mismatches. The extent of grid adaptation requirements depends on the scale and type of renewable energy technology. High-level energy scenarios with long temporal and large spatial perspectives in general do not elaborate on the extent of grid adaptation requirements implicit from the future energy mix suggested in those scenarios. Part of that lack of specification may be explained by the unavailability of suitable tools to make high-level assessments of the impact of high penetration rates of intermittent renewable energy on existing energy infrastructure.

This research provides a general-purpose tool to aid in the interpretation of shares of intermittent renewable energy in future energy scenarios. By highlighting general self-consumption characteristics of intermittent renewable energy with regard to various sizes of community-scale household-sector demand patterns, this research adds high-level insight into the implications of growing decentralized generation on energy infrastructure. Central to this research are two questions:

- What are typical sizes of consumer bases that can, on average, absorb the energy generated by certain intermittent renewable energy generation capacity within their typical demand patterns?
- How do different intermittent renewable energy sources compare with regard to the penetration levels from which additional energy infrastructure is likely to be required to manage imbalances between demand and supply?

A model-based approach is used to derive abstract illustrations of self-consumption characteristics of typical decentralized renewable energy generation technologies in a residential sector context. The sections that follow first provide relevant background material, then outline the approach used in this study, and thereafter present the results. A discussion on the derived spatial fingerprints concludes this research.

7.2 Decentralized renewables

The clusters of future energy scenarios outlined in Chapter 3 of this report suggest that even in conservative scenarios the share of renewable energy in the energy mix is likely to increase twofold, increasing from about 10% in 2010 to about 20% by 2050. More sustainable scenarios suggest that the share of renewable energy in the energy mix may even increase as far up as 50% by 2050. The renewable energy discussed in most future energy scenarios includes electricity generated using a combination of sources that are typically deployed on a decentralized, comparatively small spatial scale, such as solar-pv, wind turbines and biogas from anaerobic digestion. By 2050, shares of such decentralized energy sources may be in the wide range of roughly 10%-30%, with suggested maximum penetration levels of almost 50%.

Power from solar-pv and wind turbines is often associated with supply intermittency and/or unpredictability, while for biogas the supply is typically stable and continuous. In general, such decentralized renewable energy sources relate to difficulties to match energy supply and demand (Akhmatov & Knudsen, 2007; Eltawil & Zhao, 2010; Lund, 2005)[1,2,3]. Resulting surpluses and shortages require interaction with peripheral infrastructure such as energy grids or storage facilities to mitigate any possible imbalance between energy supply and demand (Wolfe, 2008)[4].

Different sources of renewable energy have different typical generation patterns due to intermittency and/or unpredictability, and thus each have their own characteristic issues with regard to energy system integration and demand-supply balancing. For solar-pv, power generation is dependent on the amount of solar irradiation at the location of the installation. Solar irradiation follows a highly predictable day-night sinoid pattern coupled with a seasonal sinoid pattern. Variation and uncertainty with regard to actual irradiation relative to theoretical irradiation may be caused by weather irregularities such as cloud cover and/or precipitation. For power from solar-pv the balancing issue lies not in its predictability, but in scheduling. Solar-pv power production peaks around mid-day when irradiation levels are the highest, and drops to negligible levels between sunset and sunrise. Power demand in the residential sector generally peaks after sunset, when solar-pv is unable to accommodate that demand. Power from wind turbines is theoretically available during both day and night. However, wind turbine power production is highly dependent on wind speeds. Predictability of wind speeds is generally limited, as wind speeds may vary on very short time bases. The demand-supply mismatch issue of biogas is of a different nature: biogas production is typically a continuous process, with only little variation in hourly production patterns. Such continuous supply patterns, too, do not match with the generally whimsical nature of residential energy demand patterns.

Another characteristic that distinguishes between solar-pv, wind energy and biogas are their typical deployment scales, capacity scalability and type of final energy supply. Solar-pv can be deployed on various scales, ranging from micro-installations of only several hundreds of Watts to larger scale solar-farms of multiple megawatts. Solar-pv is a popular renewable energy source in the residential sector because of its scalability, enabling households to set up private installations according to own preferences. Typical residential sector rooftop solar-pv installations generate up to 1 or 2 kW_e. The deployment scale of wind is typically larger. Apart from micro-scale rooftop-mounted turbines with generation capacities less than several kW's, wind turbine capacities generally range from several hundred kW's to several MW's. Thus, typical wind turbine installation scales are substantially larger than single-household. Typical farm-based biogas produced through anaerobic digestion occupies a capacity range somewhat similar to wind power: up to between 1 and 2 MW_e. The crucial difference between biogas and solar-pv or wind energy is that biogas is not limited to supplying power as the final energy type. By combustion in a combined heat and power facility (CHP), next to power a substantial amount of heat energy can be produced. Typical heat production capacity is generally in the same range as power.

Several simulation studies have focused on the practical implications of high shares of intermittent renewable energy with respect to energy infrastructure (ie. Mason et al., 2010; Connolly et al., 2011; Krajacic et al., 2011a; Krajacic et al., 2011b; Elliston et al., 2012)[5,6,7,8,9]. Those studies typically deploy small temporal resolution models to simulate, assess and optimize the integration of intermittent renewable energy in country-scale power systems. Research on smart grids and smart energy management often highlights the problem of demand and supply mismatch with regard to decentralized power generation. Such research generally applies a micro-scale approach to derive situation-specific energy balance optimization solutions (ie. Driesen & Belmans, 2006; Driesen & Katiraei, 2008; Mohd et al., 2008)[10,11,12]. Most smart-grid research focuses on issues related to power, although natural gas or biogas may have some role to play in smart grids (EU, 2011)[13]. Optimization options proposed and investigated in smart-grid research contexts include (but are not limited to) demand management such as load scheduling and energy buffering. Without grid adaptation, additional infrastructure or specific energy system management algorithms, up to about a third of typical northwest European household energy consumption may be supplied by solar power (Thompson & Infield, 2007; Hashemi et al., 2014) [14,15].

Future energy scenarios with a wide spatial perspective and long-term time horizon, such as those considered in the context of The Big Picture, are considerably abstract by nature and generally provide only limited detail with respect to specific technologies or infrastructure management. Insights from applied studies into meso- or micro-grid optimization are only of limited use in the interpretation of typical Big Picture scenarios. However, practices from applied studies such as model simulation do provide a foundation from which to derive more general and abstract insights into the behaviour of different intermittent renewable energy technologies vis-à-vis energy systems.

7.3 Methodology

To assess the natural integration scale of intermittent renewables, a slightly modified version is deployed of a dynamic material flow model that was constructed in the context of a sister project within EDGaR ('Decentralized gas storage to balance demand and supply', also known as 'FlexiStore'). The model is a deterministic simulation model designed to assess the effect of decentralized biogas storage on the potential to locally consume significant amounts of locally produced renewable energy including biogas, solar-pv and wind. The model simulates a local energy system in which demand is fulfilled through allocation of various local or non-local, renewable and non-renewable energy sources. Figure 57 provides a simplified schematic representation of the model.

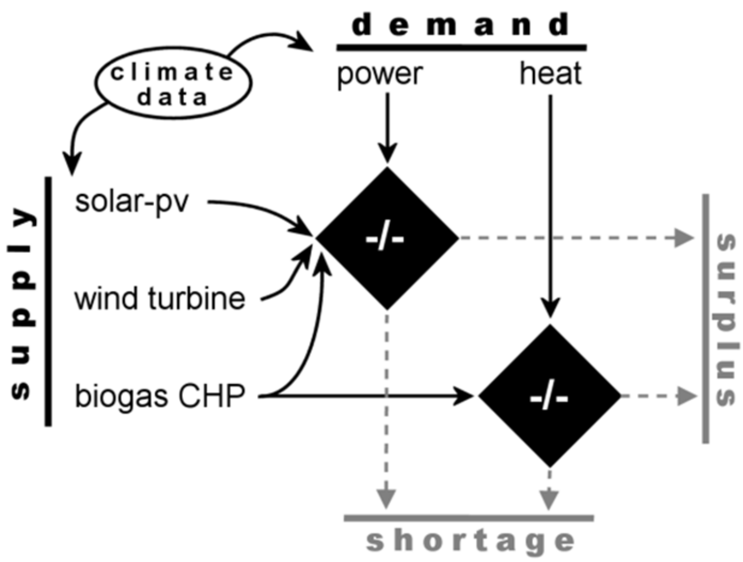

Figure 57: Schematic representation of the adapted model used to simulate the integration of intermittent renewable energy in a residential sector energy system.

Model simulations represent one full year, calculated on an hourly basis. The input consists of typical supply and demand patterns spanning 8760 hours. The input patterns are a mix of actual, historical measurement data and generated or synthesized data. Central to both the supply and demand patterns are actual climate data. This climate data consist of the hourly weather data gathered at weather station Eelde, the Netherlands, between 2001 and 2010 (KNMI, 2013)[16], plus an additional 'typical' climate year (ECN, 2012a)[17]. The demand and supply patterns are generated from the climate data (ECN, 2012b)[18], and where necessary, converted to hourly patterns through combination with an alternative dataset

(ECN & Benders, 2012)[19]. Energy demand patterns make a distinction between four different types of residences: newly built, renovated houses, apartments and existing, older houses, and between power, space heating and water heating. Table 12 lists key figures indicative of the energy demand pattern characteristics. For this research, only the renovated house residential demand pattern was used. The energy supply patterns include power from solar-pv and wind turbines, and biogas for heat and power. Table 13 lists key figures indicative of the energy supply pattern characteristics. The model does not take transport energy loss into account, but it does implement a normal distribution spread of demand patterns for larger numbers of households. For this research, the modified version of the model excludes energy storage options, and excludes the requirement to fulfil demand. Imbalances between energy demand and supply during the course of simulations are only registered rather than actively mitigated through interaction with peripheral energy infrastructure.

Table 12: Key parameters of model residential energy demand patterns (MJ)

Element of energy demand		**Household type: renovated**
Power	Annual total	11.7 GJ
	Average	1.35 MJ/h
	Standard deviation	0.66 MJ/h
	Maximum	2.81 MJ/h
Space heating	Annual total	11.0 GJ
	Average	1.25 MJ/h
	Standard deviation	1.94 MJ/h
	Maximum	9.93 MJ/h
Water heating	Annual total	9.0 GJ
	Average	1.03 MJ/h
	Standard deviation	1.95 MJ/h
	Maximum	6.93 MJ/h

The energy source's spatial fingerprints are derived from several consecutive model simulations, each with an increasing number of consumers for a constant generation capacity. By varying the number of consumers we vary energy demand and thus the absorption capacity of the energy generated by the intermittent source. In addition, the demand pattern is smoothed for larger numbers of consumers, as a result of which the potential mismatches between demand and supply are reduced. The energy demand size spans a range that encompasses a typical total amount of annual energy generation for the different intermittent energy sources.

For solar-pv and wind power, the simulations are carried out for each of the available climate year datasets to derive an error margin reflecting the influence of yearly weather differences. Since weather patterns do not affect biogas output, we varied biogas simulations not by climate year. Instead, we simulated only a single biogas utilization profile in which all biogas produced is directly combusted to generate power. For each of the simulations, we register the total amount of surplus renewable energy generated over the course of the simulation; derive the utility ratio as the share of energy demand that was directly supplied through local generation. We answer the two research questions on the basis of visualizations of the simulation results.

Table 13: Key parameters of model renewable energy supply patterns

	Solar-pv	Wind	Biogas
Installation	40 m^2 of $200W_p$=$8kW_p$ South orientation 45° tilt angle	100kW, Hub height 35m, Uptime: 100%	200.000 Nm^3/year CH_4-content 60% CHP_{ne}: 40%
Annual total power	23 GJ	753 GJ	1572 GJ
Average	2.6 MJ/h	86 MJ/h	180 MJ/h
Standard deviation	4.5 MJ/h	107 MJ/h	0 MJ/h
Maximum	21.4 MJ/h	360 MJ/h	180 MJ/h

7.4 Results

The results show that power generated from solar-pv, wind turbines and biogas each have a distinctly different self-consumption fingerprint, as illustrated in Figure 58, Figure 59 and Figure 60, respectively. The model-derived self-consumption characteristics of each of the investigated renewable energy sources will be discussed separately below.

Figure 58 shows the self-consumption characteristics of an 8kWp solar power installation. The blue curve in Figure 58 shows the self-consumption ratio, or the share of power produced from the applicable solar-pv installation that could be utilized directly. The red curve in Figure 58 shows the share of directly used solar-pv power relative to the overall total power demand of the various demand sizes. The extra dashed curves represent the averaged results of the same simulation, but for an installation of 4kWp (20m2x200Wp).

For power from a $8kW_p$ solar-pv installation, the self-consumption potential for a single household is fairly minimal. Only about 15% of the annually generated power can be utilized directly, leaving the vast majority of power requiring an alternative destination. The intersection point at two households marks the demand size at which net energy neutrality may be achieved if suitable temporary storage can be deployed for the share of solar energy that cannot be utilized directly. At this point, still only about a quarter of the annually generated power can be utilized directly. The self-consumption ratio of this solar-pv installation reaches 50% for a demand size of five households. At that demand size, the $8kW_p$ solar-pv installation only provides a fifth of the overall energy demand of those five households.

The yearly solar-pv production caused by weather pattern variation is rather minimal. Between the 11 climate years used in the simulation, the self-consumption ratio of this solar-pv installation only varies in the single percent range. This is largely in line with notions of relative of solar-pv power production certainty as solar irradiation follow rather predictable patterns.

Figure 59 shows the self-consumption characteristics of a small-scale 100kW wind turbine. The blue curve in Figure 59 shows the self-consumption ratio, or the share of power produced from the applicable wind turbine that could be utilized directly. The red curve in Figure 59shows the share of directly used wind power relative to the overall total power demand of the various demand sizes.

The self-consumption pattern of power from a 100kW wind turbine reflects its larger generation capacity relative to solar-pv. Self-consumption for single numbers of households remains below 10%. 25% self-consumption can be achieved for a demand size representing about ten households. At 50 households drawing power from the same wind turbine, the self-consumption curve intersects the curve representing the share in overall total power demand. At the intersection, the self-consumption ratio and the energy supply share are both 50%. The self-consumption curve approaches 100% from about 250 households, but by then the share of wind power relative to total power demand has dropped below 20%.

Weather patterns have a markedly more prominent influence on the self-consumption characteristics of wind power than for solar-pv. Between the 11 simulation years, the difference between the best and worst self-consumption ratios can be as large as 10%. The influence of weather variation is most prominent for demand sizes up to about 200 households, after which the curves representing different simulation years start to converge.

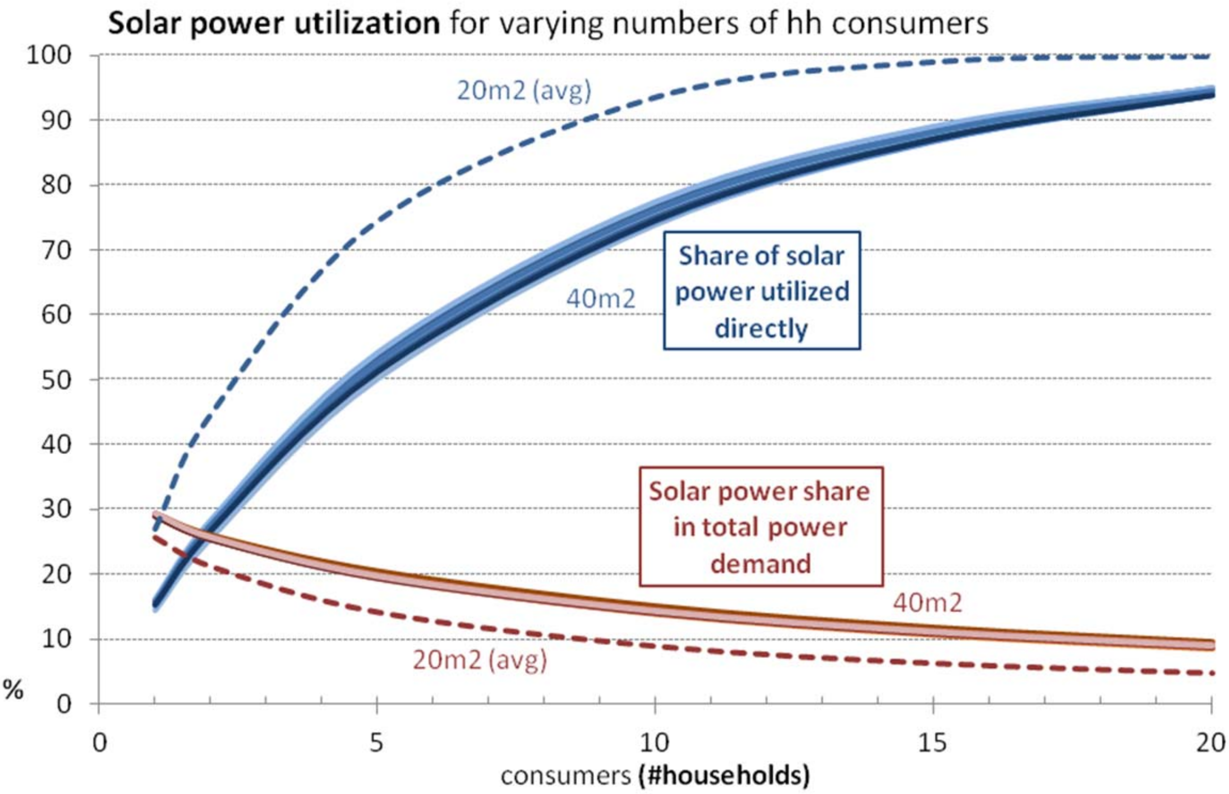

Figure 58: Self-consumption characteristics of an 8kW$_p$ (40m^{2}x200W$_p$) residential-scale solar power installation.

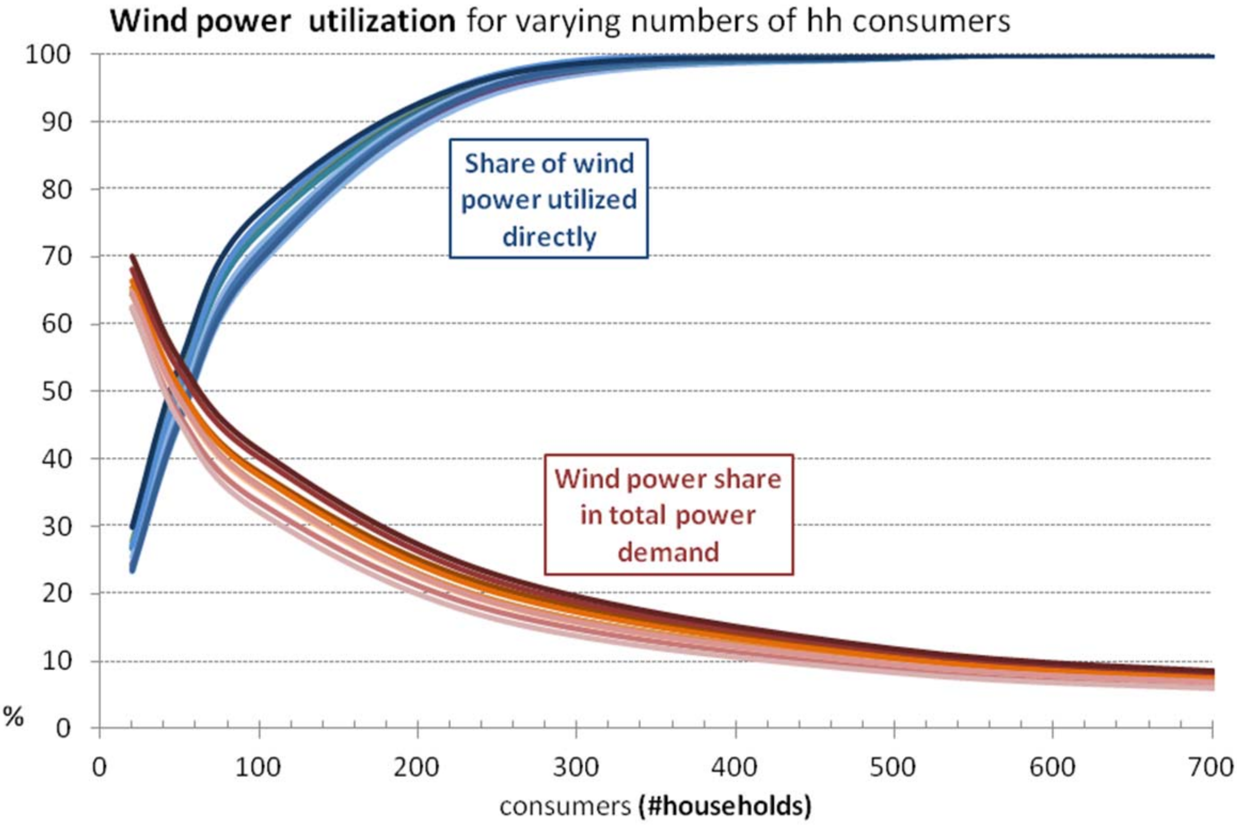

Figure 59: Self-consumption characteristics of a single small-scale, 100kW wind turbine.

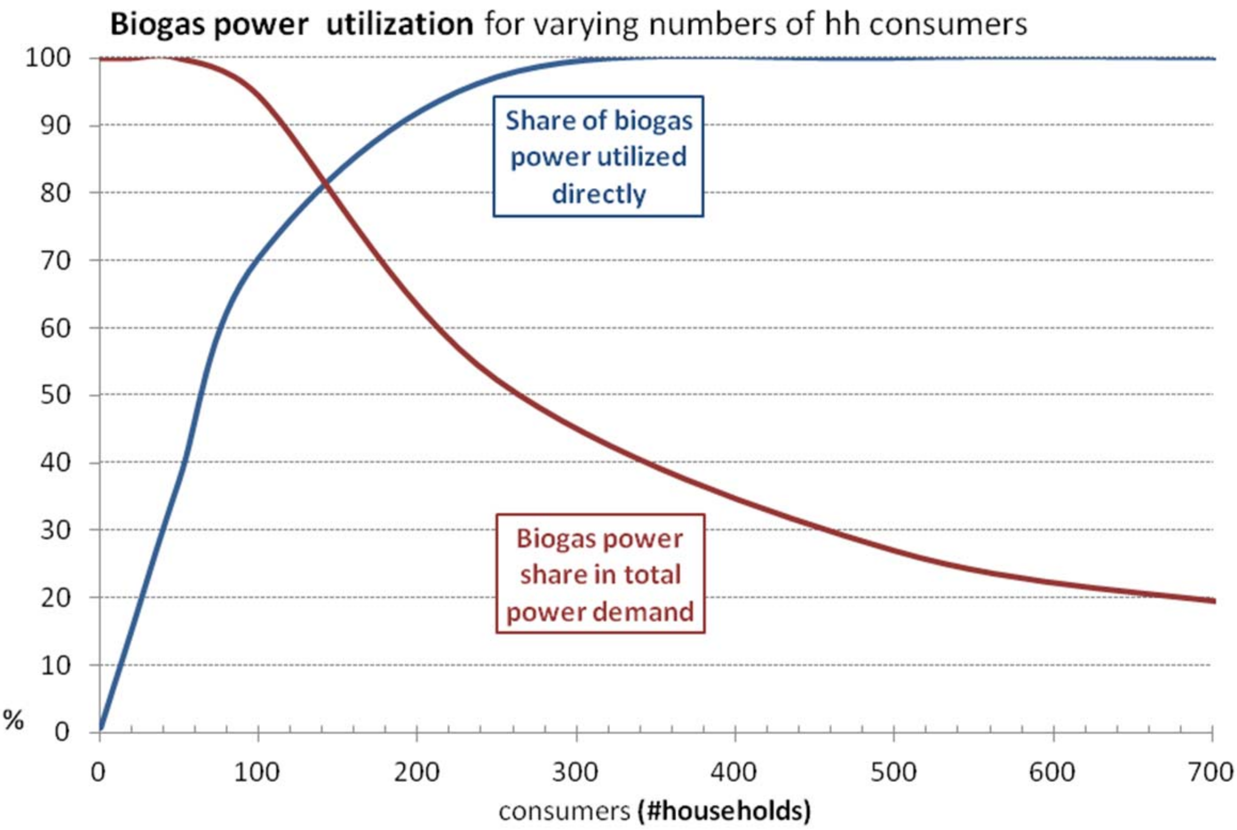

Figure 60: Self-consumption characteristics of a biogas-fuelled power generator.

Figure 60 shows the self-consumption characteristics of a biogas-fuelled power generator. The blue curve in Figure 60shows the self-consumption ratio, or the share of power produced by the generator that could be utilized directly. The red curve in Figure 60 shows the share of directly used biogas power relative to the overall total power demand of the various demand sizes.

Power production from biogas is arguably weather-independent, and can be modelled as a stable and continuous power supply stream that is available during all hours of the day. To some extent, the supply-demand balancing characteristics of biogas power are reminiscent of those of wind power. This is clearly reflected in the self-consumption curve of biogas power, where the similarity in shape with the self-consumption curve of wind power is indicative of similar match and mismatch patterns. For biogas power, too, the self-consumption curve passes through the 50% mark for a demand size representative of about 70 households. 100% direct utilization of biogas power can be achieved for demand sizes representing approximately 300 households and over. The major difference between biogas power and wind power is the position of the curve representing the share of biogas power in the total energy supply. The continuous supply pattern of biogas power enables full demand coverage, if capacity is sufficient. In this case, power from biogas may cover 100% of the power demand for up to 60 households. For larger demand sizes the share of biogas power in the energy supply declines following a sigmoid curve.

The positioning of that curve relatively high on the y-axis means that the self-consumption curve and the energy supply share curve intersect at larger demand sizes and at a higher self-consumption ratio. From Figure 60 it can be seen that the intersection between the two curves occurs at a demand size representing about 150 households, and the associated self-consumption ratio at that point is over 80%. Until that intersection, so for demand sizes smaller than 150 households, the modelled biogas-fuelled power supply may potentially cover the total aggregated power demand of those households if adequate buffering or storage options were available. The high self-consumption ratio at the intersection of the curves indicates that for higher demand sizes full coverage of energy demand can be ensured with comparatively little requirements for grid interaction or storage relative to power from solar-pv or wind turbines.

7.5 Discussion

The results of this research present general model-derived self-consumption fingerprints for power produced by solar-pv, wind turbines and biogas. Although the self-consumption characteristics are substantially different from one another, they all have in common that high self-consumption ratios are only achieved for large demand sizes and large numbers of households. Demand sizes for self-consumption ratios over 90% are typically several times larger than the typical total annual power production. At those demand sizes, the contribution in the overall total energy supply is in general also strongly reduced.

Higher self-consumption ratios correspond to lower impact on the grid the installation is connected to. If we assume that the impact on the grid is negligible only at (almost) complete self-consumption and no surplus power fed into the net, then this research indicates that in the residential-sector energy mix the share of solar power may only remain below 10% and the share of wind power below 20%. Any shares higher than that would lead to surplus power fed into the grid and thus affect grid stability. However, previous research suggested that power grids may be somewhat resilient to the feed-in of small amounts of surplus power (Hashemi et al., 2014)[15]. To some extent that may explain the difference with non-impacting solar power penetration levels of 30% (Thompson & Infield, 2007)[14] and 34% (Hashemi et al., 2014)[15] reported in literature. Other explanations would have to be sought in methodological differences such as demand pattern generation. Thomson & Infield (2007) use a combination of actual measurement data and model-generated patterns define diverse demand patterns for a fixed set of 1,262 consumers. Hashemi et al. (2014)[15] extrapolate actual power consumption data measured at a small number of households. This research follows a comparatively more theoretical and abstract approach, using model-derived demand patterns only, multiplied and stochastically smoothened for larger demand size. Despite explicit pattern smoothening, peaks and troughs in pattern become more explicit with larger consumer sizes. Actual, real-world demand patterns may show less prominent peaks and troughs.

This research used data typical for a situation as it may exist in the Netherlands, today. Differences in both spatial and temporal parameters of the simulations may lead to different outcomes. From a spatial perspective, climate aspects affect both demand and supply patterns. Household-sector power demand in the Netherlands typically peaks during evenings, reflecting behavioural patterns of families returning home and switching on lights and appliances. Those peaks are generally more pronounced in wintertime, when early dusk and darkness increase demand for lightning. Daytime household power demand is comparatively little. While the Dutch power demand patterns may be typical for northwester Europe, it may not apply for other areas such as, for example, southern Europe (Spain etc.), where different climate characteristics may lead to different demand patterns. In southern European countries, daytime household power demand may be higher due to different behavioural patterns and the use of different appliances (air-conditioning). Moreover, climate conditions in southern European countries may also lead to different power supply patterns. Solar irradiation is higher in Spain than in the Netherlands, but power generation by wind turbines may be more fruitful in the Netherlands than in Spain. From a temporal perspective, it is important to note that the patterns used in this research are relatively recent, and do not reflect potential future technology developments. In the household sector, likely developments that could affect this research's results are, for example, improvements in insulation and shifts to more efficient lighting and appliances. Such developments may affect both gas (heat) and power demand patterns.

The shapes of the curves illustrating the self-consumption characteristics as shown in Figure 58, Figure 59 and Figure 60 may be somewhat different if we'd allow load scheduling and additional (grid) energy storage infrastructure. Load scheduling is a form of demand management that can reduce the burden of surplus power on the local grid by shifting demand peaks laterally on the timeline (Widen, 2014)[20]. The potential and impact of load scheduling may be different from one household to another, and from one area to another, as the extent of the mismatch between energy supply and demand is dependent on the type of energy consuming appliances installed and the location of energy sources relative to their natural supply streams. Depending on the effect of load scheduling, the graphs illustrating self-consumption characteristics derived in this research will look different. In all likelihood, the self-consumption curve increases more strongly, whereas the curve representing the share in the overall total energy demand will decrease more gradually. 100% self-consumption ratios may be reached for smaller demand sizes, but not immediately as it is unlikely that load scheduling is possible for all energy consuming appliances in a household. The addition of storage is independent of household characteristics, and may even increase self-consumption potential to 100% for minimal demand sizes. Storage works two ways: it prevents overvoltage (Hashemi et al., 2014)[15] and undersupply (Nijhuis et al., 2014)[21], both of which may negatively affect grid stability. If the storage capacity is large enough and meets situation-specific load and supply criteria, then all supply-demand mismatches may be eradicated. However, characteristics of current power storage technology deem it unlikely to be deployed on a scale large enough to mitigate all power supply-demand mismatches. Biogas, however, may be stored more easily: biogas output can be moderated using the pressurization range of the production facility, but the potential is limited and the periodicity is on a multi-day scale (Hartlief, 2015)[22]. For larger buffers or different response times dedicated storage facilities would be required.

Following the acceptable non-impacting penetration rates derived in this research, we may argue that the shares of renewables reported in high-level, long-term future energy scenarios is very likely to require grid adaptation. Future energy mixes with up to 50% renewables in the energy mix, and over 30% decentralized and/or intermittent renewables such as wind and solar-pv may require significant modifications to the grid in order to maintain grid stability in the face of potentially large energy surpluses. Nevertheless, the self-consumption fingerprints derived in this research also indicate that at such high penetration levels, self-consumption may be relatively high as well. Thus, in order to assess the extent of grid adaptation requirements, not the entire amount of power produced in decentralized settings needs to be accounted for. For power generated from decentralized wind turbines, for instance, penetration rates of 30% correspond to self-consumption potential of over 70%. Such high self-consumption ratios imply that possibly less than 30% of the produced wind power is fed into the grid. Only about a third of the amount of wind power needs to be accounted for in assessments of grid adaptation implications, rather than the full amount. Another important notion is that the range of possible renewables penetration over the next decades is sufficiently wide to include scenarios for which the extent of required grid adaptation could be minimal to negligible.

7.6 Conclusions

Solar-pv, wind power and biogas are common renewable energy sources featured in many future energy scenarios. These energy sources are typically deployed in decentralized generation contexts. Each of these energy sources has a typical minimum deployment scale. In this research a model-based approach is deployed to derive a distinct set of self-consumption characteristics for each of these renewable energy sources. The self-consumption characteristics are indicative of the implications high penetration rates may have on the energy system and as such may help in the interpretation of renewable energy in future energy scenarios.

Application of these self-consumption characteristics on the post-energy transition end states derived in the context of The Big Picture suggests that grid adaptation may be required for high penetration levels of decentralized renewables. Nevertheless, as a result of high self-consumption ratios the extent of grid adaptation requirements likely depends on only a small portion of the suggested contribution of decentralized renewables in the energy mix, rather than the entire contribution.

Key findings:

- Different decentralised renewable energy technologies have different grid implication dynamics relative to varying demand scales. Part of those differences can be explained through differences in weather dependency.
- For power from solar-photovoltaics (solar-pv), inherent mismatch between typical supply patterns and typical power demand patterns imply that only a small share of the energy mix can be contributed by power from solar-pv without substantial grid implications. Conversely, larger shares of decentralised solar-pv power may be associated with more significant grid implications.
- Power generated by wind turbines is more strongly affected by variation in weather patterns than power from solar-pv, but its daylight-independent supply patterns enables a larger demand-supply matching potential. Therefore, the share of wind power that can be integrated into the energy mix without substantial grid implications is larger than for power from solar-pv.
- Biogas-based decentralized power supply is fairly constant and predictable. As such, the no-grid-implications share of biogas power is the largest of all three decentralized renewable power sources considered in this research.
- Energy futures involving large shares of decentralized renewable power in the energy mix are likely to involve substantial grid implications. However, part of the power generated on a decentralized platform is consumed locally. Only the part that is not consumed locally/directly accounts towards grid implications. Grid implications for larger shares of decentralized renewables may thus be less than what could be assumed from the gross total of generated power.

7.7 References

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8 CASE STUDY: POWER TO GAS - A TECHNOLOGICAL INNOVATION SYSTEM APPROACH

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8.1 Introduction

The three end states presented in Chapter 3 show a considerable share of renewable energy in the energy mix as it develops. This corresponds with the European energy policy and plans as they are stated in Energy 2020[1], Energy trends 2030[2] and the Energy Roadmap 2050[3].

The growing share of renewable energy will for a large part be realized with wind, hydroelectric and solar power. Besides having both low life cycle carbon emissions, wind and solar power are also intermittent energy sources. This increases the need for overall flexibility in the energy system strongly[4] [5].

The energy system has to adapt to intermittent energy sources, such as wind power and solar energy, which provide energy in a fluctuating manner. Energy storage is the solution. In times of excess electricity production the energy has to be stored. Power to Gas is a technology that offers this storage option.

The basic principle of the power-to-gas concept is the bidirectional linking of the existing infrastructure units (the electricity grid and the gas grid) with the goal of establishing a new way of managing loads and generation, which enables high proportions of fluctuating electricity generation from renewable energy sources to be accommodated in the energy system. To date, this link only exists in terms of generating electricity from natural gas (gas to power), but not vice versa (power-to-gas)[6].

The power-to-gas principle is shown in Figure 61. Excess electricity is converted into hydrogen using electrolysis. The hydrogen can be used in three ways[7]. In the first place the hydrogen can be injected in the gas grid but only up to a limited amount since the gas grid is designed to transport and store natural gas and not hydrogen[8,9]. Secondly the hydrogen can be converted into methane. Methane can be injected into the gas grid on a large scale. The CO_2 that is needed for methanation can be provided by a bio gasification plant[10] or through carbon capture storage (CCS). The third option is of course to use the hydrogen in industry and transportation and not inject it into the gas grid.

Figure 61 shows that the natural gas grid can store the excess renewable energy. It is important to notice that the storage capacity of the gas grid is large and that the storage can be used to cope with seasonal fluctuations as well.

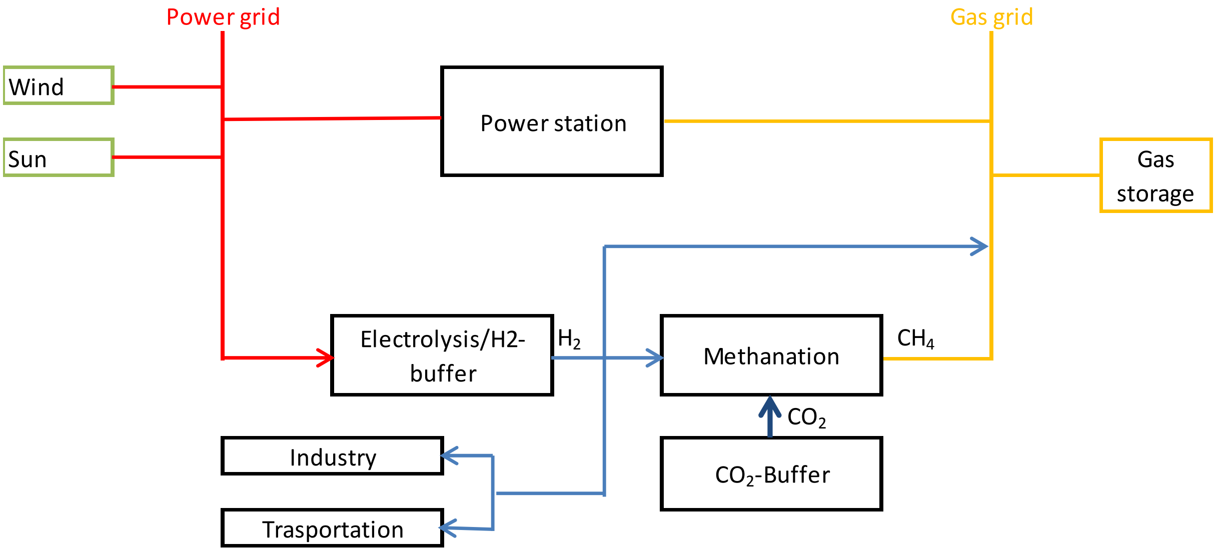


Figure 61: Power-to-gas concept for bidirectional coupling of the electricity and gas grids.

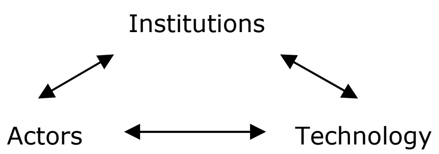
Three end states were defined. These end states require technological innovation. One innovation that is needed to accommodate the end states is the storage of excess renewable energy. Power-to-gas can provide this storage but the technology is facing hurdles. This chapter describes the factors that will determine if power-to-gas will be an important technology in the energy transition.

8.2 Methodology – a system approach

What will determine if power-to-gas will be an important technology in the energy transition over the next years? A technology does not develop in one place and it is not developed by one actor. One can look at the development of a technology as a process that takes place in a technological innovation system (TIS). The TIS includes all actors and institutions that are involved in the development, diffusion and utilization of a technology.

The central idea of this analysis is that the analysis of technological change should focus on systematically mapping the activities that take place in innovation systems resulting in technological change. Since these activities have the function to contribute to the goal of the innovation system, which is the generation and diffusion of innovations, the activities are often called functions of innovation systems[11] [12].

Many actors and institutions are involved in the development of power-to-gas. Since the actors and institutions do not act alone they are viewed as a system with multiple interdependencies.



Actors are numerous, ranging from public to private and from innovator to end-user. *Institutions* are governments, agencies, law and others. A system approach is used to emphasize the dynamics between actors, institutions and technological factors[13].

The basic unit of the analysis is the event. Within the context of a TIS analysis, an event can be defined as an instance of rapid change with respect to actors, institutions and/or technology, which is the work of one or more actors and which carries some public importance with respect to in this case the Power to

Gas TIS. Examples of such events are studies carried out, conferences organized, plants constructed, policy measured issued, etc.

A successful system should fulfil the following functions:

1. Entrepreneurial activities
2. Knowledge development
3. Knowledge exchange
4. Guidance of the search
5. Market formation
6. Resource mobilisation
7. Support from advocacy coalitions

This Technological Innovation System approach is based on Motors of sustainable innovation by Roald A. A. Suurs.

The main research question is: *In what way does the power-to-gas Technological Innovation Systems affect the energy technology trajectories leading to the end states?*

Using the Technological Innovation System approach the sub questions are:

1. *How does the power-to-gas Technological Innovation System perform on the defined functions?*

   The answer to this question will provide insight in the strengths and weaknesses of the Technological Innovation System. Are there for example significant entrepreneurial activities, is there meaningful knowledge development and exchange, and so on. The progress will be recognized through so called events. An event can be a publication, a commercial initiative, a new subsidy or any other signal that can be considered as a contribution to the Technological Innovation System.

2. *What progress does the power-to-gas Technological Innovation System need to make to accommodate the different end states?*

   This question will address the end states. The focus will be the contribution that power-to-gas can have related to the different end states. It is possible that power-to-gas will be more relevant for one end state compared to the other end states.

The TIS approach has a technology as its starting point. The development of a technology is not place based. At different locations all over the world entrepreneurial activities can start and research can be initiated. On the other hand regulation and policies are most of the time not worldwide and technology often develops in a regional context. This study looks at the power-to-gas TIS from a European perspective and will put some emphasize on the Dutch situation.

8.3 Entrepreneurial activities

Entrepreneurs are at the core of any TIS. The classic role of the entrepreneur is to translate knowledge into business opportunities, and eventually innovations. The entrepreneur does this by performing market oriented experiments that establish change, both to the emerging technology and to the institutions that surround it. The entrepreneurial activities involve projects aimed to prove the usefulness of the emerging technology in a practical and/or commercial environment. Such projects typically take the form of experiments and demonstrations[14]. Public actors can be entrepreneurs as well, as long as their actions are directed at conducting market-oriented experiments with an emerging technology.

Over 30 power-to-gas demonstration plants are currently reported on the internet and in literature[15,16,17]. At this moment most projects are in the construction or planning phase. The largest existing plants will be discussed.

In 2013 Audi opened a power-to-gas plant in Werlte (Germany) with a 6 MW capacity. It converts surplus renewable electricity in hydrogen and methane. The renewable synthetic methane, called Audi e-gas, is provided for Audi customers of the A3-tron g, an Audi vehicle. Customers can order a quota of e-gas when they purchase the car. This enables them to take part in an accounting process that ensures that the amount of gas that they put in their vehicle at the natural gas filling station is supplied to the grid by the Audi e-gas plant[18].

Also in 2013 E.ON inaugurated a power-to-gas (P2G) unit in Falkenhagen in eastern Germany. The unit uses wind power to run electrolysis equipment that transforms water into hydrogen which is injected into the regional gas transmission system. The hydrogen becomes part of the natural gas mix and can be used in a variety of applications, including space heating, industrial processes, mobility, and power generation. The unit, which has a capacity of two megawatts, can produce 360 cubic meters of hydrogen per hour[19].

In Grapzow (Germany) E.ON has installed in 2012 a 1 MW power-to-gas system connected to a 140 MW wind farm. The plant's owners have the option to use the hydrogen in an internal combustion engine to produce electricity, or inject it directly into the local natural gas grid, depending on operational needs[20].

Enertrag installed in Prenzlau (Germany) three 2 MW wind turbines directly connected to an electrolyser[21]. The hydrogen that is produced is used in several ways. During low wind periods, the stored hydrogen, mixed with biogas, can be used to fuel two combined heat and power units, for additional electricity production. From the point of view of the grid operator, the hybrid power plant will then be operating as a base load power station. The hydrogen can also be used for fuelling cars. TOTAL Deutschland GmbH is a partner in de project. Total operates service stations where cars can be fuelled with wind-hydrogen produced in Prenzlau. The hydrogen is transported in tankers from Prenzlau to Berlin[22].

Table 14: Operating power-to-gas plants in Germany (10) and the Netherlands (1).

City	Project name	Operating since	Application
Hamburg	Wasserstofftankstelle HafenCity	2012	Production of hydrogen Hydrogen used for transportation (busses)
Werlte	Audi e-gas Project	2013	Production of methane Injection in gas grid Certificates for Audi vehicles
Frankfurt Am Mein	P2G demo Thuga group	2013	Production of hydrogen Inject in gasgrid
Herten	H2Herten	2013	Production of hydrogen Hydrogen used for transportation and other fuel cells
Niederaussem	CO2rrect	2013	Production of methane and methanol
Bad Hersfeld	Metanisierung am Eichhof	2012	Production of methane Inject in gasgrid
Stuttgart	Verbundproject Power-to-Gas	2012	Production of methane
Falkenhagen	Pilotanlage Falkenhagen	2013	Production of hydrogen Inject in gasgrid
Grapzow	Windpark RH2-WKA	2012	Production of hydrogen Use hydrogen to produce electricity Inject in grid
Prenzlau	Hybridkraftwerk Prenzlau	2011	Production of hydrogen Use for electricity use for transportation
Schwandorf	Power to Gas in Eucolino	2012	Production of methane using Microorganisms. Injection in grid or storage.
Rozenburg (NL)	P2G in Rozenburg	2013	Production of methane Injection in local grid

Analysing the existing projects it is obvious that they all use electrolysis to turn electricity into Hydrogen. After all, that is what makes them power-to-gas projects. There are some differences that stand out. First of all there is the option of methanation. Six of the existing projects produce methane and inject it into the gas grid. The methanation is realized using different technologies. The other five projects do not methanise the hydrogen. Three out of those five projects use the hydrogen in the transportation sector. The other two projects inject the hydrogen in the gas grid or convert it back into electricity.

All those projects can count as entrepreneurial activities as defined in the TIS literature. They are market oriented experiments trying to prove the usefulness of the emerging technology. It is also important to notice that all projects have a recent date. Initial plans are of course made some years ago but the operating projects have gone into production over the last few years. For the power-to-gas TIS this means that entrepreneurial activities have taken off and have a positive effect on the emerging technology.

8.4 Knowledge development

The knowledge development function involves learning activities, mostly on the emerging technology but also on markets, networks, users and other factors. Learning activities can be laboratory experiments but also trial projects. Without knowledge development there will be no technological innovation[23].

Power to Gas uses electrolysis of water to produce hydrogen. The technology is not new; Zenobe Gramme invented the Gramme machine in 1869 to produce hydrogen using electrolysis of water. It is therefore arbitrary to decide when power-to-gas started as a technology to be used to transform surplus electricity into gas. In this chapter, research over the last 10 years is considered to be part of the power-to-gas TIS. The largest studies are categorized according to their main topic and will be discussed briefly.

8.4.1 Studies on electrolysis and hydrogen

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public private partnership founded in 2008 supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Its aim is to accelerate the market introduction of these technologies, realizing their potential as an instrument in achieving a carbon-lean energy system[24]. The FCH JU helps to carry out the 7th framework programme for research and technological development (FP7). For 2013 the FCH JU contributes €68 million to 27 projects[25]. The projects are categorized in five so-called application areas:

- Transportation and refuelling infrastructure;
- Hydrogen production and distribution;
- Stationary power generation and CHP;
- Early markets;
- Cross cutting issues.

Most FCH JU projects are relevant for the power-to-gas TIS. The programme is therefore a positive contribution to the TIS.

8.4.2 Studies on power-to-gas and the gas network

The Naturalhy project was funded by the European commission's sixth framework program (2002 – 2006) for research, technological development and demonstration[26]. The project started in 2004 and the final report was published in 2010. The project studied the possibility to use the existing natural gas system for hydrogen. The possible impact of adding hydrogen to natural gas on the durability of the network was an important part of the project. Also measures to control and monitor the condition of the network were analysed. Safety aspects of adding hydrogen to the network were another subject. The end user aspects were studied as well. Research was also done on the possibility to separate hydrogen from a hydrogen/natural gas mixture by the use of membranes.

The main goal of the Naturalhy project was to identify showstoppers. This also determined the scope of the project. Materials that are used in the natural gas system which can easily be replaced by another – hydrogen proof - material were for example not considered to be a potential threat to the durability of the network. The final report emphasizes that given the size and the complexity of the project it is important not to jump to simple conclusions. The general outcome of the project though was that no showstoppers were identified. For the power-to-gas TIS the Naturalhy project therefore was a positive impulse.

In Germany the DVGW carried out an extensive study analysing the main power-to-gas issues[27]. In the first place the H2-tolerance of the German natural gas grid was researched. The main conclusion is that the existing gas infrastructure can handle a 10% volume addition of H_2 in the gas grid. Furthermore four possible power-to-gas applications in Germany were studied. One of the subjects was the difference between injecting hydrogen into the local grid versus injecting into the interregional grid. Injecting in the local grid causes a significant limitation in the H_2 volume that can be added. The DVGW also examined the economics of power-to-gas. The variables that are most important to decide on the financial feasibility of power-to-gas are the utilization of the power-to-gas installation (in hours) and the price of electricity.

The HyUnder project studies the possibilities for large scale and long term storage of renewable electricity by hydrogen underground storage in Europe. The project compares hydrogen underground storage with other storage options. Given de European energy policy goals the need for storage is explored. The conclusion is that, although a thorough quantification of the energy storage needs in the EU has not been undertaken yet, the necessity of energy storage to compensate the intermittency of renewable energy is obvious and that energy storage will play a key role in the future European energy structure, as it is described in the Energy 2020 program and the Energy Roadmap 2050 by the EU. The project also concludes that the only feasible option for large scale energy storage is to employ underground hydrogen / SNG storage in salt caverns. SNG provides the additional option to be stored in all kind of storages in the natural gas grid. Because of high investment costs systems with hydrogen underground tube storage or storage in pressure vessel bundles are not appropriate for long term storage of large volumes[28].

8.4.3 Studies on power-to-gas in the energy system

In June 2013 DNV KEMA published "Systems analyses Power to Gas: a technology review"[29]. The study compares power-to-gas to other energy storage technologies. The technologies should fulfil several functions, in the DNV KEMA study so called service applications:

- Frequency support: stabilizing the grid frequency almost instantly in case of very sudden large decreases in power generation
- Uninterruptable power supply: providing emergency power when the input power source fails
- Community energy storage: store energy at a local level
- Home energy storage: storage dedicated for household applications
- Forecast hedging: the use of stored energy to mitigate penalties when real-time generation falls short
- Time shifting: the storage of energy generated during low demand periods and discharged during high demand periods
- Transmission and distribution capacity management: possible avoidance of network upgrades

The study concludes that the value of power-to-gas is in its able to deliver community energy storage services, time shifting and transmission and distribution capacity management. This outcome contributes in a positive way to the knowledge development function.

8.4.4 Studies on the financial feasibility of power-to-gas

In 2006 the Institute for Energy and Transport (IET) – part of the joint research centre (JRC) from the European commission- published "Bridging the European wind energy market and a future renewable hydrogen-inclusive economy". The approach of this study is to determine, via life-cycle cost-benefit assessment, the long-term competitiveness and economic implications of power-to-gas. The study takes into account that the costs and benefits of power-to-gas are aggregated at different economic levels. The investment costs and product revenues for example are assumed to be the project owners. The benefits from improved network management are realized by the consumer of electricity in the price he pays for electricity. The benefits from local environmental conditions (avoided particulate emissions) are enjoyed by the local community of consumers. The benefits for global environmental conditions (reduced greenhouse gas emissions) are enjoyed by all members of society.

The function of knowledge development was definitely met by this study. It is hard to categorize the contribution as positive or negative. Four scenarios are outlined varying in the wind penetration in the energy mix and in the strength of the hydrogen and climate change push. The production costs of Hydrogen through power-to-gas are much higher than the Hydrogen market price. In other words, power-to-gas is an expensive way to produce Hydrogen. The additional benefits of power-to-gas, avoided CO_2 emissions and avoided balance costs, are not compensating the high production costs. A scenario with high wind penetration, low electricity prices and high CO_2 and hydrogen prices gives a positive cost-benefit outcome demonstrated in lower electricity prices. The study assumes that electricity companies will pass on benefits to the consumers through lower prices.

In September 2008 ECN published "Conversion of excess wind energy into hydrogen for fuel cell applications"[30]. The study starts with estimating the excess wind energy in the Netherlands in 2020. The political ambition to have 6 GW offshore and 2-4 GW onshore wind power in 2020 is taken as a starting point. Using the electricity demand data and the wind speed data from 2004 the result for 8 GW installed wind power is an excess wind power of about 4.5 TWh. The minimum cost estimate for producing hydrogen using the excess wind power is 4.4 €/kg. The costs are high because the load factor for the electrolysers is low. Using all wind power to produce hydrogen results in production costs of 5 €/kg. Even though the use of the capacity of the electrolysers improves, the costs of electricity – using a mean 0f 0.08 €/kWh- raises the costs of the hydrogen.

DNV KEMA reports using different sources that the estimates of excess wind power differ from 0.5 TWh per year to 10 TWh per year in 2050. Another KEMA study from 2010 concludes that a 12 GW wind capacity in 2020 in the Netherlands will lead to no more than 0.5 TWh curtailment per year[31]. Different scenarios are considered. The relatively low curtailment implies less need for power-to-gas technology.

The conclusion regarding the knowledge development function is that there have been many power-to-gas research programs and publications over the last 10 years. The general outcome for the power-to-gas TIS is positive. The knowledge base is growing and so far no showstoppers are identified.

8.5 Knowledge exchange

The function of knowledge exchange concerns the exchange of information through networks, publications, conferences and other means that are used to share information. Knowledge exchange is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors, and market. Here policy decisions (standards, long term targets) should be consistent with the latest technological insights and, at the same time, R&D agendas should be affected by changing norms and values[32,33].

For the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), cooperation between government, businesses and research institutions is a main target. The three members of the FCH JU are the European Commission, the NEW Industry Grouping and the N.ERGHY Research Grouping. The NEW Industry grouping has 68 companies working in the field of fuel cells and hydrogen and they represent a major part of the sector[34]. The N.ERGHY Research Grouping represents the interests of European universities and research institutes in the FCH JU. Currently 58 international research institutions are a part of N.ERGHY[35]. As mentioned before the FCH JU has 27 projects carried out and they are all Hydrogen related. The projects themselves all have several organizations participating.

The International Energy Agency (IEA) is an autonomous organization which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA's four main areas of focus are: energy security, economic development, environmental awareness, and engagement worldwide. The IEA has developed a Hydrogen Implementing Agreement. The strategy of the IEA's Hydrogen

Program is to facilitate, coordinate, and maintain innovative R&D activities through international cooperation and information exchange. Knowledge exchange is stimulated by the IEA because of its focus on international cooperation. Task 24 from the Hydrogen Implementing agreement provides an overview for technologies which have direct influence on development and implementation of systems integrating wind energy with hydrogen production.

The Joint Research Centre Institute for Energy and Transport (JRC IET) provides support to European Union policies and technology innovation to ensure sustainable, safe, secure and efficient energy production, distribution and use and to foster sustainable and efficient transport in Europe. The SETIS program belongs to the key scientific activities of the JRC IET and provides information on 37 fuel cells and hydrogen projects and 45 wind energy projects[36].

The entrepreneurial activities that are a part of the power-to-gas TIS are also a clear example of the knowledge exchange function. Appendix B shows the partners per project. Almost all projects have multiple partners with different backgrounds such as research institutions, gas companies, electricity companies and suppliers of power-to-gas technology.

The North Sea Power to Gas Platform is an example of a network of stakeholders that come together to share information and experiences. The platform was initiated in 2012 and has had five meetings since the start. 14 member organizations have joined the platform.

The research that is seen as a part of the knowledge development function contributes to the knowledge exchange function in two ways. First of all, the research programs in general result in publications, presentations and conferences. In the second place, just like the entrepreneurial activities, most research programs have multiple partners participating in the projects. Appendix C shows the participating partners in the largest recent power-to-gas research programs. Since almost all research programs and entrepreneurial activities involve several participants the conclusion is that the knowledge exchange function in the power-to-gas TIS is fulfilled in a positive way.

8.6 Guidance of the search

The guidance of the search function refers to the activities within the TIS that shape the needs, requirements and expectations of actors with respect to their further support of the emerging technology. Usually, various technological options exist within an emerging technological field. The guidance of the search function represents the selection process that is needed to direct scarce resources to the most promising options[37,38].

For power-to-gas the growth of intermittent renewable energy is crucial. Only when there is significant excess renewable electricity it becomes urgent to have power-to-gas technology. The European Commission states in its Energy 2020 strategy that it will implement the SET plan without delay[39]. One of the six initiatives in the SET plan is the European wind initiative. The key objective of this initiative is to double the power generation capacity of the largest wind turbines, with off-shore wind as the lead application[40]. The European wind initiative is now being implemented by EU institutions, member states, TPWind and the European Energy Research Alliance (EERA). The budget of the European wind initiative is €6 billion (public and private resources)[41].

In March 2013 the Dutch government published “Rijksstructuurvisie Windenergie op land”. It was decided that for onshore wind energy a number of areas were considered to be fit for wind projects of 100 MW and more. These projects will have to answer to national regulation whereas smaller projects have to meet local (provincial) regulation. This way the Dutch government wishes to realize 6000 MW onshore wind energy by 2020. The vision includes subsidies for 2013 for a total of €3 billion for the production of renewable energy (not just wind). For offshore projects the new national policy will appear in 2014.

The guidance of the search function at a high level compares power-to-gas to other technologies to store intermittent renewable energy. Those other relevant large scale energy storage technologies are pumped hydro energy storage, compressed air energy storage and stationary batteries. Research shows that the strengths of power-to-gas technology are the possibility to offer storage on a large scale and to store energy in the range of hours to several weeks. On the other hand the power-to-gas energy efficiency is low compared to other storage options[42,43,44,45]. As far as guidance of the search is concerned the comparison with other storage technologies seems to encourage further power-to-gas development based on its strengths. Improving the energy efficiency is a priority.

Within the power-to-gas TIS the guidance of the search function has several subjects. They can be analysed in a structured way using the power-to-gas process. The first step is the conversion of excess electricity into hydrogen using electrolysis. The electrolyser uses either Alkaline, Polymer Electrolyte Membrane (PEM) or Solid Oxide Electrolysis (SOE) technology. Alkaline electrolysis is a well-established technology but the efficiency of the process, the purity of the hydrogen and the performance at low loads should improve. PEM technology is more efficient but has higher costs. SOEC electrolysis is in a laboratory stage[46,47]. Currently several projects study Alkaline and/or PEM electrolysis[48,49]. On this subject the guidance of the search is ongoing. There are no recent breakthroughs that are decisive for the choice of electrolysis technology.

After the conversion of excess electricity into hydrogen there are different ways to use the hydrogen. First of all the hydrogen can be used in transportation or in industry. The FCH JU reports 20 projects concerning transportation and refuelling infrastructure[50]. Some of the entrepreneurial activities also involve transportation. In more than 10 European cities hydrogen fuelling stations can be found[51].

The hydrogen can also be added to the gas grid. This option has three main advantages. The storage capacity of the gas grid is large, the existing infrastructure can be used and the transportation of gas is cost-effective. Two large studies suggest that adding hydrogen to the gas grid is probably feasible under certain conditions[52,53]. One of the conditions is the percentage of hydrogen that is added to the natural gas. Converting the hydrogen into methane is an alternative route. Methane behaves like natural gas and can be added to the gas grid without restrictions. On the other hand methanation makes the power-to-gas process less energy efficient and CO_2 is needed to produce the methane. Both methods are currently used in the entrepreneurial activities that are discussed[54,55,56] and there is ongoing research on the injection of hydrogen and methane into the gas grid[57]. Again it is too early to say if hydrogen is going to be added to the gas grid on a large scale and if methanation is going to be used while doing this.

If hydrogen is added to the gas grid it might be desirable to be able to separate the hydrogen from the gas mixture for other applications later on. Using a membrane system this separation is possible but has high capital costs[58]. The FCH JU has one project concerning separation[59]. It seems that the separation technology does not have the centre of attention in the power-to-gas TIS.

In the power-to-gas TIS the guidance of the search function involves two main issues. In the first place power-to-gas has to become more energy efficient. Several electrolysis technologies are being studied but there is no best technology identified yet. In the second place it is not clear in what way the produced hydrogen should be used to get the highest benefits out of power-to-gas technology. If hydrogen transportation is going to be applied on a large scale it may not be necessary to inject hydrogen into the gas grid. On this subject the guidance of the search function is in progress and has not identified a preferred solution yet.

8.7 Market formation

The market formation function involves activities that contribute to the creation of a demand for the emerging technology, for example by financially supporting the use of the emerging technology. In case of sustainable innovations, there is usually no commercial product unless the institutional framework is adjusted to account for external costs. Therefore, in this case, the system function is typically fulfilled by governments, through the setting up of formal institutions[60].

8.7.1 Regulation

For power-to-gas the market formation is in the first place facing a lack of regulation. At this moment the responsibility concerning power-to-gas is unclear. Is power-to-gas the responsibility of the electricity producer, electricity distributor, gas producer, gas distributor or some other party? Despite all the power-to-gas demonstration projects it is unlikely that there will be large scale power-to-gas plants before the regulator has set up the regulatory framework. In the Energy agreement[61] power-to-gas is mentioned when adaptations in the energy infrastructure are discussed. The Energy agreement states that energy storage is needed and that power-to-gas technology has to be examined. Responsibilities or the need for regulation are not discussed. Recent changes in the Gas law and the Electricity law have not provided a regulatory framework for power-to-gas. Still such a framework is necessary for market formation to develop.

Regulation is also important to achieve economically viable P2G implementation. At present, the only value that can be gained from P2G technology is in the production of a gas with re-sale value – hydrogen or SNG. Much of the real value to the energy system comes from elsewhere - in the avoided capital cost of extra infrastructure, in the enabling of maximum utilization of renewable electricity, and in the increase in renewable content of the gas networks. All these need to be given value through appropriate regulation to give P2G developers the confidence that they can implement a market ready solution[62].

8.7.2 Regulatory risk

There is a direct relation between market formation and the perceived risks. When the businesses consider the project risks too high then there will be no market. What risks do businesses face when they invest in power-to-gas technology? Two risk categories that can be identified (among others) are regulatory risk and market risk[63].

Regulatory or institutional risk concerns the risk of adverse changes in the policy context. Policies and measures might change during the project cycle which may have significant impacts on the profitability of a project. Examples are changes to or even ending of policy support schemes or changes to the market design. As most markets for renewables are being regulated under policy schemes, this risk is of particular importance to renewable energy technologies[64]. Once installed the regulation has to be reliable in the long run. Regulatory risk is caused by unexpected changes in the rules[65].

The policy context for power-to-gas includes the Energy 2020 strategy, the European wind initiatives and in the Netherlands the national plans for wind on land and wind at sea. It is important that the plans of the government are perceived as convincing. In response to the plans of the government Energie-Nederland, a Dutch organization for the assembled Dutch energy producers, transporters and other parties, signals some problems. Some of the assigned areas are not chosen from a technical feasible point of view. In reality there might be not enough sufficient space for 6,000 MW in the plans. Another concern that Energie-Nederland has is the availability from the subsidies for wind projects. The regulation provides incentives to apply for subsidies with low cost projects. In the end those projects don’t turn out to be financial feasible. Bigger and more expensive wind projects miss out on the subsidies and will not be realized according to Energie-Nederland[66].

The CPB (the Dutch agency for economic policy analysis) adviced negative on the Dutch onshore wind plans. A cost benefit analyses shows that the economic crisis and the large availability of coal due to the shale gas growth in the USA has caused excess electricity producing capacity. Expanding the capacity – with wind energy or otherwise – will not be profitable. The CPB advises to postpone the new wind projects for five years[67].

8.7.3 Gas quality and regulatory risk

To store hydrogen in the gas grid is not only a matter of technological feasibility. It is also necessary that adding hydrogen is confirmed by the relevant regulation. In 2011 KEMA and Arcadis published "Gaskwaliteit voor de toekomst", a study on the possible composition of gases in the system[68,69]. The study was ordered by the ministry of economic affairs, agriculture and innovation. First the study mentions the requirements that the policy on gas quality has to meet. For power-to-gas the most important requirement is that there is a need for a policy that offers certainty for investments. If power-to-gas eventually means a gas grid containing 10% hydrogen then this has to be according to the future gas quality standards. As long as these standards are not clear investors will hesitate to invest in power-to-gas. The most important conclusions of the report is that the gas quality for the future needs further specification to give investors in appliances and producers of gas the right information that they need for their decisions. This is also recognized by the topteam energy, a platform that is a part of the Dutch topsector policy. The need for (international) regulation is one of the problems that the team would like to solve[70].

8.7.4 Economic risk

Important economic risks are demand risk (uncompetitive pricing policy of renewable projects) and price risk (changes in market prices of energy carriers and/or certificates for climate change abatement of renewable production)[71].

If the hydrogen or methane is too expensive due to the high costs of power-to-gas technology there will be a lack of demand. Power-to-gas installations are expensive and since they are only used when excess electricity is available the installation will not be operating all the time. This means that the high fixed costs have to be compensated in limited time. The revenue of power-to-gas will probably not cover the costs if the revenue is restricted to the price that is received for the gas. An additional benefit of power-to-gas is the contribution to the balancing of the electricity network. The value of this contribution could be considered to be revenue as well.

Because power-to-gas does not seem to be financially feasible different models are looked upon. In Germany there is a proposal to obligate the regional energy producers to buy the green gas at a price that covers the costs for the investor. The extra costs will be passed on to the consumers. Since the green gas is a small part of the total energy use the extra costs will be limited[72].

Compared to other options (batteries, pumped hydro systems and others) the large scale and long-time storage of excess electricity through power-to-gas looks promising. Large scale stationary storage of hydrogen enables synergies with both e-mobility by the application of hydrogen powered fuel cell electric vehicles and the direct utilisation of hydrogen in industry. Given the achievable prices for hydrogen in different applications, based on the assumption that hydrogen in the transport sector can be sold in a bandwidth between 6 €/kgH_2 (hydrogen delivered to refuelling station) and 8 €/kgH_2 (accepted hydrogen sales price at the refuelling station for end users), it is revealed that hydrogen as a fuel provides the most valuable sales pathway. The other utilisation pathways may, in fact, offer a larger potential in light of volume, but their potential with regard to economic opportunities is clearly below that of the transportation sector. Also a major disadvantage of the methane systems is their comparatively low overall efficiency[73].

Another approach is taken by the CENER Centre[74]. Their model provides an economical assessment of a wind-hydrogen energy system. They emphasize the possibility to sell wind electricity at the best possible price. When prices are low, the energy should be stored as hydrogen. Selling at the best possible price might improve the overall rate of return. For a 42 MW wind farm using historical data it turns out that adding power-to-gas to the system results in a better price (€/kWh) but not in a higher rate of return. The investments needed for the power-to-gas equipment bring along higher costs that are not made up for by the extra revenues due to better trading.

SEO Economic Research studied the costs and benefits of different measures to reduce CO_2 emissions[75]. They qualify power-to-gas as a costly but necessary technology to meet the 2050 target of 80% reduction of emission. The most cost efficient technologies are energy savings, wind on land, CO_2 capture and nuclear energy. ECN and the Planbureau voor de leefomgeving published a roadmap for 2050[76] where they also find that given the reduction of emission target a growth in renewable energy production should be expected. This growth creates a need for storage that power-to-gas can fulfil.

8.7.5 Market formation

The market formation function in the power-to-gas TIS identifies a number of barriers. In the first place there is a lack of regulation and it is therefore unclear who has the responsibility to balance the electricity network applying power-to-gas. Secondly it is unsure whether current regulations will result in a sufficient growth of intermittent renewable energy. There are European and national programs and plans to support this growth but they may not be sufficient and they are criticized for being unrealistic. A third barrier is the lack of long term regulation on the subject of gas quality. Finally power-to-gas does not seem financially feasible. The contribution of power-to-gas in balancing the network has to be taken into account because other costs may be avoided. The conclusion is that the market formation function identifies a number of problems for the power-to-gas TIS.

8.8 Resource mobilization

Resource mobilization refers to the allocation of financial, material and human capital. The access to such capital factors is necessary for the development of the power-to-gas TIS. Typical activities involved in this system function are investments and subsidies[77]. As discussed above, there is only a need for power-to-gas if there is a large amount of intermittent renewable energy. This means that the funds directed at stimulating renewable energy in an indirect way increase the need for power-to-gas. Therefore looking at the function of resource mobilization requires a broad perspective. Investments and subsidies for power-to-gas technology represent direct resource mobilization for the TIS but resources for intermittent renewable energy sources are relevant as well since they contribute to market formation.

8.8.1 Subsidies

Subsidies can be found at both European and national level. The Seventh Framework Programme from the European Union wants to make Europe the leading world forum for science and technology. The specific program Cooperation – a part of the Seventh Framework - aims to support cooperation between industries, research centres and public authorities. Energy is one of the nine themes of the Cooperation program. The budget allocated to the Energy theme is € 2,350 million for the period 2008 – 2013. A share of €467 million of this budget is earmarked for research on fuel cells and hydrogen and is implemented by the fuel cells and hydrogen joint undertaking (FCH-JU). The €467 million from the FCH-JU is matched by €470 million from the industry[78,79].

Only a part of the Seventh framework programme budget for the Energy theme is spent on research related to hydrogen. The Energy Policy for Europe introduces a set of European energy measures that should realize the goals of the Energy theme. The measures and goals concern among others the internal energy market, energy efficiency and renewable energy. The budget for the Energy theme is therefore not at all earmarked for power-to-gas technology. The funds directed at stimulating renewable energy in an indirect way increase the need for power-to-gas. An example is the more than €110 million that has been provided by the European Union since 2002 for wind energy research[80,81].

The Dutch government's industrial policy is based on nine so called top sectors. Energy is one of the top sectors and is divided in seven Top consortia for Knowledge and Innovation (TKI). One of the TKI's has gas as its subject. The TKI Gas has a €50 million budget in 2012 but only a small part is invested in power-to-gas related topics[82,83].

8.8.2 Investments

It is important to realize that the European and national subsidies do not finance research and pilot projects by themselves. They are always matched by other funds that are also needed to have sufficient resources. Whether research or projects are financed through subsidies or private investments depends on the life cycle stage that the technology is in[84].

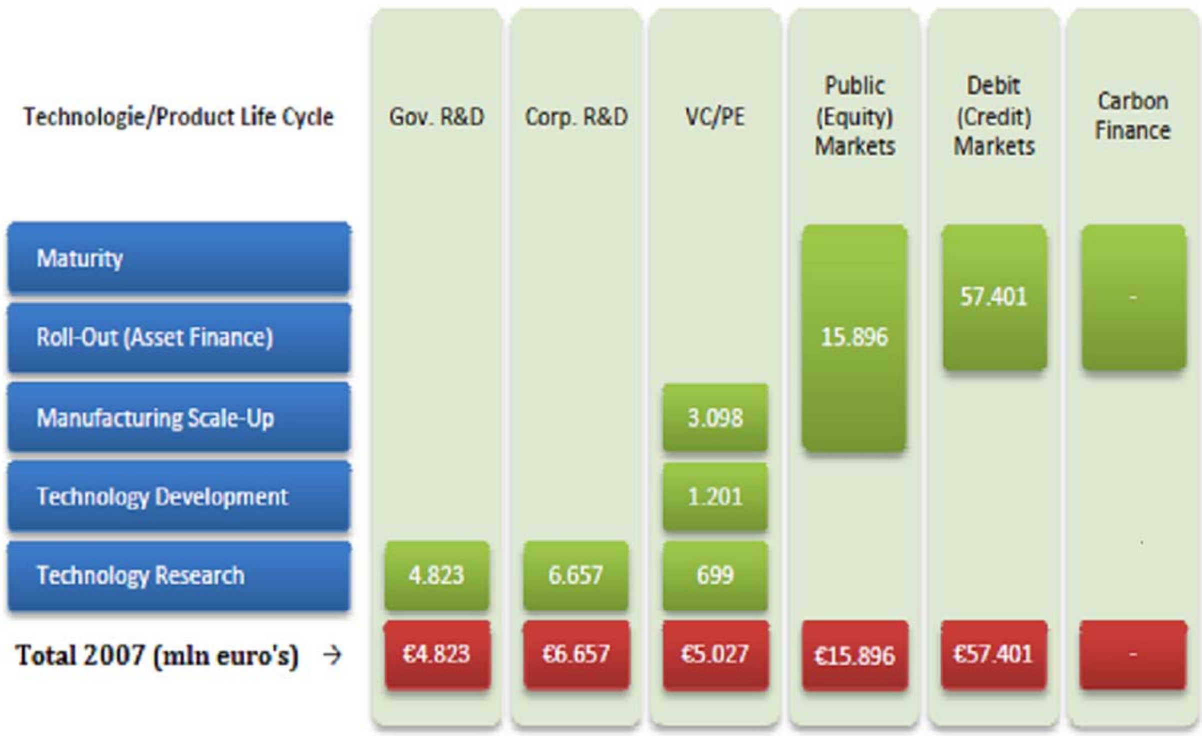


Figure 62: Global capital market for sustainable projects 2007.

(Biemans, 2009)

Figure 62 shows that a technology in its early stage –technology research and technology development - is financed through subsidies, businesses and venture capital. The entrepreneurial activities in the power-to-gas TIS (Table 14) confirm this. All activities have private and public parties involved.

Using the broad perspective where the growth of intermittent renewable energy is a positive contribution for the power-to-gas TIS Figure 63 shows the installed capacity for electricity generation from renewables in the European Union. It is clear that there is a large growth of installed wind capacity that implicates a growth in mobilized resources as well. The solar energy is among the other sources of renewable energy and has grown as well.

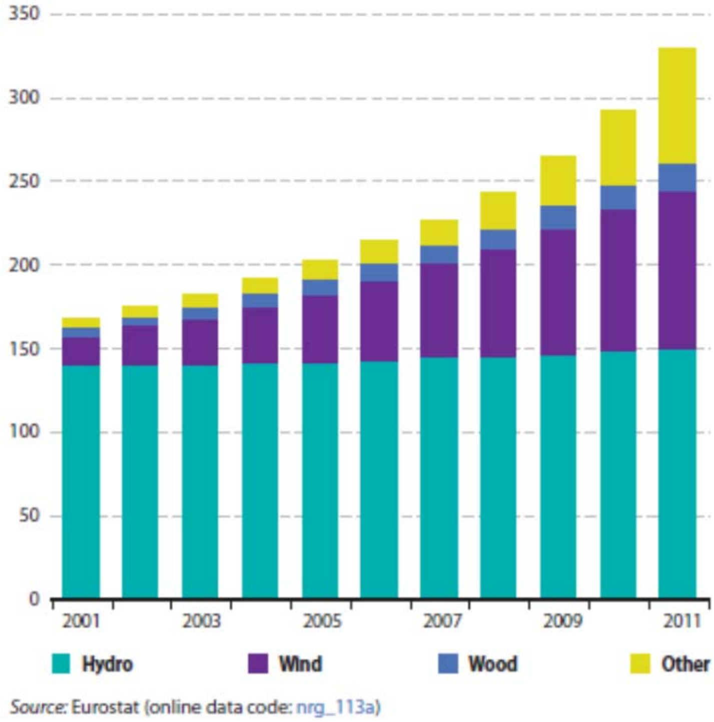


Figure 63: Installed capacity for electricity generation from renewables, EU-28[85]

Bloomberg[86] reports rising new investments in renewable energy in Europe between 2004 and 2011. In 2012 and 2013 new investments fall to a lower level. For the power-to-gas TIS the fall in new investments is negative. Looking at the need for a strong growth in intermittent energy sources a rise in new investments in renewable energy is needed.

The conclusion concerning resource mobilization is that the large amount of entrepreneurial activities in recent years shows that resources have been available. On a European level subsidies exist and are matched by private capital. The growing installed capacity for electricity generation from renewables also contributes to the power-to-gas TIS in a positive way.

8.9 Support from advocacy coalitions

The rise of an emerging technology often leads to resistance from actors with interests in the incumbent energy system. In order for a TIS to develop, it is necessary to overcome this resistance. Lobbies and advice activities are used to create support from advocacy coalitions[87,88]. To analyse the support from advocacy function, the lobby groups that are related to power-to-gas have to be found. In the European transparency register 15 lobby groups are registered with hydrogen mentioned in the description of the goal of the organization. Over 50 lobby groups have wind in the description of their goal[89]. Some of the lobby groups have hydrogen or wind energy as their core business other lobby groups have other goals that come in the first place. For them the promotion of hydrogen or wind energy is a secondary goal. The largest lobby groups that focus on hydrogen or wind energy will be described briefly.

The European gas research group (GERG) was founded in 1961 and promotes innovation in gas technology. GERG wants to strengthen the safe transport, distribution and use of natural and renewable gases. It is a major objective of GERG to maintain strong links with the European Union and to contribute to the discussion of policy on activities concerning natural gas R&D in Europe by making available its expertise, advice and support[90]. GERG is therefore an important advocacy coalition with 28 gas industry members from 14 countries.

The European Hydrogen Association (EHA) represents 21 national hydrogen and fuel cell organisations and the main European companies active in the hydrogen infrastructure development. The EHA communicates on important issues regarding industrial and regulatory needs to key decision makers at EU level[91].

The NEW industry grouping (NEW-IG) has 68 companies working in the field of fuel cells and hydrogen and they represent a major part of the sector. Their objective is to promote the interests of the fuel cells and hydrogen industry at a European level by engaging with European decision-makers[92].

The N.ERGHY Research Grouping represents the interests of European universities and research institutes in the FCH JU. Currently 58 international research institutions are a part of E.NERGHY

The European Wind Energy Association (EWEA) promotes the utilization of wind power in Europe and worldwide. It represents 700 members from almost 60 countries. The EWEA develops and communicates effective strategic policies and initiatives to influence the political process in a direction that maintains and creates stable markets and overcome barriers to the deployment of wind energy[93].

The support from advocacy coalitions function is met by the power-to-gas TIS as far as the existence and presence of lobby groups is concerned. Whether the lobby activities result in the desired actions is another matter. The entrepreneurial activities, the existing research programs and the available funds all suggest that the lobby activities do have the desired results. Examples of issues that are not realized so far are gas quality standards that allow hydrogen in the gas grid and the legal framework for power-to-gas.

8.10 System dynamics

So far the different functions from the power-to-gas TIS have been discussed separately. This has given a valuable insight in the progress that has been made in each function. It also has been a static approach. In this section the system dynamics will be discussed.

The power-to-gas TIS seems to start with entrepreneurial activities. The expected growth of renewable energy will cause more intermittent electricity and a balancing problem on the electricity grid. The guidance of the search function starts the entrepreneurial activities. Innovative research, including demonstration projects, is initiated. The businesses and research institutions then require resources to cover part of their costs and to compensate the financial risks they take. In the power-to-gas TIS funds have come available and projects have started. The outcome of the projects feeds back into the dynamic system and is an impulse for new projects. The entrepreneurial activities interact with knowledge development and knowledge exchange. This too has been observed in the power-to-gas TIS.

Figure 64 shows an illustration of the dynamics between functions in the power-to-gas TIS. It is possible to place the events that have been discussed in this chapter in this dynamic system. The policy context for power-to-gas includes the Energy 2020 strategy, the European wind initiative and in the Netherlands the national plans for wind on land and wind at sea. The energy policy activates the guidance of the search. The expected growth in wind and solar energy causes a (potential) balancing problem on the electricity networks so a solution has to be found. Business and research institutions start projects and claim resources. The most important events concerning knowledge development are the FCH JU projects, the Naturalhy project, DVGW research and the HyUnder project. The entrepreneurial activities are a response to the guidance of the search impulse as well. Research centres and businesses build advocacy coalitions to lobby for resources to support research and entrepreneurial projects.

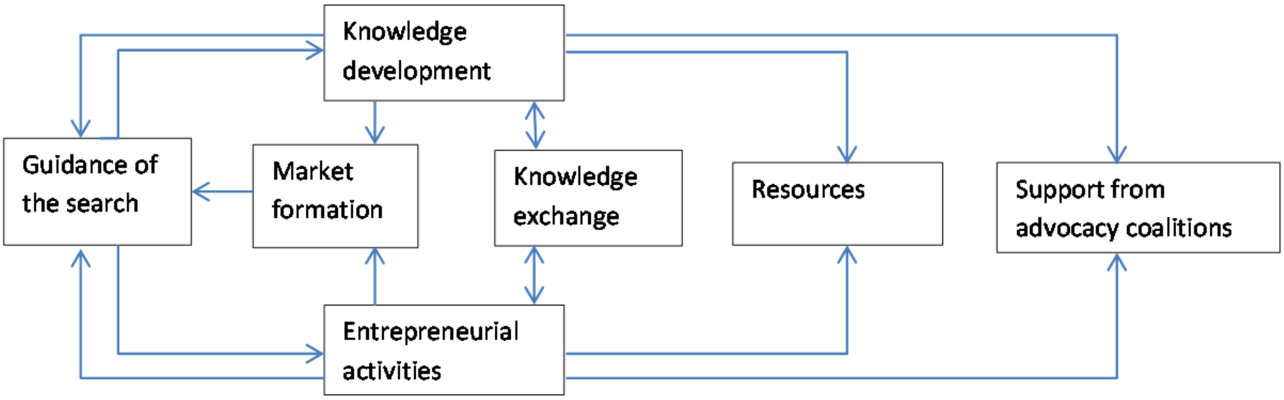


Figure 64: The power-to-gas TIS as a dynamic system.

So far the general outcomes of the projects have resulted in positive feedback loops. Most research and demonstration projects support the feasibility of power-to-gas. The guidance of the search is continued at the same path and new projects are initiated. The seventh framework programme is followed by Horizon 2020 supporting new power-to-gas related projects. The fuel cells and hydrogen joint technology initiative (FCH JTI) resulted in the foundation of the fuel cells and hydrogen joint undertaking (FCH JU). The entrepreneurial activities have also resulted in new and more projects. In Stuttgart a ZSW pilot project from 2009 has been followed by a larger project in 2012. In Eichhof a Fraunhofer IWES power-to-gas pilot has resulted in a second phase including methanation.

Negative feedback loops are found looking at the market formation function. Appropriate regulation to achieve economically viable P2G implementation is missing[94]. The Energy 2020 strategy has to be carried out but are not perceived by all as convincing[95,96]. There is also a need for new regulation on gas quality standards[97,98]. So far the identified problems have not resulted in a drastic change in the guidance of the search. New research and pilot projects are still carried out even though the market formation is lagging behind.

8.11 Conclusions

The power-to-gas TIS shows a lot of progress on most functions. Over the last years a growing number of research projects and entrepreneurial activities have been developed. This has led to knowledge development and knowledge exchange. Funds to finance the projects have become available. An important matter now is if the need for power-to-gas solutions is urgent enough to keep the power-to-gas TIS in an upward spiral. This urgency is in TIS terminology part of the guidance of the search function.

The first conclusion has to be that a convincing European and national energy policy aimed at a substantial growth of wind and solar energy is the most important condition for power-to-gas to become a needed and applied technology. The European energy policy and plans as they are stated in Energy 2020[99], Energy trends 2030[100] and the Energy Roadmap 2050[101] do show this commitment. The European wind initiative – part of the SET plan - wants to enable wind energy to supply 20% of Europe's electricity in 2020, 33% in 2030 and 50% in 2050. It is clear that the European ambition is large enough to cause a need for power-to-gas technology. The implementation of the ambition has to be a driving force for power-to-gas to become widely applied. If the implementation of the European plans gets delayed or if the ambition is scaled down, this will obviously reduce the need for power-to-gas solutions.

The need for a substantial growth of wind en solar energy asks for support from advocacy coalitions. The growth of wind and solar energy cannot be taken for granted based on the presence of an ambitious formulated European energy policy. The large investments cause criticism and this could result in a turning point for renewable energy. A significant and continues effort to organize support for growth of wind and solar energy are a second condition for power-to-gas to play a part in the future energy system.

Power-to-gas technology has to be improved to eliminate a number of technological and economic barriers. To add 10% hydrogen to the natural gas network measures have to be taken to ensure that the existing gas turbines, appliances, steel tanks and underground storages are ready for a changed gas mixture. Another pathway is methanation. Using hydrogen to produce methane offers the advantage that methane can be injected into the natural gas network without restrictions. In both cases an increase in energy efficiency of power-to-gas technology is needed to improve the power-to-gas business case. Entrepreneurial activities, knowledge development and knowledge exchange are needed to realize the requested progress.

The regulatory framework for power-to-gas at the moment shows some deficiencies. Power-to-gas is the linking pin between the electricity grid and the natural gas network. Regulation is needed to determine if power-to-gas is the responsibility of the electricity producer, electricity distributor, gas producer, gas distributor or some other party. Despite all the power-to-gas demonstration projects it is unlikely that there will be large scale power-to-gas plants before the regulator has set up the regulatory framework.

Another regulatory issue are the gas quality standards. To store hydrogen in the gas grid is not only a matter of technological feasibility. It is also necessary that adding hydrogen is conform the relevant regulation. The gas quality standards for the future need further specification to give investors in appliances and producers of gas the right information that they need for their decisions.

Power-to-gas installations are expensive and since they are only used when excess electricity is available the installation will not be operating all the time. This means that the high fixed costs have to be compensated in limited time. The revenue of power-to-gas will probably not cover the costs if the revenue is restricted to the price that is received for the gas. Additional benefits of power-to-gas are the contribution to the balancing of the electricity network, the avoiding of capital costs of expanding the electricity network and the utilization of renewable electricity. The value of this contribution could be considered to be revenue as well. Regulation is needed so that the power-to-gas investor does not only carry the costs but also gets rewarded for the realized benefits.

The legal framework, the gas quality standards and the regulation to support investments are all part of the market formation function. The power-to-gas advocacy coalition can contribute to the market formation function by lobbying for the needed regulation.

Using a TIS approach to analyse power-to-gas development has been useful. The position that power-to-gas will have in the future energy system will depend on the realization of wind and solar ambitions, the technological progress on power-to-gas energy efficiency and the making of a regulatory framework both for gas quality standards and for investment conditions. All TIS functions need to make progress but this is especially true for the market formation function.

What will determine if power-to-gas will be an important technology in the energy transition over the next years? One can look at the development of a technology as a process that takes place in a technological innovation system (TIS). The TIS includes all actors and institutions that are involved in the development, diffusion and utilization of a technology. For a technology to develop successfully the TIS should fulfil several functions. For power-to-gas technology pilot projects are realized, studies are carried out and funds are available both for projects as for research. The functions called entrepreneurial activities, knowledge development, knowledge exchange and resource mobilization are all met. The function that faces the most problems is called market formation. There is not yet a regulatory framework for power-to-gas. Investors in power-to-gas also need to be rewarded for the benefits that they realize such as the contribution to the balancing of the electricity network, the avoiding of capital costs of expanding the electricity network and the utilization of renewable electricity. Policy directed at market formation is therefore recommended.

Key Findings:

- Power-to-gas technology needs a substantial growth of wind and solar energy.
- Research and entrepreneurial activities are contributing to power-to-gas technology.
- A legal framework is needed to enable potential investors to take long term decisions.

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9 CONTEXTUAL AND SYSTEMIC FORCES IN ENERGY VALLEY - THE NETHERLANDS

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9.1 Introduction

This chapter describes how contextual factors and system reactions influence end state developments based on a systems approach. The chapter uses the case study of Energy Valley of the Netherlands to illustrate the influence of contextual factors on the regional energy system and how the system responded and developed. The illustration below captures system interactions with its context and eventually the resulting end state.

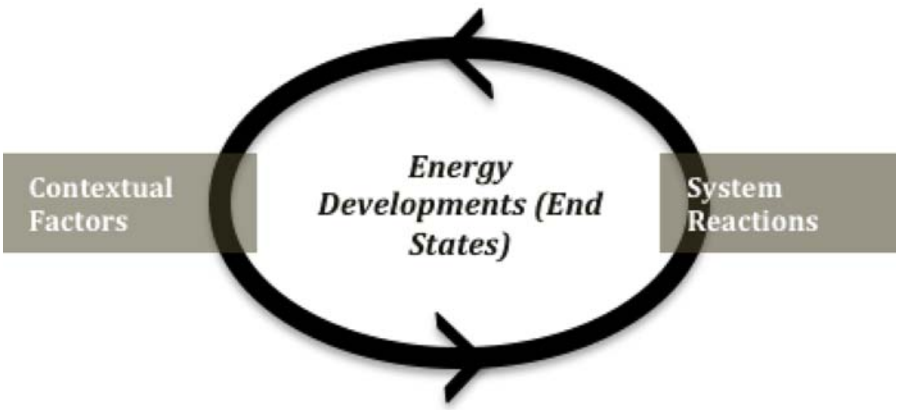

Figure 65: Systems approach

The illustration shows that energy systems respond to contextual factors and this in turn affect contextual factors. Decisions and behaviour in this energy system are influenced by contextual factors, which in turn result in energy developments. This continued loop of interactions would finally result in a particular 'end state' for such a system. The term 'end states' has been described in the introductory chapter and this chapter shows how such end states could be influenced by various contextual factors and systemic responses.

When talking about 'energy systems' this analysis takes a broader perspective and looks at 'energy' as being embedded in social, economic, and political systems and that such a system could be a district, region, country, or a regional block such as the EU. The analysis looks at 'energy' as being located in a specific location with a defined boundary and it can be of different scales. In the research, Energy Valley was examined as an energy system embedded in a larger energy system, which is the national energy system and this in turn, is embedded in a European energy system. Each of these systems can be examined separately, but each of these next level systems is interconnected and contributed to other levels. EU decisions and developments influenced Dutch decisions and developments and therefore that of Energy Valley. At the same time, Energy Valley developments reflected national and EU developments. This analysis compares Energy Valley and national energy developments to that of EU developments for similarities and differences in their systems patterns and behaviour later in the chapter.

Finally, it must be noted that this chapter builds on a previous chapter on 'drivers of change', which focuses on the macro level contexts in which energy developments take place, whilst this chapter looks at contextual factors influencing energy developments at the micro level, specifically from a systems perspective.

The rest of the chapter has 5 sections. Section 9.2 describes salient aspects on Energy Valley and the research to be able to frame the analysis presented in this chapter. Section 9.3 describes 'contextual factors' and how these framed Energy Valley's energy system developments initially and then in Section 9.4, the 'system responses' are described and again, Energy Valley's energy system responses are illustrated to show what this means. In Section 9.5, a comparison of Energy Valley's energy system development and that of the EU is discussed to understand how energy systems are embedded in larger regional systems and how these systems interact. In the final section, implications of the analysis [and of a systems approach] are discussed in the light of 'end states'.

9.2 Research on Energy Valley case study

Energy Valley is an energy cluster covering the Northern part of the Netherlands and was established in 2003 by stakeholders including local policymakers in response to EU and national energy liberalization policies. Energy Valley faced two major strands of development. The first, a gas driven national energy sector facing the transition to more sustainable, liberalised European energy market and the second, the economic development of a periphery region. Energy Valley cluster as a case study offered exploration into these two interconnected developments driven by changing EU and global contexts.

Energy Valley was established in 2003 and has seen changes in its scope, visibility and developments as a result of changes in its context. In order to understand how energy systems develop, the research chose a complex adaptive systems approach, which offered a systems perspective on how systems change due to responses of its agents to changes in its environment. This approach offered both micro and macro level systems perspectives which meant that local micro interactions and behaviours of agents could be understood within broader macro level energy and contextual developments. The study looked at system developments at the local, national and EU levels and these examples will be used to illustrate how energy systems develop in their (local) contexts. The research on Energy Valley was a qualitative study based on stakeholder and expert inputs supported by secondary sources of information.

9.3 Contextual factors

Contextual factors in this analysis include drivers of change, history and geography of the system, stakeholders and collective definition and boundaries of the energy system.

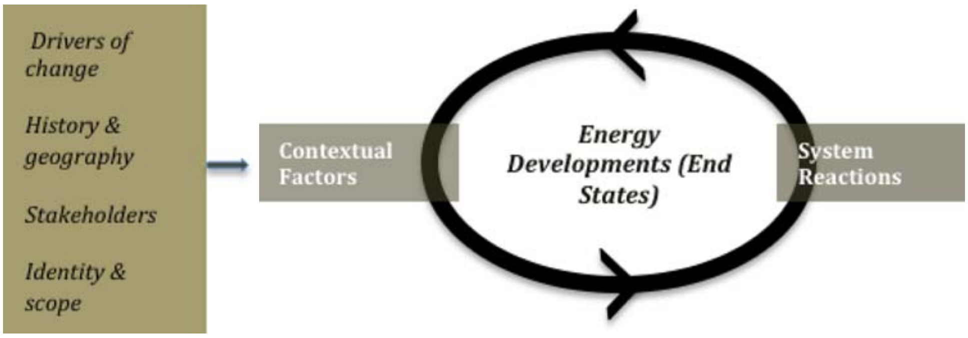

Figure 66: Contextual Factors in Energy Systems

To illustrate, discovery of gas in the North NL and the development of the gas industry for NL and EU determined the key stakeholders, namely, gas corporations, the national government and regional governments. This led to an energy system built on gas as the key resource. This initial energy system dominated by gas with its stakeholders and definitions of the system responded to specific drivers of change.

9.3.1 Drivers of change

Drivers of change in this analysis are understood to be drivers that change the system as a whole. It has been found in this study that drivers in energy systems can be external or internal drivers. The case study of Energy Valley illustrates which drivers of change were relevant to its system changes. There were nine significant external drivers and seven internal drivers. Below are some highlights of these drivers of change and their relevance to a gas dominated system of Energy Valley.

External drivers of change in Energy Valley

- *Geo-political shifts*

  Major geo-political shifts such as the emerging power shifts towards Asian economies and the renewed Russian political threats to Europe are examples of drivers that required strategic responses in Energy Valley.

- *Energy security threats*

  Dependence on external energy sources (EU imports 53% of its energy needs and of this, imports for crude oil is 90%, natural gas is 66% and solid fuels 42%) and incidents such as the recent Russian threats to European gas supply (Russian gas contributes 39% of its gas imports) needed to be addressed.

- *Large scale power outage and blackouts in Europe*

  The need for improved grid infrastructure across Europe to increase reliability is directly linked to energy security issues. Major outages and blackouts in Europe that had cascading effects in other parts were present in the recent past and therefore all regions had to comply with new EU directives and legislations to mitigate such effects, including major grid investments.

- *EU market liberalization*

  EU liberalization of electricity and gas markets was introduced to support consumer choice and increased competition. Energy systems are directly affected.

- *EU legislations*

  The legislations supported EU's goal towards a more reliable and sustainable use of energy and more flexible markets led by demand-side focus. Specific legislations governed grid interconnections and efficiency of energy systems to support development of a European internal energy market. Energy Valley needed to comply.

- *Sustainability and climate change*

  Long-term energy sustainability agendas that included climate change resulted in compliance of Member States to meet CO_2 and renewable energy targets. The EU saw gas as a fossil fuel and this had implications for Energy Valley and the Netherlands.

- *New energy resources and balancing*

  EU targets for renewable energy and energy efficiency (Policies: 2020, 2030, 2050 Energy Roadmaps) were directly relevant to developments in Energy Valley. The increased need for balancing as a result of large-scale introduction of renewable energies offered new opportunities for the gas sector in Energy Valley.

- *US cheap coal and shale*

The US shale revolution and its move towards increased renewable energy in their energy mix resulted in excess and cheap coal being dumped in European markets, including the Netherlands. This had a strong impact on energy demands by power plants and therefore affected climate change and sustainability agendas and developments locally.

- *Technology developments*

  The shale revolution, cheaper solar and wind energy, viable smart grid technologies, bio-fuels, fuel cells and hydrogen fuels are examples of the impact of technological developments on market developments. Unpredictability was a major concern.

Internal drivers of change in Energy Valley

- *Depletion of gas resources*

  Depletion of the Groningen gas reserves has been estimated around 2030 at the current rate of extraction. Energy Valley's gas contributes almost two-thirds of the energy needs of the Netherlands. Earnings in 2013 were more than 15 billion euros from gas revenues. The gas industry has direct implications for local and national economies.

- *New gas reserves and biogas*

  Biomass gasification, production of syngas, creation of green gas hubs are examples of new developments in Energy Valley changing the local gas and energy sectors.

- *Increased earthquake risks*

  Increased earthquakes and damage to property directly related to gas exploitation in the Energy Valley region were creating tensions between local population, local politicians and gas corporations and national government where conflicts in interests, roles and power relations played a role.

- *National policies*

  As mentioned earlier, government economic interests in the gas revenues were conflicting with citizen safety and electoral pressures. Long-term gas contracts and legal obligations to trading partners outside of the country versus citizen and green movements were tensions in the system. National policies were leading and therefore relevant to Energy Valley's energy system.

- *North Netherlands as economic lag region*

  Energy Valley is a periphery region of the Netherlands that has lower economic growth than the national average (-3% vs. 0.75% in 2014). Regional development agendas were competing with energy transition developments and national economic priorities.

- *Citizen movements and developments*

  As mentioned earlier, a growing distrust in energy corporations and government related to conflict of interests regarding gas exploration and earthquake risks, the rising energy prices and need for autonomy and self-sufficiency were some of the key motives of citizens and grassroots movements to initiate decentralized energy solutions. Parallel to this was also the 'green' sustainable movement. Citizens producing energy were dubbed 'prosumer', producing consumers.

- *Role of local governments*

  The urgency of local governments in the economic lag region of Energy Valley to create jobs and economic growth was prevalent. The depletion of gas resources was a major threat to further economic depression coupled with youth urban migration pulls. Earthquakes risked aggravating the attractiveness of the location. The regional development agenda was a strong driver in the region that included job creation, innovation boost and mitigating earthquake issues.

9.3.2 History and geography

Discovery of gas in the 1950s has and continued to have a major impact on the local energy system of Energy Valley. The region has built its infrastructure, energy mix and economic development policies based on the *gas industry and revenues*. The Dutch government has a dominant stake in the gas resources (50% state ownership) and are directly connected to national strategic interests. The local energy system of Energy Valley is therefore tightly connected to the national energy system. The *trading history* of the Netherlands and its current 'BV NL' ('Netherlands Incorporated') strategy framed economic interests as being leading. Gas is traded internationally and has larger implications beyond Energy Valley.

The *periphery and lag region* positions of the region meant that economic and social structures needed to be addressed. The region is dominated by *agriculture and rural economies* on the one hand, and, *large chemical and energy intensive manufacturing industries* related to national policies of the past related to availability of cheap energy. *Energy expertise* and energy related industries were dominant. However, there were other economic sectors dominant in the Energy Valley region and *regional differences* were present, for example, water and recreation, food and agro-based industries (Friesland), horticulture (North Holland North), agriculture and dairy farming (all provinces), forestry and tourism (Drenthe) and heavy industry and harbour facilities (Groningen), etc.

Lack of strong R&D investments and knowledge centres, public and private centres were also key feature of the system. The limited knowledge base was a key concern for Energy Valley.

9.3.3 Stakeholders

Energy Valley was initiated to address a serious threat of losing the local gas industry and expertise built up in 50 years as a result of EU liberalization policies and future gas depletion. The need to preserve existing gas expertise in the local economy was an important driver to Energy Valley. The key stakeholders developing Energy Valley were therefore *regional governments*, *gas corporations* and *local educational institutes*. However, gas dominance in Energy Valley's energy landscape meant that *gas industry* stakeholders and the *national government* had strong positions in the current system.

9.3.4 System definition - identity and scope

Identity and scope of an energy system is directly related to its key stakeholders. In Energy Valley, stakeholders from policy, business, academics, and regional development agencies were present and 'policy' included local and national policy makers and decision-makers. *Dominant stakeholders* in the energy system were identified as the national government, gas related stakeholders and provincial governments due to historical and geographical factors. This meant that the differences in stakeholders resulted in different definitions and boundaries for the system. Given the dominance of its particular stakeholders, *three main frames, 'economic', 'energy transition' and 'regional development'*, were evident in Energy Valley. This in part led to complex and conflicting agendas as already mentioned in earlier sections.

The regional development focus of local policy makers meant that initially a *regional and internal focused* strategy was present although the national and trading aspects of the gas business had strong national and international scopes. The activities supported by Energy Valley's strategic focus in the initial working programmes were very much on energy and regional developments.

9.3.5 Interconnectedness of contextual factors

Drivers of change, history and geography, stakeholders and system definition are all interconnected as captured in the previous sections. The illustration below captures this interconnectedness.

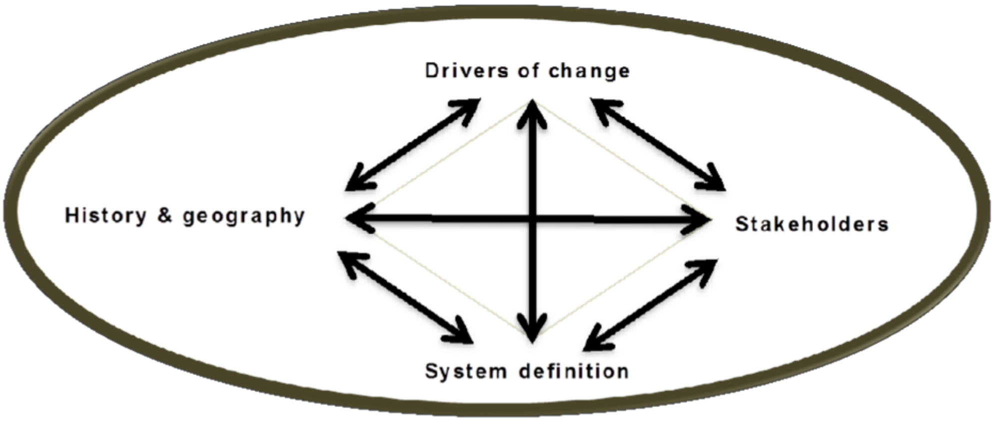

Figure 67: Interconnected Contextual Factors

Energy Valley's gas dominated system determined its stakeholders, and therefore their conceived identity and scope of the energy system and both these factors were shaped to a large extent by its (perceived) history and geography of gas and socio-economic factors related to national and regional interests. Drivers of change are connected to an energy system's definition, its identity and scope, as certain drivers influence decisions of scope, need new strategic focus, etc. In Energy Valley, the need to redefine gas dominance in its initial energy system was due to drivers of sustainability, pending depletion of local gas sources, etc.

9.4 System reactions

According to complexity approaches, systems change when agents in the system respond to changes in their environment. The total system change can be understood by exploring different aspects of a system that contribute to such a change. In this analysis, aspects contributing to system reactions include: *'pulls' of the system* which is the direction in which a system tends to move; *coping strategies* of agents that include developing and gathering new knowledge, resources and skills; *differences that matter* for future strategies; *transforming interactions* and collaborations. Finally, these aspects add up to a macro level system change visible in *emerging system patterns*.

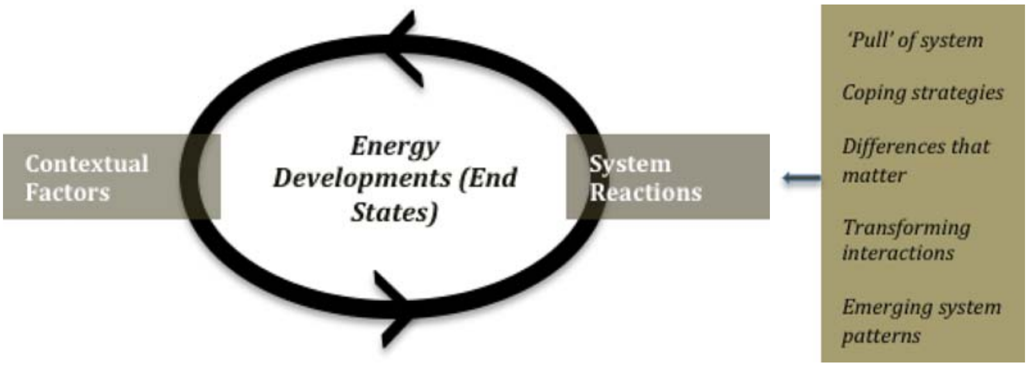

Figure 68: Contextual Factors and System Reactions in Energy Systems

To illustrate system reactions in Energy Valley, there was a pull towards more sustainable and decentralized energy solutions, connections between gas, oil and renewables. In addition, a key coping strategy was the creation of Energy Academy Europe that would bring fragmented knowledge, research, education and stakeholders together. An example of transforming interactions and collaborations was found in EnTranCe, a multi-stakeholder open innovation environment close to market. Examples of emerging system patterns were the increased presence of bottom-up initiatives next to top-down policy directives interplay of gas and electricity, cross-sector collaborators such as bio-based economy. The following sections give more details on the system reactions of Energy Valley.

9.4.1 'Pull' of the system

A system responds to changes in its environment and there is often an underlying direction towards which the system tends to move. In Energy Valley, the drivers of change and responses by individual agents in the system resulted in more complexity and increased unpredictability and a general movement towards the 'outside'.

The energy system was initially an internal and regional oriented system. But the changes in the context saw various shifts in this system. One example was the position of 'gas' in the energy mix. It was no longer secure due to the increase in new sustainable energy solutions. This meant that a pull to redefine and reposition gas in the new energy system. Related to this was the decentralization movement of citizens and grassroots organizations. This also meant a tendency towards more demand-side focus instead of the traditional supply-side dominance.

The lack of R&D, innovation resources and facilities, talent, policy constraints, etc. resulted in a tendency to explore possibilities outside the local system. Pilots in the UK were carried out where regulations were less stringent for new innovations. The strong 'pull' to seek solutions outside Energy Valley was a serious threat of further depletion of capacities and attractiveness of the region if this resulted in a 'cluster drain'. Programmes and mandates from the European Union supported internationalization tendencies, and provided additional resources to regional systems, enhancing the attractiveness of 'the outside'. Being connected internationally was not in itself negative, but the 'pull' of the outside could be a threat if it did not contribute to strengthening the system's capabilities.

9.4.2 Coping strategies

There was a need to deal with the changing landscape of Energy Valley's energy system. Stakeholders identified different strategies for its future and these included creating new and different infrastructure to deal with the emerging (complex) energy system; including new stakeholders such as local intermediaries, citizen and grassroots organizations, Small and Medium-sized Enterprises (SME), etc. in the search for broader system-wide changes; creating new cross-sector value chain collaborations; creating educational programmes with multi-disciplinary competences; creating new institutions and innovation spaces, etc. All stakeholder groups underlined the urgency for different approaches and changes in the existing policy, business, education and innovation practice. There was also an acknowledgement of the need for both large-scale and decentralized solutions, and a more inclusive strategy.

9.4.3 Differences that matter

In order to meet the new challenges due to the changes in Energy Valley, the innovation potential of the system had to be analysed. Exploring 'differences that matter' in a system with new combinations of potential differences in a system could result in innovation. In Energy Valley, new and different competences and capacities needed to be explored to resolve the increasing complexity in the system through new combinations (German notion of 'neue Kombination'). For example, *innovative SME collaborating with large corporations and industry* with their resources and market reach could result in accelerated commercialization of innovations, including access to international markets. *Combining fragmented research and knowledge disciplines* present in the different universities in Energy Valley could accelerate more focussed and collective solutions for energy development challenges. *Regional differences* in Energy Valley with differences in goals, ambitions, resources, market structures, networks, etc. could be used to forge new networks, new cross-sector solutions, new business model testing, etc. The *regional and national interests* were also significant and could offer different solutions to both systems. Energy Valley had physical space and large agricultural land and farms that offered biomass solutions as a sustainable energy source whilst national government needed to deal with CO_2 targets and these two different goals could be achieved through the use of the differences of each system. Potential or 'missing' stakeholders in Energy Valley such as environmental groups, civil organizations, and 'prosumers' had different values, goals and motives from the established stakeholder groups. Combining these differences could offer a broader reach to the energy sustainability agenda.

9.4.4 Transforming interactions

When interactions take place that come from new combinations, a change takes place that transforms the original interactions. An example in Energy Valley was the creation of EnTranCe which began in the skybox of the local football club where informal discussions of different local energy businesses and the energy research centre led to the creation of an open innovation multi-disciplinary centre where businesses, students and research could come together to solve energy transition challenges. The 'gas' stakeholders had a strong systems approach and this has been adopted in EnTranCe as a key competence. Energy Academy Europe is another example of a collective initiative that resulted in a special institution for energy to overcome fragmentation and lack of 'energy' in curricula.

A different example of transforming interactions was the integration of energy – between electricity and gas, renewables and existing energy systems, micro-level energy system management for homes and neighbourhoods, meso-level energy hubs connecting businesses in transition parks, green gas hubs, and macro-level energy collaborations across regional boundaries such as in Hansa Energy Corridor and ENSEA (North Sea) projects.

Another example of transforming interactions in Energy Valley were the development of integrated energy vision clustering strengths of the different Provinces in 'De Plus van Noord Nederland', of different sectors in the 'Bio-based Economy', and aligning to national agendas in the 'Green Deal' and 'Switch' agreement and programmes.

A more inclusive strategy of extending dialogues to consumer and grassroots movements on energy developments in Energy Valley region meant that the system was changing in terms of its relationship to these groups, from end users to participants and increasingly strategic partners.

9.4.5 Emerging system patterns

The transforming interactions of Energy Valley were visible indications of changes in the system. These changes were coming together due in part by the responses of agents in the system and their coping strategies, building on innovation potential of ‘differences’, and the underlying ‘pulls’ of the systems. On a systems level, new or emerging patterns could be discerned in Energy Valley. These patterns indicated that the energy system was becoming *more complex*, which is partly due to the system becoming *more ‘open’* as seen by the inclusion of new players, new sources of energy, more international orientation, new business models, etc.

The scope of the system was changing to become both *more local* and *more international* and there was evidence for a *more systemic approach* that went beyond the traditional notion of energy systems. Following the systemic approach, a more emergent and organic development of the energy system was visible even as more policy and top-down coordination was taking place in Energy Valley. Included in this shift were *more flexible and varying* strategies that embraced both local and international developments, traditional and renewable energy solutions on small and large-scale as necessary, thematic and on-line community developments that were self-organizing as well as strategic projects focused on ‘gas and energy roundabout’ policies in line with national, trans-regional and EU developments. Collaborations on international and EU levels across Energy Valley’s system were another emergent pattern that reflected major shifts of the system from the once regional and locally oriented system.

9.4.6 Interconnectedness of system developments

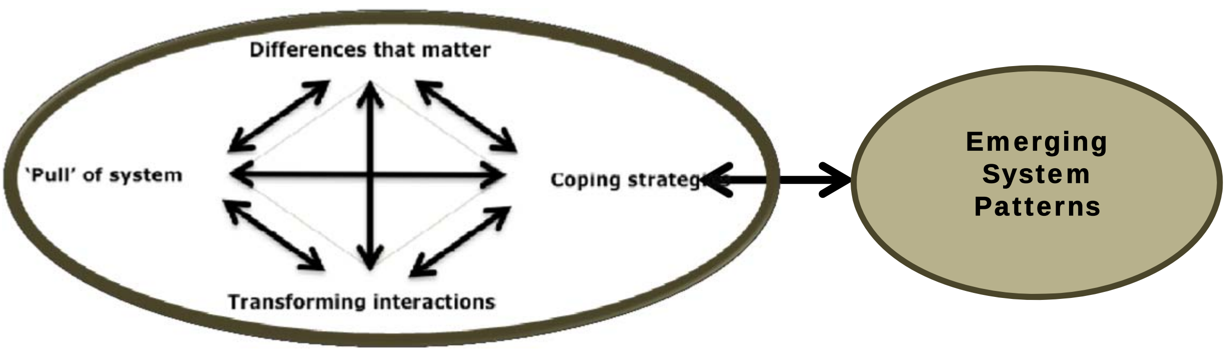

Figure 69: Interconnectedness of System Reactions

The system reactions are interconnected as shown above in the diagram and together these result in macro level system patterns as already described in the section above. When gas is re-positioned as a balancing power source in Energy Valley (‘pull’ of system), then realizing an integrated fossil, renewable and gas energy system (‘differences’) is more feasible. This allows other energy carriers to be seen as complementary rather than competitors (transforming interactions), which in turn facilitates open innovation and collective initiatives as ‘coping strategies’. More collaborative and integrated approaches become part of new system patterns.

9.5 System patterns in Energy Valley / NL and EU

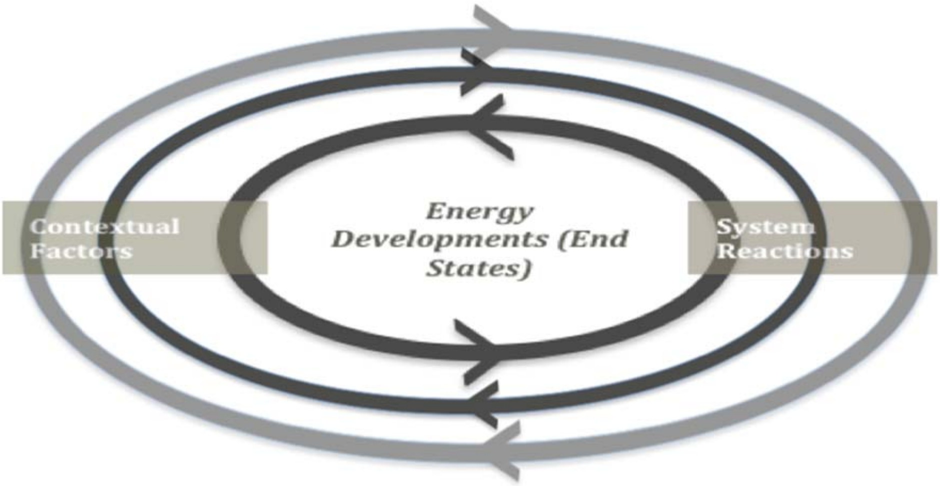

Figure 70: System in System interconnections of Energy Developments

The analysis explored how Energy Valley and the Dutch national systems reflected system patterns at the EU level. Complex Adaptive Systems (CAS) approach explains how systems are embedded in larger systems and how systems interact and feed into each other. The diagram above captured the embedded nature of energy systems as understood by CAS.

In the comparison of the three levels, Energy Valley, the Netherlands and the EU, the shifts in the contexts were similar, namely, the *growing complexity and unpredictability* of energy system developments as were the *external drivers of change* (geo-politics, financial and euro crises, new technological advances, energy market developments, etc.). Similarly, in all three levels, *energy systems were embedded in larger socio-, political, economic and ecological systems*. In all three levels, *economics was leading* and this framed energy developments in terms of enabling competitiveness. Common themes related to this are energy security, sustainable energy solutions, CO_2 mitigations, innovation, and smarter grid connections. *Regional social cohesion* and job creation was a key issue to Energy Valley and the EU.

On the other hand, whilst Energy Valley and the NL had a gas-dominated history similar to the UK, the EU had a wider diversity of energy sources and systems. The 'pull' of Energy Valley's system was to *keep gas in the energy mix* whilst the EU was focussed on *independence of external sources of fossil fuels* plus its commitment to *climate change* resulted in a strong 'pull' towards renewables. At the same time, the EU had a *diverse 'energy system'* with 27 different Member States (MS) with their different infrastructures, energy sources and socio-economic structures stemming from their different history and geography. In Energy Valley on the other hand, whilst regional differences were present, *national economic frame and policies were dominant*.

A common system development in all three levels was the acknowledgement of a *need for collective commitments* to build multi-disciplinary competences, cross-sector and new value chain innovations, new business and governance models, and more trans-regional and international collaborations to meet the new and complex challenges of energy. There were more visible coordination and connections in energy infrastructure and markets in all levels, more and different alliances and collaborations, new governance structures, more decentralization of energy movements, more trust and engagement to realize collective goals, more sustainability, technology and consumer push, etc. The system level patterns at all three levels had some differences but in general, there were many parallels in their system developments.

9.6 Implications for end states and energy futures

The system of Energy Valley at the beginning of the analysis showed how gas was the dominant factor in the system and how the stakeholders, strategies and solutions were all related to the traditional gas sector. In the second part of the analysis, the system reactions, the role and definition of gas in the new Energy Valley system had changed. Gas was also bio-gas, sync gas, gas from different sources and players, gas was also connected to smart grids and had re-positioned itself as a balancing and storage carrier within a more diverse energy system. This meant new and different 'coping strategies' including new competences and expertise beyond gas. A different aspect of the system change was the earthquake risks brought about by gas exploitation. The position of gas in the larger socio-economic system was weakened by such developments. The future of gas in the energy mix in Energy Valley has become polarized between the local and national economic interests and therefore new 'coping strategies' needed to be considered where citizen acceptance and national interests needed to be balanced.

9.6.1 Contextual factors, system behaviour and end states

In this analysis, the role of contextual factors has been explored in the light of Energy Valley's energy system and the resulting system reactions. The analysis also included an exploration of how Energy Valley was embedded in the national and EU systems. Based on this analysis, a number of conclusions can be drawn that have implications for end state developmental pathways. The following considerations play a role in these developments and can contribute or limit end state developments. The considerations have been categorized under their respective headings of contextual factors, system reactions and system in systems.

Contextual factors and end states

Role of contextual factors

Energy systems are more than technological systems

Each energy system is subject to local and global contextual factors and it is more than only drivers of change, it includes history and geography, stakeholders and system definition

Interconnectedness and unpredictability of system interactions as a result of contextual factors

Elaboration on role of contextual factors

Energy transition is not only a technical challenge but economic, (geo) political, environmental, behavioural and (civil) societal aspects play an important role. Moreover, these aspects are interconnected and unpredictable and are therefore difficult to anticipate and know what impact they could have on chosen pathways.

The future is not predictable (gas prices, earthquakes, technological advances) and therefore more attention is needed to 'fitness' of strategy to drivers of change where alertness and responsiveness to current trends and developments are important. Too much focus on long-term planning may miss current trends and opportunities elsewhere.

Focus on one dominant energy system (e.g. gas dominance) could lead to lock-in effects inherent in contextual factors. External drivers of change, e.g. a major earthquake, could have major impacts on such future end states. A diverse energy mix offers flexibility and resilience.

System reactions and end states

System reactions
Due to unpredictability of energy future, planning strategies are limited in their value and therefore, more resilient strategies are needed. These could include • being open to broader developments • creating trust amongst a larger group of stakeholders and engaging with 'new' stakeholder • engaging in interdisciplinary solutions, innovations and knowledge sharing • supporting new businesses to reach critical mass, and to be part of the energy system • creating broader system definitions and approaches, e.g. energy as eco-system • acknowledging self-organizing processes next to coordinated policy

Elaboration on system reactions

Interconnectedness and unpredictability of 'other' factors increases the urgency to engage and include stakeholders outside of energy in developments to expand the perspective and scope of strategy frameworks of energy clusters.

- Connections (especially to outside the 'normal') as opposed to fragmentation and 'silos' are vital to break down 'lock-in' risks and to make an energy system more resilient:
  - Including other stakeholders, for example, engaging politicians at all levels, connecting to consumers and consumer intermediaries especially since consumer and demand-side focus is becoming more influential
  - Connections to other disciplines instead of mono-disciplinary approaches
  - Connections in an enlarged scope, examples being gas to renewables, international connections, other sectors, value chain approach instead of product development in isolation
- Building ecosystems to accelerate innovation and knowledge sharing:
  - Includes open innovation, international, interdisciplinary, inter-sectorial, consumer involvement, focus on variety, etc.
  - Government's role in facilitating ecosystems including capacity building and knowledge development to support knowledge acceleration and excellence.
  - Major push needed to boost start-ups, large corporations and R&D centres to create critical mass to attract and keep expertise and talent in the region.
  - Attractiveness of the region is a major challenge that would influence future of the cluster. Energy Valley needs to deal with this to avoid 'cluster drain'.
- Centre and periphery issues where relevant such as a shift to include stakeholders in the margins (environmentalists, 'prosumers', consumers, innovators, funding partners), or a shift in system position from peripheral regions to more strategic positions as was the case in Energy Valley.

- Better alignment and connections between future scenarios and frames of key players need to be addressed. Balancing 'frames' of climate change, competiveness and economics, regional cohesion agendas and other local frames needed since this could result in affecting end state developments. Particularly, where
  - energy as a theme served different goals and agendas
  - major differences and misalignments in urgency and priorities were present
- Systems, and particularly complex systems, are subject to self-organizing processes. Acknowledgement of such processes and facilitating decentralized initiatives as part of good governance is needed in addition to coordination through top-down policies and guidance
- Building trust as a key aspect of energy system developments is important since this is strongly connected to how local energy systems react to new and planned development pathways. This includes
  - trust between different types of businesses, between government and businesses, citizens and governments and businesses
  - trust in large scale investments and projects especially when new technology is involved
  - trust in the 'care-taker's role' of the government and the long term sustainability of societies

System in system and end states

System in systems

Local and EU energy systems are interconnected

- Lower level systems feed into higher-level systems and therefore various local energy systems' developments and their respective energy end developments will contribute to a higher order system of end states

Elaboration of system in system

- Local energy systems are connected to EU systems and this offers opportunities to connect and tap into competences, resources, energy sources, to increase scope, scale and capabilities to accelerate energy system developments locally but it also works both ways and offers national and EU level systems opportunities to accelerate and influence their preferred energy developments.
- On a systemic level, being aware and connecting to other systems' developments is an opportunity for growth, visibility and influence and at the same time, it increases complexity and unpredictability of end state pathways.
- Local energy systems tend to be 'locked in' to their contextual factors and system reactions as described in this analysis. Connecting to other local energy systems and to the EU could help temper lock-in pulls. At the same time, at the higher EU level, the diversity of the different local energy systems and their end state pathways and goals make the EU system more resilient. Diversity of the higher level system could act as a buffer for any lack of resilience of energy systems to external shocks (drivers of change) and therefore an issue to be considered for the

'big picture' is that there could be different end states in a larger EU system but that the higher level system of the EU needs to be diverse and resilient to future drivers of change.

9.6.2 Complex energy systems

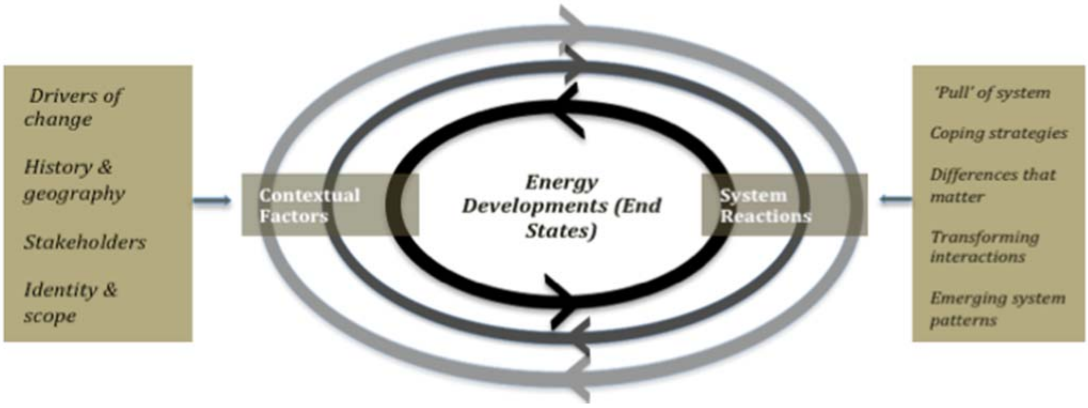

Figure 71: Complex Systemic Energy Developments

Based on the systems analysis as described in this chapter end states are determined by contextual factors of the (local) energy system and the energy system's reactions to such changes. The configurations for a specific energy system are continuously being shaped by the interaction of contextual factors and system reactions. And end states of local systems feed into higher-level end states, which in turn are affected by contextual factors and system reactions that then determine energy end states of the whole system-in-system. For Europe, local and regional energy end states feed into the European end state developments and therefore a systemic analysis of local and European end state contextual factors and possible system reactions could provide a more specific picture of constraining and supporting factors towards end states. In addition, as mentioned in the system in system analysis, the notion of different end states in local energy systems is a plausible scenario, which in turn could support a more diverse and resilient energy system at the EU level. This last consideration, of systemic interconnectedness, could become a relevant agenda in the EU's development of its Internal Energy Union and its end state pathways.

9.6.3 Implications for Big Picture - 3 End states

Potential limiting factors as 'risks' have been identified below for the end states, particularly from the EU perspective, to illustrate key contextual and systemic factors that could affect pathways to energy end state scenarios.

- **Risk of underestimation of 'system reactions'** as energy systems are not technology systems but social systems
  - System reactions on unexpected incidents such as nuclear disasters, shale gas risks, offshore oil disasters, earthquakes, political crises have shown their impact on energy policies and practice.
  - System reactions on slow trends (boiled frogs), for example, climate change, and on sudden breakthroughs (game changers), for example, fracking technology.
  - Micro level system reactions on price developments, ecological damage, push for autonomy and self-sufficiency, etc., as seen in the 'prosumer' and green movements, decentralized energy systems and emergence of small innovative firms.

End States: Larger risk in BAU, less risk in GAS, and least in RES.

- **Risk of miscalculation of role of governments** and regulations at European, national and regional levels
  - European Union's drive to be independent from foreign supplies (energy security focus) and its transition to low carbon society. Captured in new 'Resilient Energy Union' vision of secure, sustainable, competitive, affordable energy for every European.
  - EU's ambitions translate to national and regional regulations, for example, renewed focus on North Sea Grid to reduce Russian gas supply dependence.
  - European Union's innovation policy and funding programmes focus on strengthening regions and clusters to increase competitiveness of small and medium businesses, particularly in new emerging industries. Energy efficiency, smart grid and decentralized innovations are energy related examples. This includes shifts to regional vs. national levels, strengthening the regional and local energy systems primacy.

End States: BAU and GAS scenarios more vulnerable than RES.

- **Lock-in risk due to current dominance of fossil fuels**
  - Assumption of abundant fossil fuels (gas in GAS scenario), power of fossil fuel corporations, short-term thinking and growth of energy needs results in more exploration, more infrastructure for fossil and non-fossil, more expertise, etc. (more of same = lock-in).
  - Underutilization of 'other solutions' (as in RES scenario), cross-sectoral, cross-disciplinary open innovation developments.

End States: BAU and GAS have largest risk, RES least.

The table below captures the risks with a brief explanation for EU end states.

Table 15: Implications of Risks for End States

Key Risks	Risk for BAU	Risk for GAS	Risk for RES
Underestimation of 'system reactions'	++	+	- -
	Short-term thinking particularly in BAU scenario makes it more vulnerable *In RES, variety of stakeholders including demand-side innovative firms, NGOs and consumers reduce tunnel vision and increase flexibility of system.*		
Miscalculation of role of governments and regulations	++	+	- -
	Current dominance, lobby and short-term thinking of fossil fuel industry feeds into optimism of continued influence and lack of alternatives for current scenarios on the short-run *National sovereignty still dominant in EU and fossil fuel industry have powerful positions* *EU ambition to be low carbon and energy independent is a push for RES*		
Lock-in risk	++	+	-
	Similar to 'role of government' risk *Current dominance and power of fossil industry and a lack of alternatives strengthen search of solutions in 'known' RES are dependent on new innovation and therefore less risk of lock-in*		

9.7 Key findings

General

- EU's end states are unpredictable due to contextual factors and energy systems reactions
- Local energy systems influence EU end states and v.v.
- Local energy mix variations in end states (e.g. gas dominance in NL) contribute to EU's diversity and less lock-in risk, and this increases EU energy system's resilience.

Risks

- Underestimation of 'system reactions'
- Risk of miscalculation of influence of governments and regulations especially BAU
- Risk of lock-in especially in BAU and GAS

Opportunities

EU's combined drive for energy independence and low carbon economy ambitions create opportunities for leadership in innovation (push for RES)

Note: The 'Contextual and Systemic Forces in Energy Valley' analysis was based on a PhD research project focussing on energy cluster dynamics that overlapped the study of 'end states' in the context of Energy Valley. Drs. Karel van Berkel was part of the research team contributing to the study. (Expected completion of PhD thesis, 2015; article on end state analysis will be submitted for publication, mid-2015).

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10 CONCLUSION

This report aimed to identify the structural changes and transition pathways with a particular focus on the role of gas. Furthermore it aimed to recognize the implications and possible limitations of these transition pathways to a future proof energy supply. The main research question of this report is as follows: "*What are potential robust energy end states after the transition and what will be the role and share of both renewable energy and in particular natural gas in Europe*?"

Drivers impacting energy systems

In order to understand the dynamics behind the forming of energy end states this research firstly introduced drivers of change impacting the energy environment. A plethora of drivers of change will shape energy systems of the future. This report discussed the relevant drivers of change and their possible influence on the future energy systems, according to the World Energy Council's framework using five interlinked areas. The five areas are: Politics, Social factors, Economies, Resources and the environment, Energy systems and technology. A key finding is that the international political and economic order is becoming more multipolar than three decades ago, and that drivers of change can have a different effect in different parts of the world.

The role of social and political actors on energy systems is likely to be more prominent. In Europe, this will be noticeable at the local, national and international level. At the local level, high-impact social ideas like green consumerism and limited acceptance of energy systems that result in major trade-offs, could be important drivers of change. Nationally, the empowerment of individuals and communities relative to the state and as producers of some forms of energy and the politicization of energy-related issues will be key drivers of change. Internationally, energy issues will at least remain important or become even more so in the foreign and security policies of countries and the geopolitics of non-state actors.

Energy transition end states

To derive at potential robust end states this report explored numerous energy scenarios to distil three energy transition end states. These end states were subsequently scrutinized by examining their implications and potential limitations. The end states that surfaced from the analysis are labelled as:

4. **Renewables (RES) -** Somewhat stabilizing energy demand and strong increased share in renewable energy.
5. **Business as Usual (BAU) -** Increasing energy demand supplied by a balanced mix of energy sources.
6. **High Gas (GAS) -** More than doubling energy demand and satisfied by a large share of natural gas.

Although the end states were derived using primarily quantitative analysis, they can be characterised by the principal factors of the PESTE framework as shown in Table 16.

Table 16: Characterisation of end states by PESTE framework

Factor	RES	BAU	GAS
Political	Most effective policies and measures to promote RES, long term perspective, stringent regulations and in increasing cost of CO2.	Focus on short term national security, developed countries assume more responsibility for climate change, RES support continues, increased CO2 price.	Focus on short term national security, RES support continues, increased CO2 price.
Economic	Global population and GDP increase, investment in infrastructure increases.	Global population and GDP increase and drive energy demand (especially in developing countries); energy efficiency grows in developed countries.	Global population and GDP increase, developing countries catch up in economic growth, high commodity prices.
Social	Climate change awareness shift, increasing tensions between rural and urban communities.	Income redistribution affects energy efficiency in developing countries, increased environmental consciousness.	Concerns about energy security.
Technological	Significant development and maturity of the existing technologies, efficiency increase, modal shift in transport, increased R&D expenditure and innovation.	Increased energy efficiency, progress in CCS, hydrogen, and unconventional fossils.	Progress in unconventional fossils' recovery, energy efficiency, CCS, no dominant technology.
Environmental	Significant emissions reduction after 2020.	Moderate emissions constraints.	Global emissions increase, no significant international agreements to reduce emissions in place.

Although the end states differ in their final energy mix and absolute amount of energy consumption, there are several similar factors. From an economic perspective, all three end states assume an increase in global population and GDP. Similarly, CO_2 prices and energy efficiency are expected to increase as well and there's a continued support for renewable energy sources under all three end states, albeit to various degrees.

On the other side though, there are differences as well. While emissions are expected to decrease in the RES end state, they are set to moderately increase under BAU and GAS. Also, unconventional fossil fuels are projected to play an important part under BAU and GAS, whereas, unsurprisingly, renewable energy technologies are projected to mature under the RES end state.

A more detailed look into the GAS end state shows that its actuality is connected to a large increase in energy consumption and CO_2 emissions. Furthermore, in contrast to what is normally assumed, natural gas is projected to play a significant role primarily when climate awareness is lower on the agenda; in contrast to the RES and BAU end states. Also, natural gas seems to play an important role when policy makers are more concerned about energy security than climate change, when no clear choices are made regarding favourable technologies and when limited international coordination takes place.

Implications for energy and particular gas system

To describe the role and share of both renewable energy and in particular natural gas in Europe this report described the implications for each of the three end states, including possible investment requirements in gas and renewable infrastructure.

A model has been developed that allows for a translation of the final energy demand mix into primary energy requirements by adapting the underlying energy system. As may be expected, the RES end state has the largest implications, in terms of end-users requirements and land use. First of all, electrification, as a result of the choices made in this end state, is reflected mainly in the transportation sector as electric vehicles, as well as electric space heating in the residential and tertiary sectors become essential for the realization of this end state. Furthermore, energy use is shifted to land use which is a consequence of the implementation of large amounts of renewable sources. This is especially the case for biomass under the RES end state, in which about 50% of the agricultural land in the European Union is needed for growing energy crops. Furthermore it is noteworthy that in all three end state, the industrial sector does not change much. Therefore, there are no major changes in the production structure and activities.

Specifically zooming in on the existing gas infrastructure, analysis showed that it is well equipped to support the realization of the RES and BAU end state. Evidently, this is directly related to the decline or stabilizing gas demand in Europe under these two end states. However, the gas infrastructure is also well-suited to support the increasing gas demand in the GAS end state. Although it would be required to build additional importing pipelines, the analysis shows that the internal gas network as presently available in Europe is capable to satisfy this increase in demand. From this respect, no considerable limitations are expected from the availability of the gas infrastructure.

Focusing on the role of renewable energy technologies, analysis revealed that different decentralized renewable energy technologies have different grid implication dynamics relative to varying demand scales. Part of those differences can be explained through differences in weather dependency.

- For power from *solar-photovoltaic (solar-pv)*, inherent mismatch between typical supply patterns and typical power demand patterns imply that only a small share of the energy mix can be contributed by power from solar-pv without substantial grid implications. Conversely, larger shares of decentralized solar-pv power may be associated with more significant grid implications.
- Power generated by *wind turbines* is more strongly affected by variation in weather patterns than power from solar-pv, but its daylight-independent supply patterns enables a larger demand-supply matching potential. Therefore, the share of wind power that can be integrated into the energy mix without substantial grid implications is larger than for power from solar-pv.
- *Biogas*-based decentralized power supply is fairly constant and predictable. As such, the no-grid-implications share of biogas power is the largest of all three decentralized renewable power sources considered in this research.

Energy futures involving large shares of decentralized renewable power in the energy mix are likely to involve substantial grid implications. However, part of the power generated on a decentralized platform is consumed locally. Only the part that is not consumed locally/directly accounts towards grid implications. Grid implications for larger shares of decentralized renewables may thus be less than what could be assumed from the gross total of generated power.

Case studies on success factors and barriers for energy systems

In order to fulfil the need for practical examples and analysis of applicable technologies this report discussed the case of power-to-gas, biomass and the local North Netherlands situation. These case studies tried to pin-point the specific needs for the gas industry for the three end states.

Innovation of technology trajectory: Power-to-gas

The energy system has to adapt to intermittent energy sources, such as wind power and solar energy, which provide energy in a fluctuating manner. Energy storage is one of the possible solutions. In times of excess electricity production, excess energy has to be stored. Power-to-Gas is a technology that offers this storage option. The position of power-to-gas in the future energy system depends on the wind and solar ambitions, power-to-gas technological progress and the development of a regulatory framework for both gas quality standards and investment conditions.

Technology developments can be analysed using the technological innovation system (TIS) framework. The TIS includes all actors and institutions involved in the development, diffusion and utilization of a technology. For a technology to develop successfully the TIS should fulfil several functions. Theory indicates that all TIS functions need to make progress in order for power-to-gas to become a feasible solution for balancing energy supply and demand. Currently power-to-gas technology pilot projects are realized, studies are carried out and funds are available for both projects and research. The functions called entrepreneurial activities, knowledge development, knowledge exchange, and resource mobilization are all met. Especially the market formation function requires substantial efforts, part of the problem in this function is the fact that there is not yet a regulatory framework for power-to-gas.

Limitations of biomass availability

Since it is expected that biomass technologies, especially biomass digestion, will contribute considerably to the required volume of renewables in the future energy mix, this report assessed the limitations of large scale biomass use in Europe. For a densely populated country (such as the Netherlands) it is impossible to produce the biomass fuels to supply their own system. This is further complicated by the competition between food and energy. Not only the food and fuel discussion, but also due to competition between feedstock for other applications (e.g. bio plastics). Looking at a possible business case for biomass, it is more obvious to work with economic cascading. This means that organic streams available for energetic purposes have a degraded quality compared to the use of dedicated energy crops.

When looking at the BAU end state, which seems to be the most obvious when it comes to biomass consumption one needs 4.5% of land available in the EU in order to fully supply the transport sector with biogas. This could theoretically be accommodated within the BAU end state. However, this would be more complicated for the RES and Gas end state with higher demands. This is a clear limitation.

Local energy system dynamics: Energy Valley

When talking about ‘energy systems’ this analysis takes a broader perspective and looks at ‘energy’ as being embedded in social, economic, and political systems and that such a system could be a district, region, country, or a regional block such as the EU. The analysis looks at ‘energy’ as being located in a specific location with a defined boundary. In this research, Energy Valley was examined as an energy system embedded in a larger energy system, which is the national energy system and this in turn, is embedded in a European energy system. Each of these systems can be examined separately, but each of these next level systems is interconnected and contributes to other levels. EU decisions and developments influenced Dutch decisions and developments and therefore that of Energy Valley. The analysis showed that the future of gas in the energy mix in Energy Valley has become polarized between the local and national economic interests and therefore new ‘coping strategies’ needed to be considered where citizen acceptance and national interests needed to be balanced.

The Big Picture - the future role of gas

What will be the role of natural gas in Europe in 2050? Based on the three main energy scenarios presented in this report, the gas volumes in the energy mix will range roughly between 300 bcm/yr to 700 bcm/yr. Despite the possible shift to the lower volumes which are still substantial, capacity will become increasingly important. Gas is truly the preferred fuel to balance intermittent renewable energy supply. There will be a need for underground gas storages to balance the gas system and there will be a need for gas source diversification as domestic European gas production will decrease dramatically. The existing and planned gas infrastructure in Europe is sufficient in the lower (RES) and medium (BAU) scenarios with regard to natural gas. In case of a shift to the larger volumes of fossil gas (GAS), there is a need for extra gas infrastructure which is not planned yet in Europe.

The energy and gas situation in Europe in 2050 is not exemplary for the rest of the world; even regional and local differences within Europe may persist or evolve in this multipolar energy world. A uniform EU policy on energy and gas ('mature Energy Union') will take a long journey which may be not be concluded in 2050. The RES scenario has strong implications for end-user markets and will need strong uniform regulation. It is highly questionable whether the shift to renewables may be realized in time.

APPENDICES

Appendix A - The Big Picture energy flow model

For the detailed quantification of the energy transition end states the University of Groningen made a model in which the energy flows and conversions between demand and supply are calculated. In this appendix a description of that model is provided.

A.1 Calculation scheme

In Figure 72 a scheme is presented in which the steps are shown that had to be taken from the qualitative scenario description to the implications for the gas infrastructure and the limitations in availability of resources.

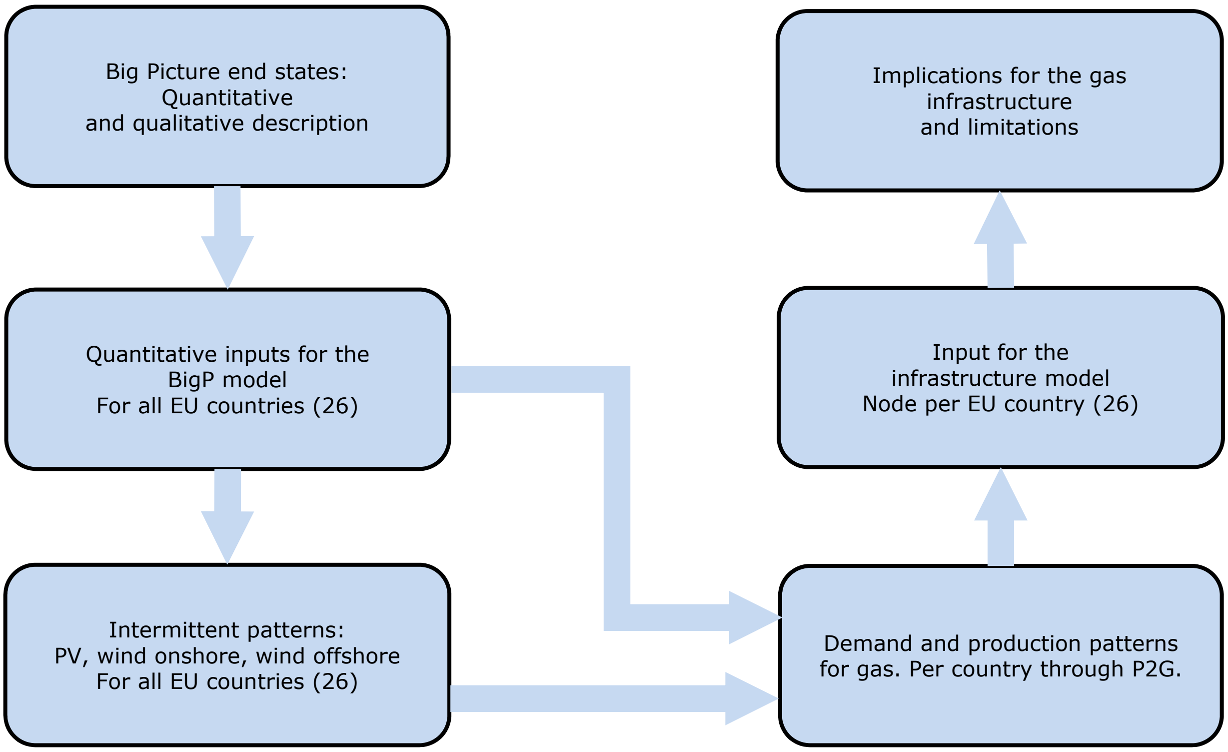


Figure 72: The calculation scheme as implemented in the Big Picture project

Combined with renewable supply patterns (see Section A.5) results the matching of demand and supply in a demand for infrastructure. These demands were compared with the present infrastructure with the ENIGMA gas infrastructure model.

A.2 Description of the Big Picture energy flow model interface

Figure 73 shows the dash board of the Big Picture model. Besides dash board, this figure also shows quantitative results in the form of coloured bars (in the centre and at the bottom of the named rectangles: panels). The arrows show the connection between sources, conversion technologies, carriers and sector demand. A mouse click on almost all panels leads to an input screen were data can be adjusted.

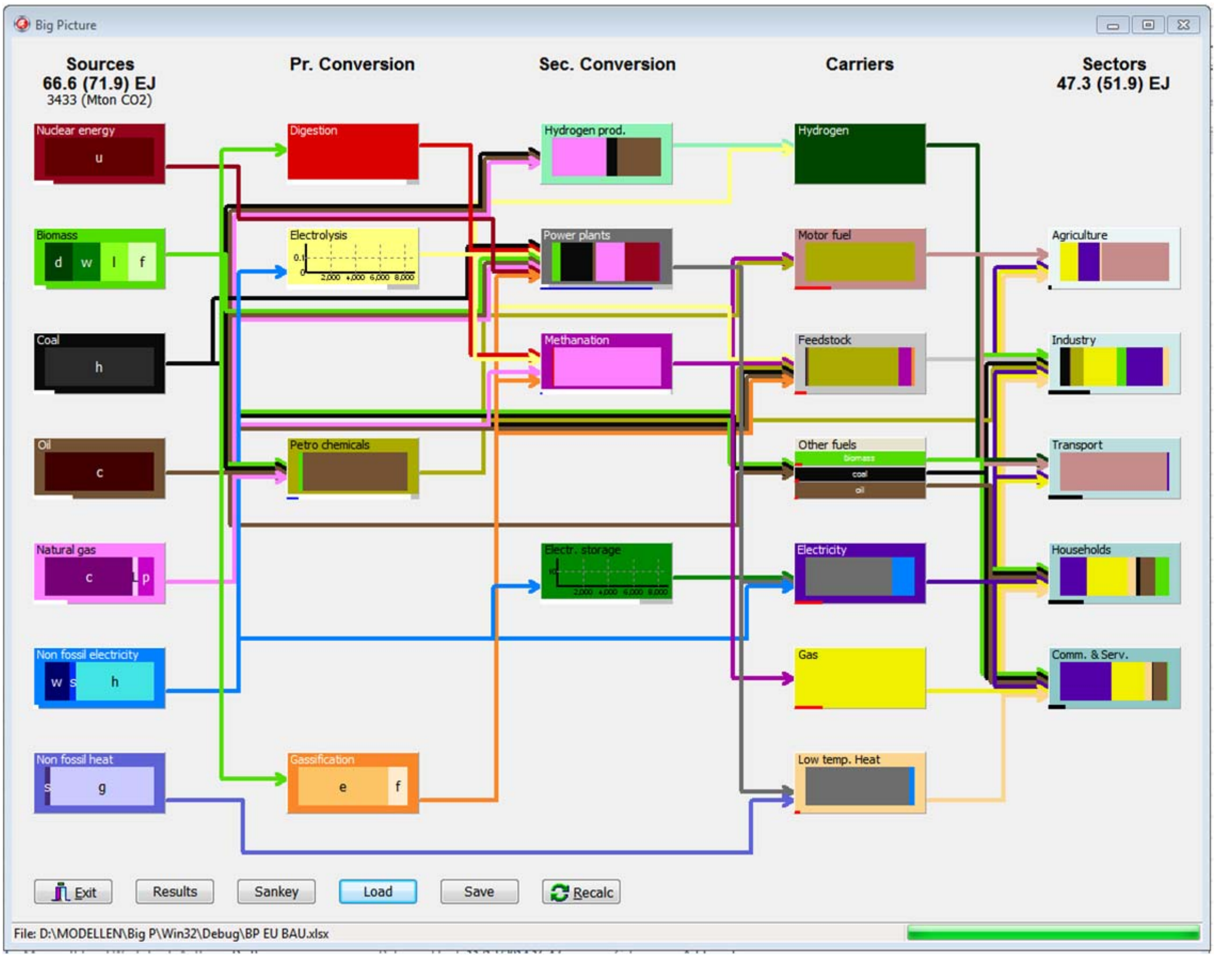


Figure 73: Dashboard and results screen of the Big Picture Energy module.

(In the model demand and supply are matched. The calculations run from right to left (from sector demand to sources).

In Figure 74 the dash board is explained in more detail. In this figure the semi-quantitative information present in the dash board is explained. The calculations of the model start right with the sector demand for energy/feedstock for certain functions or subsectors as the starting point and ends left with the demand for resources. In between carriers are calculated from the demand and the carriers are produced from natural resources by means of several one or two steps conversions. By selecting one of the: source, conversion, carrier or sector panels, a new window is opened in which the user can change the input data. An example is given in Figure 75; here the energy demand for the residential sector can be changed as well as which type of technology will be used for space heating and hot water.

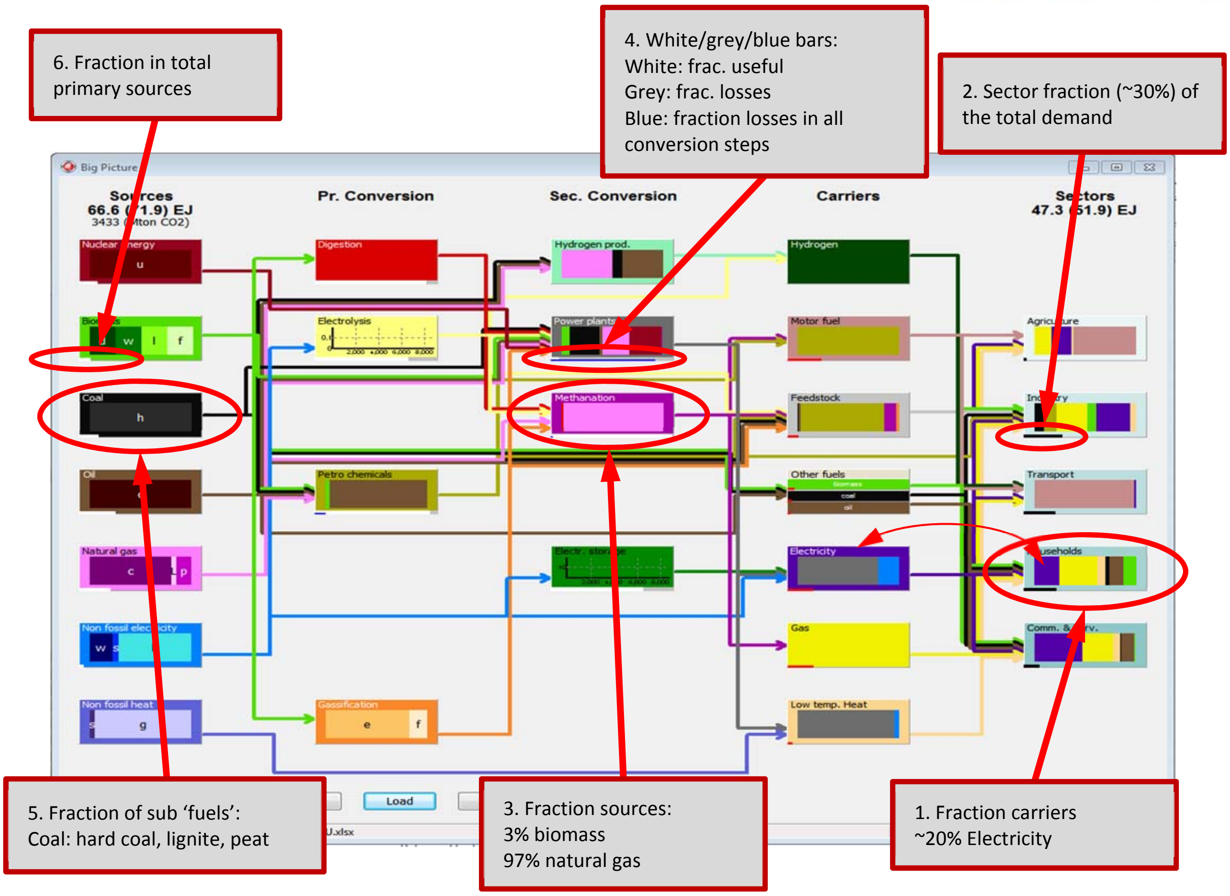
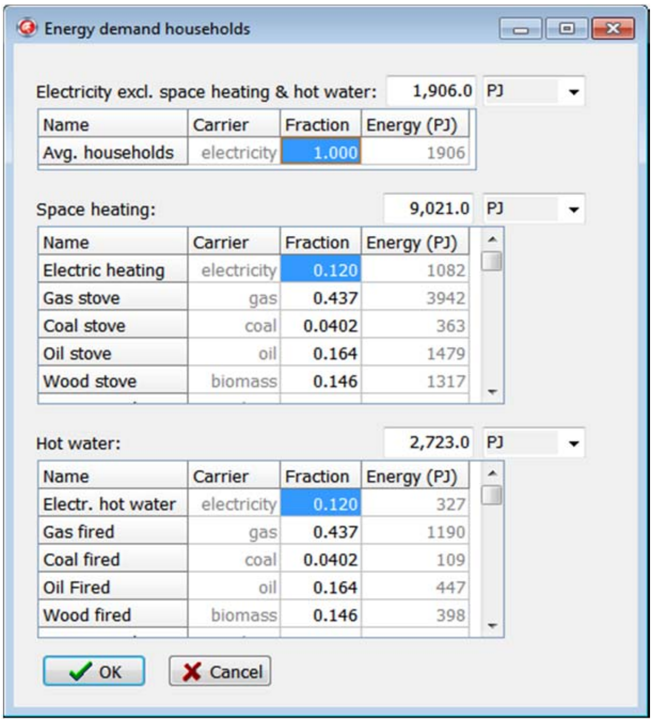


Figure 74: Dashboard and results screen of the Big Picture Energy module



Energy demand households

Electricity excl. space heating & hot water: 1,906.0 PJ

Name	Carrier	Fraction	Energy (PJ)
Avg. households	electricity	1.000	1906

Space heating: 9,021.0 PJ

Name	Carrier	Fraction	Energy (PJ)
Electric heating	electricity	0.120	1082
Gas stove	gas	0.437	3942
Coal stove	coal	0.0402	363
Oil stove	oil	0.164	1479
Wood stove	biomass	0.146	1317

Hot water: 2,723.0 PJ

Name	Carrier	Fraction	Energy (PJ)
Electr. hot water	electricity	0.120	327
Gas fired	gas	0.437	1190
Coal fired	coal	0.0402	109
Oil Fired	oil	0.164	447
Wood fired	biomass	0.146	398

OK Cancel

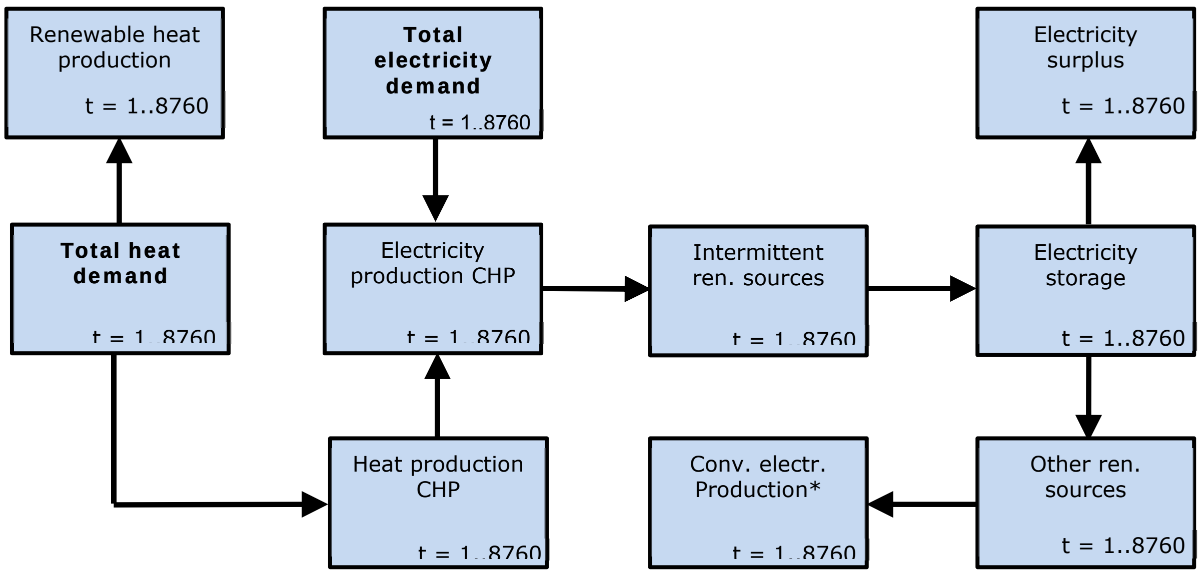
Figure 75: Input form Household energy demand

In most of the input windows the fractions of available technologies can be changed. For example in the electricity panel the user can decide which part of the consumed electricity should be produced with renewable sources and which part from thermal power plants. In the "non-fossil electricity" panel the user can decide how this electricity will be divided over the available non-fossil sources (Solar PV, wind offshore, hydro etc.).

A.3 Calculation scheme

As written above, the calculation is done from right to left in the model interface, which means from demand to source. Calculations are done on an hourly basis to do justice to the intermittent sources like wind and solar-PV in relation to the electricity demand. If no patterns are available the demand or production will be spread evenly over the year.

Electricity & low temperature heat production



* incl. nuclear, biomass co-firing and biogas

Figure 76: Calculation sequence for the electricity and heat production

Figure 76 shows the steps and their order of the production of electricity and heat as far as these are related. The heat demand generates a certain amount of electricity in CHP units with a heat demand driven pattern. This co-generated electricity is subtracted from the overall electricity demand. In the next step intermittent renewable sources are used to fulfil the demand. In case the production is higher than the demand, the surplus will go electricity storage units if available. When there is less production the stored electricity will be used. Since units can have certain amount of electricity stored at the beginning of the year, no more electricity can be subtracted from the storage units than will stored during the year. So at the end of the year the stored volumes are as large as they were in the beginning of the year. If all storage units are fully loaded and there is still an oversupply, this electricity can be used for other purposes which will be described below. After the intermittent source and storage is subtracted from the residual electricity demand the non-intermittent renewable sources (non-biomass) are the next in line. The remaining electricity will be produced by thermal units (fossil, nuclear and biomass).

As written above it is possible that a certain amount of electricity is produced but could not be used directly or via storage of electricity. In this case several options are present in the model to handle this oversupply. Figure 77 shows these options and the order which can be selected by the user. If the user decided that the oversupply should be used it will go to the selected electrolysis units otherwise the oversupply will not be used and will be dumped. After the hydrogen production by electrolysis several options are possible. The produced hydrogen can be used directly in for example hydrogen cars, used as feedstock in the chemical industry, used in fuel cells for electricity production or it can be used to produce methane by methanation. In case the user wants more renewable produced hydrogen for one of the defined purposes than can be produced from the oversupply this is possible by specifying this.

Handling of electricity surplus

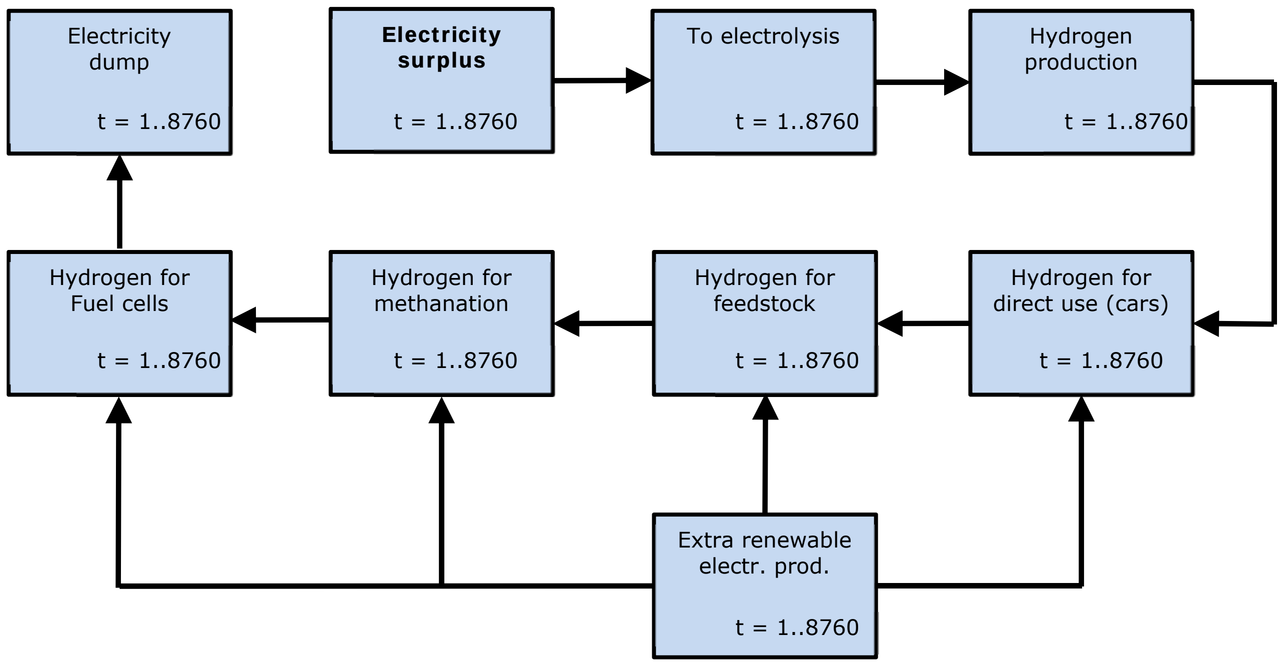


Figure 77: Calculation sequence of the use of renewable electricity surpluses and the optional production of additional hydrogen and / or methane.

Figure 78 shows a week pattern of an example run. These patterns show the calculated results from the steps described above. The green line is the original electricity demand. The brown line shows what is left of this demand after subtraction of the electricity generated in CHP units. The red line shows the intermittent supply which is higher than remaining demand (brown line) for several hours. The orange line shows the remaining electricity after subtraction of the direct used intermittent sources. The black line shows the electricity stored each hour. This is limited by the storage load capacity of 4.5 GW in this example, the horizontal parts at 0.016 PJ. In times there is no surplus of renewable sources the stored electricity can be used. The remaining electricity after using the stored electricity is expressed by the grey line. The production of the stored electricity is limited by the unload capacity: 4.5 GW in this example. Finally the surplus after storage goes to the electrolysis units: the blue line.

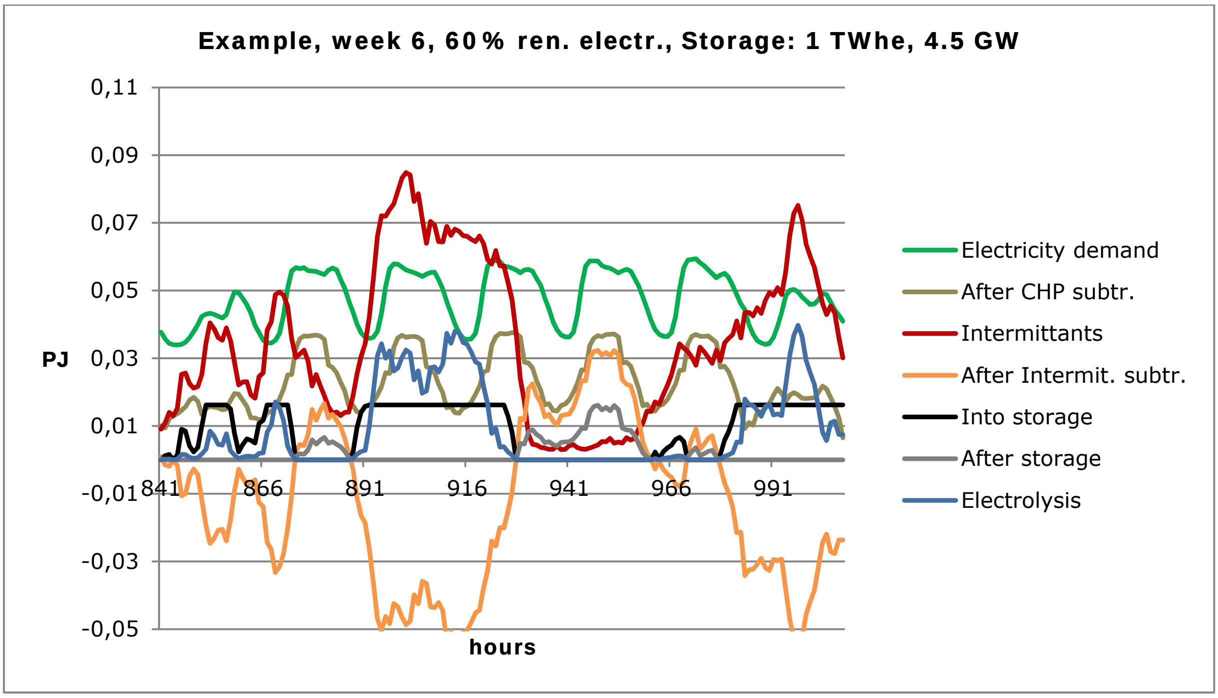


Figure 78: Example output for a week (week 6) in an hourly pattern.

The "After storage" line shows that part of the demand which should be filled with conventional (fossil) power to make the demand be matched by the production.

A.4 Energy data structure

To determine the energy demand in the base year 2010 IEA Energy balances were used[1]. The sectors used in the model are represented in these energy tables (See Table 17). Since renewable energy sources are aggregated in the IEA tables other sources were used to obtain more detailed data on wind energy, onshore and offshore[2], Solar PV, Hydro and Pump Hydro Storage[3], CSP, Geothermal electricity.

Europe	2010	(ed2013)									
CONSUMPTION	coal&peat	crudeoil	oilproducts	naturalgas	nuclear	hydro	geothermal, solartc,	Biofuels &waste	electricity	heat	total
Transfers	0.00	7.32	-4.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.20
Statistical differences	-0.40	0.80	-4.71	0.46	0.00	0.00	0.00	-0.04	-0.10	-0.04	-4.05
Electricity plants	-142.22	0.00	-9.66	-75.10	-243.09	- 46.49	-20.06	-23.22	244.20	-0.29	-315.93
CHP plants	-71.61	0.00	-12.10	-67.27	-2.78	0.00	0.00	-22.74	61.36	47.46	-67.73
Heat plants	-5.30	0.00	-1.46	-9.80	0.00	0.00	-0.15	-6.17	-0.23	18.28	-4.83
Blast furnaces	-17.04	0.00	-0.67	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	-17.74
Gas works	-0.20	0.00	-0.18	0.09	0.00	0.00	0.00	-0.01	0.00	0.00	-0.30
Coke/pat. fuel/BKB plants	-3.06	0.00	-0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-3.80
Oil refineries	0.00	-697.33	691.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-5.89
Petrochemical plants	0.00	15.20	-15.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.42
Liquefaction plants	-0.79	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.29
Other transformation	0.02	0.23	0.00	-0.59	0.00	0.00	0.00	-0.14	0.00	-0.39	-0.88
Energy industry own use	-5.64	0.00	-39.44	-18.49	0.00	0.00	0.00	-0.16	-25.30	-5.24	-94.29
Losses	-1.01	-0.01	-0.06	-4.32	0.00	0.00	0.00	-0.03	-20.31	-4.90	-30.60
TFC	**42.597**	**4.531**	**523.153**	**284.804**	**0**	**0**	**2.672**	**83.328**	**261.487**	**55.932**	**1258.47**
INDUSTRY	**26.485**	**2.111**	**34.355**	**86.12**	**0**	**0**	**0.033**	**24.704**	**94.855**	**16.227**	**284.901**
Iron and steel	13.22	0.00	1.42	8.55	0.00	0.00	0.00	0.02	10.67	0.42	34.38
Chemical and petrochem.	3.69	2.11	5.59	18.94	0.00	0.00	0.00	1.46	17.48	7.20	56.50

Non-ferrous metals	0.41	0.00	0.76	2.99	0.00	0.00	0.00	0.05	7.33	0.26	11.82
Non-metallic minerals	5.42	0.00	9.05	13.56	0.00	0.00	0.00	3.50	6.46	0.21	38.21
Transport equipment	0.09	0.00	0.43	2.77	0.00	0.00	0.00	0.01	4.36	0.76	8.48
Machinery	0.14	0.00	1.92	7.41	0.00	0.00	0.00	0.13	11.05	0.77	21.49
Mining and quarrying	0.15	0.00	0.84	0.79	0.00	0.00	0.00	0.04	1.54	0.20	3.57
Food and tobacco	1.49	0.00	2.98	13.45	0.00	0.00	0.00	1.21	10.18	0.98	30.31
Paper, pulp and printing	1.13	0.00	1.32	8.36	0.00	0.00	0.00	12.47	11.69	2.24	37.20
Wood and wood products	0.10	0.00	0.29	0.68	0.00	0.00	0.00	4.54	2.01	0.46	8.15
Construction	0.01	0.00	3.27	1.36	0.00	0.00	0.00	0.15	1.71	0.06	6.62
Textile and leather	0.09	0.00	0.51	2.31	0.00	0.00	0.00	0.06	2.11	0.22	5.36
Non-specified	0.45	0.00	5.81	4.92	0.00	0.00	0.03	1.05	8.22	2.36	22.86
TRANSPORT	**0.01**	**0**	**312.16**	**2.909**	**0**	**0**	**0**	**13.445**	**6.218**	**0**	**334.771**
Domestic aviation	0.00	0.00	6.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.72
Road	0.00	0.00	295.20	1.18	0.00	0.00	0.00	13.44	0.00	0.00	309.79
Rail	0.01	0.00	3.16	0.00	0.00	0.00	0.00	0.00	4.92	0.00	8.15
Pipeline transport	0.00	0.00	0.00	1.64	0.00	0.00	0.00	0.00	0.10	0.00	1.74
Domestic navigation	0.00	0.00	6.98	0.05	0.00	0.00	0.00	0.00	0.00	0.00	7.04
Non-specified	0.00	0.00	0.10	0.07	0.00	0.00	0.00	0.00	1.15	0.00	1.33
OTHER	**14.711**	**0**	**84.297**	**180.53**	**0**	**0**	**2.639**	**45.162**	**160.435**	**39.689**	**527.465**
Residential	11.27	0.00	45.95	122.66	0.00	0.00	1.96	41.02	79.18	23.98	326.03
Comm. and public services	1.77	0.00	20.96	49.72	0.00	0.00	0.47	2.19	75.96	10.75	161.86
Agriculture/forestry	1.39	0.00	14.16	3.90	0.00	0.00	0.08	1.75	4.40	0.30	26.02
Fishing	0.00	0.00	1.34	0.00	0.00	0.00	0.03	0.00	0.05	0.00	1.42
Non-specified	0.30	0.00	1.88	4.18	0.00	0.00	0.10	0.16	0.82	4.69	12.14
NON-ENERGY USE	**1.411**	**2.42**	**92.347**	**15.202**	**0**	**0**	**0**	**0**	**0**	**0**	**111.373**
in industry/transf./energy	1.22	2.42	89.81	15.20	0.00	0.00	0.00	0.00	0.00	0.00	108.64
of which: feedstocks	0.16	2.42	64.09	15.20	0.00	0.00	0.00	0.00	0.00	0.00	81.88
in transport	0.00	-0.21	2.01	0.06	0.00	0.00	0.00	0.00	0.00	0.00	1.80
in other	0.24	0.04	0.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54
Electricity and Heat Output											
Elec. generated - TWh	889.90	0.00	79.92	769.10	942.95	540.55	183.99	145.45	0.00	1.19	3552.92
Electricity plants	626.19	0.00	40.35	441.35	932.85	540.55	182.53	74.52	0.00	0.33	2838.62
CHP plants	263.71	0.00	39.57	327.75	10.10	0.00	1.46	70.95	0.00	0.86	714.34
Heat generated - PJ	824.71	0.00	197.46	1166.16	6.31	0.00	7.14	531.72	3.03	59.47	2796.01
CHP plants	648.70	0.00	147.39	829.57	6.31	0.00	0.89	347.05	0.21	28.39	2008.48
Heat plants	176.00	0.00	50.08	336.60	0.00	0.00	6.25	184.67	2.83	31.09	787.50

Table 17: IEA Energy balances 2010 (summation of 29 European countries).
The red values are used for calculations of the base year[1].

A.5 Intermittent sources

A.5.1 Wind energy

Wind data from onshore and offshore weather stations will be used. The hourly wind data of these weather stations were obtained for the year 2012, from the National Oceanic and Atmospheric Administration[4].

The altitudes of weather stations are not always the same. Because of these height differences and due the fact that wind turbines operate at higher altitudes, a correction has to be performed. Onshore wind turbines are on average height of 70 metres and offshore wind turbines are assumed to be at about 90 metres high. Wind speeds tend to increase with height; a correction for this effect is described by Wieringa and Rijkoort[5], see Equation 1.

$$\frac{v_1}{v_2} = \frac{\ln(z_1/z_0)}{\ln(z_2/z_0)} \qquad (1)$$

The wind speed at hub height is calculated by using equation 1, where v_1 is the wind speed at hub height z_1, v_2 is the wind speed at the altitude of the weather station z_2, and z_0 the roughness length of the Earth's surface. The roughness length is a measure for the roughness of the Earth's surface surrounding the weather station. The roughness length at sea of 0.00025 m and onshore a value of 0.1 is used. To convert wind speed into power, a power curve is used. When wind turbines are placed in large wind parks, the energy output is less variable than the energy output of a single turbine. To correct for this, a multi turbine power curve is used[6].

This results in one or two wind production patterns per country: 1 offshore, 1 onshore. Each pattern is constructed from 2 to 5 wind speed time series. These series are converted to electricity production patterns as described above and then averaged. So assuming a spread but connected locations of wind turbines. The turbines are located in the windier region of the country, selected by making use of a wind speed map.

A.5.2 Solar PV

Solar radiation data are obtained from SoDa[7]. Free data are available for the year 2004 and 2005. For this year global radiation data are assuming in inclination of 30 degrees directed to the South. These hourly data were recalculated to a normalized pattern with a load factor. Only one pattern, located in the centre, per country was realised with the exception of France, Spain, Italy and Sweden, Norway and Finland. For the three Scandinavian countries the pattern was located in the south, assuming PV panel will be installed in the South. For the three southern countries two patterns were realised, one in the centre and the other in the south. The latter because of substantial differences of pattern and load factor between the two locations. For Germany the differences between North, the centre and South were negligible.

A.5.3 CSP

Solar direct radiation data are obtained from SoDa[7]. Free data are available for the year 2004 and 2005. For this year direct irradiation data. These hourly data were recalculated to a normalized pattern with a load factor. CSP is assumed to be possible in France, Greece, Italy, Portugal and Spain. Only one pattern, located in the south, per country was realised.

A.5.4 References

[1] IEA (2013). Energy balances of OECD countries. International Energy Agency publications, Paris

[2] European Environment Agency (EEA) 2009. Europe's onshore and offshore wind energy potential. EEA Technical report no 6/2009.

[3] Gutiérrez, M.G. and R.L. Arántegui (2013). Assessment of the European potential for pumped hydropower energy storage. JRC scientific and policy reports, report EUR 25940 EN

[4] National Oceanic and Atmospheric Administration, 2014. Global hourly wind data. Available from: http://gis.ncdc.noaa.gov/map/viewer/#app=clim&cfg=cdo&theme=hourly&layers=1.

[5] Wieringa J, Rijkoort PJ (1983) De wind nabij de grond in verschillende omstandigheden, In: Windklimaat van Nederland, Anonymous Royal Dutch Institute, 's-Gravenhage, 33-64.

[6] Nørgaard P, Holttinen H (2004) A Multi-Turbine Power Curve Approach. Proceedings of Nordic wind power conference, Gothenburg. Available from: http://www.wilmar.risoe.dk/.

[7] Soda (2014). Solar radiation data; Solar energy services for professionals. Available from: http://www.soda-is.com/eng/services/services_radiation_free_eng.php

Appendix B - Entrepreneurial activities, key features and participants

Table 18: Entrepreneurial activities, key features and participants.

City	Project name	Operating since	Key features	Participants
Hamburg	Wasserstoff-tankstelle HafenCity	2012	Production of hydrogen Hydrogen used for transportation (public busses)	Clean Energy Partnership (CEP)
Werlte	Audi e-gas Project	2013	Production of methane Injection in gas grid Certificates for Audi vehicles	SolarFuel GmbH Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES) EWE Energie AG
Frankfurt Am Mein	P2G demo Thuga group	2013	Production of hydrogen Inject in gasgrid	Badenova AG & Co. KG Energieversorgung Mittelrhein GmbH Erdgas Mittelsachsen GmbH erdgas schwaben GmbH e-rp GmbH ESWE Versorgungs AG Gasversorgung Westerwald GmbH Mainova AG Stadtwerke Ansbach GmbH Stadtwerke Bad Hersfeld GmbH Thüga Aktiengesellschaft (Projektkoordinatorin) Thüga Energienetze GmbH WEMAG AG
Herten	H2Herten	2013	Production of hydrogen Hydrogen used for transportation and other fuel cells	Evonik Industries Westfalische Hochschule
Nieder-aussem	CO2rrect	2013	Production of methane and methanol	BayerMaterialScience AG RWE Power AG Siemens AG Invite GmbH CAT Catalytic Center RWTH Aachen Max-Planck Institut Magdeburg Fritz-Haber-Institut Berlin Leibniz Institut fur Katalyse Ruhr-Universitat Bochum

				Technische Universitat Dortmund Technische Universitat Dressden Universitat Stuttgart Karlsruhe Institute of Technology Technische Universitat Darmstadt
Bad Hersfeld	Metanisierung am Eichhof	2012	Production of methane using biogas Inject in gasgrid	Fraunhoffer IWES Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg SolarFuel
Karlsruhe	Research project	2011	Production of methane Inject in gasgrid	H-tec Fraunhofer ISE DVGW (project coordinator og three-stage methanation) IOLITEC Outotec Engler-Bunte-Institut EnBW Energie
Stuttgart	Verbundproject Power-to-Gas	2012	Production of methane	ZSW Fraunhofer IWES ETOGAS GmbH
Falkenhagen	Pilotanlage Falkenhagen	2013	Production of hydrogen Inject in gasgrid	E.ON ONTRAS-VNG Gastransport Hydrogenics
Grapzow	Windpark RH2-WKA	2012	Production of hydrogen Use hydrogen to produce electricity Inject in grid	NOW GmbH Haas Engineering Architekturburo Karsten Klunder Hydrogenics Senergie GmbH
Prenzlau	Hybridkraftwerk Prenzlau	2011	Production of hydrogen Use for electricity use for transportation	Enertrag Total Vattenfall Deutsche Bahn
Schwandorf	Power to Gas in Eucolino	2012	Production of methane using Microorganisms. Injection in grid or storage.	Microbenergy GmbH (a subsidiary of Viessmann)
Rozenburg (NL)	P2G in Rozenburg	2013	Production of methane Injection in local grid	

Sources: http://www.powertogas.info/power-to-gas/interaktive-projektkarte.html

http://www.greenfacts-magazin.de/fileadmin/PDF/greenfacts_1_2012_Doppelseite-Infografik.pdf

Iskov, 2013

Appendix C - Research programs, description and partners

Table 19: Research programs, description and partners

Name	Year	Description	Partners
FCH JU	2008 – ongoing	Public private partnership	European commission New Energy World Industry Grouping (68 companies) N.ERGHY Research grouping (58 research institutions)
International Energy Agency (IEA)	2013	Hydrogen implementing agreement.	28 member countries 20 participants in Hydrogen Implementing Agreement Task 24
Naturalhy	2010	Conversion of excess wind energy into hydrogen for fuel cell applications	40 partners: 19 companies 10 universities 5 research centers 6 other
Hyunder	2012 - 2014	Assessing the potential, actors and business models of large scale underground hydrogen storage in Europe	The Foundation for the Development of New Hydrogen Technologies Centre of Excellence of Low Carbon and Fuel Cell Technologies (CENEX) Commissariat à l'énergie atomique et aux énergies alternatives (CEA) DEEP Underground Engineering Energy Research Centre of the Netherlands (ECN) E.ON Gas Storage Hinicio LBST KBB Underground Technologies National Hydrogen and Fuel Cell Centre (Romania) Shell Global Solutions International B.V. Solvay
DVGW	2013	Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz	DBI Gas- und Umwelttechnik GmbH DVGW Karlsruher Instituts fur Technologie E.ON New build & Technology GmbH Fraunhoffer IWES VNG Gasspeicher Gmbh