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Renewable energy system in Finland
-A Business case study in steel industries

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Tiivistelmä

Neljän EU-maiden tutkimuslaitosten laatimat tulevaisuusskenaariot 100% uusiutuvista energiajärjestelmistä verrataan keskenään ja yhteistä kaikille on lisääntynyt sähköistäminen sekä sähko- lämpö ja liikennesektoreiden kytkentä. Skenaarioiden tavoitteet vaihtelevat 100% uusiutuvan energiajärjestelmän suunnittelusta aina kasvihuonepäästöneutraalin yhteiskunnan suunnitteluun, ja skenaarion tavoitteella havaittiin olevan vaikutus energiajärjestelmän suunnitteluun.

Skenaarioien välillä on suuria eroja biomassan saatavuuden oletuksissa, oletuksissa CCS:än käytöstä sekä synteettisesti tuotettujen energiaintensiivisten kaasujen ja nesteiden (PtG, PtL) tärkeydessä ja roolissa. Myös ei-energiasektoreiden kytkentä energiasektoreihin vaihtelee skenaarioiden välillä. Keskeisiä tuloksia ovat teollisuussektorin päästövähennystavoitteiden sekä biomassan saatavuudesta tehtyjen oletusten vaikutus PtG/PtL teknologioiden tärkeyteen osana energiajärjestelmää. Tämän lisäksi se, että teollisuus ja liikenne ovat kaikista vaikeampia sektoreita päästöjen vähentämiseen on myös vertauksen tulos.

Skenaarioiden vertailusta käy ilmi, että tulevaisuuden energiajärjestelmien suunnitteluskenaarioihin sisältyy merkittävä määrä epävarmuutta; aina teknisistä ratkaisuista sosiaalisiin, poliittisiin ja taloudellisiin kysymyksiin. Suomailaiseen terästeollisuuteen ja PtL teknologiaan kytkeytyvä investointipäätös analysoidaan Robust Decision Making (RDM) –menetelmällä, jota on suunniteltu isojen epävarmuuksien alla tehtyjen päätösten tueksi. Tulokset osoittavat, että PtL –investointi ei ole yhtä robusti vaihtoehto kuin monet muut investointivaihtoehdot, mutta että RDM –menetelmän sovelluksesta vastaavanlaisiin tapauksiin voi olla hyötyä. RDM voi antaa syvemmän ymmärryksen riskeistä, mutta sen käyttäminen vaatii enemmän aikaa ja sitoutumista kuin perinteinen teknillis-taloudellinen mallintaminen.

Avainsanat Renewable Energy, Robust Decision Making, Power-to-gas, Energy System, GHG neutral, Neo-Carbon Energy

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Abstract of master's thesis

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Abstract

The comparison of four future renewable energy system scenarios yields that energy system design for futures with 100% renewable energy is greatly dependent on whether the objective is to design an energy system with 100% renewable energy or to reduce GHG emissions from society as a whole. The latter seems to increase the relevance of power-to-gas (PtG) and power-to-liquid (PtL) technologies as these have the capacity to abate emissions from some industrial processes. Common factors in the four scenarios compared are higher electrification of the energy system and deeper integration of the enery sectors transport, heating and electricity.

Differences between scenarios include biomass availability assumptions, level of electrification of transport, the inclusion of CCS, and the role of PtG/PtL as well as the level of integration of non-energy sectors with the energy system. A main finding is that biomass availability assumptions vary greatly illustrating the uncertainty connected to future energy system research, and that these also seem to affect the role of PtG/PtL technologies. In addition, the drivers for investment in PtG/PtL differ between countries, with the technology playing a larger role in balancing intermittent renewable electricity sources in the scenario that relies very little on bioenergy. Furthermore, the transport and industry sectors are found to be the two hardest sectors to decarbonise.

A business case related to the integration of PtL technology in an existing steel mill in Raahe, Finland is studied with the decision supporting Robust Decision Making (RDM) method. Results indicate that other investment options are more robust to future uncertainties than the PtL option is, but that RDM can be a useful tool when evaluating decisions made under conditions of deep uncertainty. RDM can offer a deeper understanding of the risks in far-reaching decisions and offer new perspectives in energy system analysis. Simultanoeusly, it also requires more time and commitment than a normal cost-benefit analysis.

Keywords Renewable Energy, Robust Decision Making, Power-to-gas , Energy System, GHG neutral, Neo-Carbon Energy

Preface

This thesis is part of the Neo-Carbon Energy (NCE) project and the premis was to examine if the application of Robust Decision Making sheds new light on investments in the technologies related to the NCE project. In addition to this, a comparison of similar projects in other countries was added to provide a broader context; are other countries projecting similar future energy systems or not? The answer to this question can shed light on the robustness of the assumptions that are part of the NCE project.

The research for the NCE project is conducted by the Technical Research Centre of Finland VTT Ltd, Lappeenranta University of Technology (LUT) and Finland Future Research Centre (FFRC) at the University of Turku, and it is funded by the Finnish Funding Agency for Innovation (Tekes). The author wishes to thank the instructor Tiina Koljonen, the supervisor Sanna Syri as well as research scientists Juha Forsström and Eemeli Tsupari for their contributions to the research presented in this thesis as well as for their valuable support and comments. A sincere thank you also to all colleagues in the Energy Systems research group at VTT for their comments and support.

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Symbols and abbreviations

CCS	Carbon Capture and Storage
CDM	Clean Development Index
CHP	Combined Heat and Power
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide -equivalent[1]
DEA	Danish Energy Agency
DH	District Heating
DSM	Demand Side Management
ETS	Emission Trading System
EU	European Union
EV	Electric Vehicle
FFRC	Finland Future Research Centre
GHG	Greenhouse gas
IDA	Danish Society of Engineers
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution
IRES	Intermittent Renewable Energy Source
LUT	Lappeenranta University of Technology
NCE	Neo-Carbon Energy
NG	Natural Gas
NIR	National Inventory Report
PtG	Power to Gas
PtL	Power to Liquid
PCI	Pulverised coal injection
RDM	Robust Decision Making
RE	Renewable Energy
RES	Renewable Energy Source
SMR	Steam Methane Reforming
TPES	Total Primary Energy Supply
UBA	Umwelt Bundesamt, in English German Federal Environment Agency
UNFCCC	United Nations Framework Convention on Climate Change
VTT	Technical Research Centre of Finland

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[1] Greenhouse gas emissions are often expressed in terms of carbon dioxide equivalents for easier comparison of the global warming effect of different gaseous emissions. This means calculating the warming effect one gas has and then expressing the amount of gas in termns of how much carbon dioxide is needed to cause the equivalent warming to the atmosphere.

1 Introduction

Currently the energy system in Finland and other industrialised countries is in transition due to the environmental damage and political risk inherent to the existing system. Discussions on climate change mitigation have been taking up an ever-increasing share of international politics for the last decade, and there are no signs of this development being reversed.

The 21st session of the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) held in Paris in the end of 2015 spurred new ambition and hope for future international cooperation on climate change mitigation. The adoption of the Paris Agreement means that there, for the first time in history, now is a global climate deal seeking to mitigate climate change to a safe level. The Agreement includes objectives to limit the global average temperature increase above pre-industrial levels to below 2°C, to peak greenhouse gas (GHG) emissions as soon as possible and to pursue efforts to limit the temperature increase to 1.5 °C. The EU is leading the way and has pledged to reduce GHG emissions by 40% until the year 2030 in comparison to 1990. (EC, 2015; IEA, 2016a; UNFCCC, 2015)

In order to limit global average temperature rise to below 2°C as agreed upon in Paris, industrialised countries need to cut their greenhouse gas emissions by as much as 80 – 95% by 2050 compared to 1990. This means large changes to the energy system as well as mitigating, capturing or eliminating GHG emissions from agriculture, waste management and industry. Many of these changes are structural and require a new infrastructure to be put in place. Recent research has shown that with today's energy demand, the maximum flexibility of the existing Finnish energy system for integrating renewable energy is in the range of a 44 – 50% share of total primary energy consumption. The share of renewable electricity could be up to 69 – 71.5%, but any share larger than this requires added flexibility to the system in order to cope with intermittency, as well as a smaller energy demand. In the Low Carbon Finland –Platform research project, the share of carbon neutral energy was found to range between 75 and 80% of final consumption. Assumptions regarding the availability of carbon capture and storage (CCS) technology and the future use of nuclear power are critical to the results of such research. (IPCC, 2007, 2013; Koljonen et al., 2012; Zakeri, Syri, & Rinne, 2015)

A case study done for Ireland shows that it is technically possible for an energy system to be based entirely on renewables, and that such a system can provide for the same end-user energy demands as today's system, at the same price (Connolly & Mathiesen, 2014). In the case for Ireland electricity is the backbone of the system, with demand flexibility, short term storage options as well as power-to-gas (PtG) or power-to-liquid (PtL) solutions for long term storage and for use by the industry and in the transport sector. PtG or PtL technology means that hydrogen and oxygen are produced through electrolysis of water, whereafter the hydrogen can either be used as such or synthesized with carbohydrates to create liquid or gaseous fuels. The introduction of PtG and PtL is deemed necessary due to two reasons: firstly some modes of transport such as airtravel and heavy road transport are unsuitable for electrification, and secondly an electricity supply based on intermittent renewable energy sources (IRES) is in need of seasonal storage, which cannot be economically feasibly provided by batteries. Hydrocarbons are energy intensive fuels that are also needed for some applications in industry, such as high temperature heat production. Hydrogen is needed in many industrial processes[2] and could thus also be used directly without methanation.

Finland is, alongside many other countries including Germany, Sweden and Denmark, aiming to transition to a low carbon society by 2050. Out of these four countries Germany and Denmark are planning a transition to a fully renewable energy supply within the following 33 years running up to 2050, while new investment in nuclear power in Finland and the uncertain future of nuclear power in Sweden make a 100% RE system already by 2050 less probable, but do enable zero greenhouse gas emissions from energy production. Extensive research has been carried out to study the possibilities and challenges of such a transition in the Finnish context. In the Low Carbon Finland Platform 2050 project (Koljonen et al., 2012) alternative low carbon pathways were analysed, including a transformative scenario with a very high share of RES. In the ongoing Neo-Carbon Energy (NCE) project[3] 100% RES systems for Finland are analysed, and these are described in more detail in Chapter 3.3. In addition, the new national energy and climate strategy for Finland[4] includes a 100% RES discussion for the first time ever in the country's national strategy planning (TEM, 2017).

This thesis is part of the NCE research project, in which the concept is to introduce synthetic fuel production (PtG and PtL) into the energy system to support the intermittent renewable energy sources and to provide carbon neutral fuel for transport and industry. Carbon-neutral carbohydrates in either liquid or gaseus form are produced by synthesising carbon dioxide captured from the air (or from flu or process gas) with hydrogen produced through electrolysis using renewable electricity. It is also possible to produce carbon-neutral synthetic chemicals (e.g. PtX) through a similar process, but the PtX discussion is beyond the scope of this thesis. (Child & Breyer, 2015, 2016)

Due to the possibility of replacing fossil oil and gas as fuels in transport and industry and to the flexibility added to the system in terms of storage, the PtG and PtL technologies radically transform the energy system as we know it today. This transition requires new infrastructure and thus both investment and policy decisions made today have a large impact on the viability and affordability of the energy system of 2050. At the same time there are a large number of uncertainties today about what the world will look like in 2050. This calls for a decision making process that accommodates for this possible future clean energy system while still accounting for the risks inherent to investment in new technology and to simultaneous large structural changes not only to infrastructure but also to the economy and to society as a whole.

The concept of Robust Decision Making (RDM) is introduced in the context of fully renewable energy systems by examining a PtL –related business case in the steel industry with an RDM-tool. In Robust Decision Making the investment decision is tested against a vast number of possible futures, yielding results about its robustness in different possible futures. The results tell us which factors affect the success of the proposed investment, and thus the process informs rather than replaces the decision makers' deliberations. With the knowledge that certain future outcomes would make the invest-

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[2] e.g. refining, ammonia production, chemical and metallurgical industries as well as in the production of glass and electronics. See for instance (Ramachandran et al., 1998) http://www.sciencedirect.com/science/article/pii/S0360319997001122?via%3Dihub

[3] http://www.neocarbonenergy.fi/

[4] http://tem.fi/en/energy-and-climate-strategy

ment in question unprofitable or render some proposed policy decision useless, the decision maker is in control of deciding whether such futures are held probable enough to hedge against. This type of decision supporting analysis offers a new approach to coping with future uncertainty in the context of energy systems. (Bonzanigo & Kalra, 2014; Forsström, 2016; Lempert, Popper, & Bankes, 2003)

The objective of this thesis is to first map the research on very low GHG emission or 100% renewable energy (RE) systems carried out in three other EU countries in order to give a state of the art study on the design of a renewable energy system. Current policies, infrastructure and resources that set boundaries to or aid the transition to a future renewable system are dicussed briefly. Secondly, the thesis evaluates a PtL business case in the Finnsih steel industry with the help of RDM. The research aims to answer the three questions:

RQ1: How do the scenarios with very low GHG emissions or 100% RE systems of selected three other EU countries compare with each other and with the 100% RE systems portraited as part of the NCE project?
RQ2: Is the integration of PtL technology in Finnish steel production economically robust?
RQ3: What are the insights of applying RDM to an existing business case concerning PtL investment in steel industries in a high RES future?

Chapter 2 contains a litterature-based background on the pending transition of energy systems and the concept of making decisions under uncertainty as well as an introduction to Robust Decision Making. In chapter 3 the Finnsih energy system and future energy system research is dicussed and in chapter 4 the very low GHG emission or 100% RES systems research of the other three selected EU countries is presented. Chapter 5 summarises the country comparison and literature review, and chapter 6 presents the business case study for steel industries. A discussion of the outcomes of the thesis is given in chapter 7, and chapter 8 concludes.

2 Background

2.1 Energy systems in transition

More than half of global antropogenic greenhouse gas emissions stem from the production, conversion and consumption of energy, and the global energy demand is expected to increase by around 40% until 2050[5]. The projected increase in energy consumption is due to rising levels of income in many developing countries leading to the electrification of rural areas, private cars becoming more abundant and larger homes and more personal electronics needing heating and power all while the energy-intensive industrial sectors in these countries simultaneously grow. In industrialised countries the increase in electricity and transport demand can be offset by energy efficiency measures and final energy consumption can be decreased. Several research projects have shown that it is both technically and economically possible to reduce GHG emissions from the energy sector to virtually zero by the year 2050 (e.g. Connolly et al., 2014; THGND2050, DEA). Such emission reductions involve either shifting energy production from fossil fuels to emission-free renewable energy sources or nuclear power, or employing technologies to capture and store carbon dioxide emissions. (BP, 2017; EIA, 2016; IEA, 2016d; IPCC, 2014; WEC, 2016)

Today's energy systems are built around fossil fuels and renewables have hence played only a marginal role in meeting the world's energy needs since the industrial revolution. However, in 2015 61% of all new power capacity installed during the year was renewable and growth rates for solar Photovoltaic (PV) and wind power installations have continued to rise each year (GWEC, 2015; REN21, 2015; WEC, 2016). Renewable heat production capacity in the form of geothermal heat and solar thermal power is also growing and both capital expenditure and operational and maintenance costs for renewables continue to decrease. The political push for cleaner energy is palpable: 164 countries around the world had renewable energy support policies in place as of 2015. Many countries are looking at transitioning to a fully renewable power supply and some even to fully renewable energy systems, meaning power, heating, cooling and transport demands are all met with renewable energy sources. Such a change requires not only new power plants and heat production sites but also the investment in new infrastructure that enables emission-free transportation and the overhaul of the traditional energy infrastructure to facilitate for demand response and economically feasible energy storage to accommodate for intermittent renewable energy sources (IRES). (WEC, 2016)

The projected energy system transitions analysed in this thesis are those of five countries in the EU, where research in 100% renewable energy systems has been carried out for a long time and country plans share the same boundaries in the form of EU-wide common climate- and energy policy. A common denominator in the results from both energy systems research and government scenarios is that the future low-emission, high-renewable energy systems will be more integrated, with energy flows between different sectors traditionally held as separate entities (Connolly & Mathiesen, 2014;

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[5] In the 2016 edition of the World Energy Outlook the International Energy Agency (IEA) estimates a 30% increase in global energy demand until the year 2040 if countries abide by the Paris Agreement. BP oil estimates a 30% increase in energy demand already til the year 2035 (2017 Energy Outlook) while the U.S. Energy Information Administration assesses demand to grow by 48% from 2012 to 2050 (International Energy Outlook 2016) and the World Energy Council draws up two alternative scenarios until 2050; in Jazz energy demand increases by 27% and in Symphony by 61% between the years 2010 and 2050. Between the years 1990 and 2010 the total primary energy supply rose by 45%.

Zakeri et al., 2015). Figure 1 shows a schematic illustration of the traditional and the future energy system: before, the transport sector was fuelled by oil and thus did not directly interact with the electricity or heat sectors, while the future electrification of transport and the use of synthetic fuels couples the sectors, simultaneously facilitating fossil-free transport and creating more flexibility in the system as a whole. The energy system becomes more flexible as sector coupling enables a versatile energy storage mix; surplus electricity can be converted to heat with heat pumps or boilers and stored for days or even weeks in district heat storages and distributed heat storages, and when electric energy is stored as chemical energy in the form of synthetic fuels the storage period lengthens to months. In turn temporary electricity deficits can be covered by converting the thermal or chemical energy back to electricity, providing more flexibility than the minutes or hours long storage possibilities of capacitors and batteries in the electricity sector alone. (Heinonen, Karjalainen, Ruotsalainen, & Parkkinen, 2015; Salovaara, Honkapuro, Makkonen, & Gore, n.d.; Zakeri et al., 2015)

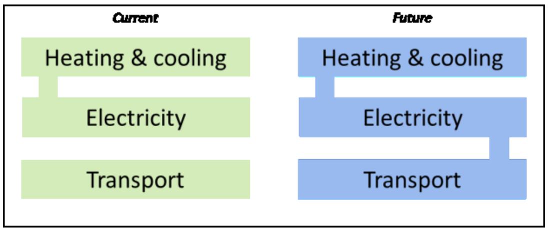

Figure 1. Sector coupling in current and future energy systems.

The power and heat sectors have long been partially integrated through electric heating and through combined heat and power (CHP) production in the Nordic countries and through the use of heat pumps, but this integration concerns the *production* of power and heat and thus does not provide flexibility after production. The energy system as a whole becomes more flexible when energy can flow in both directions between sectors, and when different sectors can thus work as both short-term and long-term storage to compensate variation in production -or in demand- in other sectors. Because renewable power sources are abundant but intermittent, the largest challenge of energy systems based entirely on renewables is solving the problem of how to add flexibility. In addition to sector coupling flexibility can be increased by expanding cross-border power grids to facilitate for geographical flexibility, and by adding energy storage such as batteries or pumped hydro to the system.

Much of the energy demand in industrialised economies comes from the industry's energy consumption, and due to this many factories have integrated power- and heat production plants. The industry contributes to GHG emissions through its energy use, but it also does so through emissions inherent to specific industrial processes; two of the most important being the production of cement and steel (IEA, 2016). The remaining portion of annual antropogenic GHG emissions not from energy production, distribution or use comes from such industrial processes, from agriculture and from waste management as well as from the so-called LULUCF (Land Use, Land Use Change and Forestry) sector. Because some processes at industrial sites with on-site power plants can be integrated further to produce for instance synthetic fuels utilising side streams or outputs of the industrial production other than process heat, and because waste can be burned for heat to avoid landfill emissions, it is possible to couple non-energy sectors with the energy system's sectors and thus reduce overall GHG emissions from society. This approach is taken in many of the future scenarios analysed in this thesis, and it expands the energy system transition to concern sectors not currently part of energy supply, conversion or consumption. Figure 2 shows the added coupling of GHG emitting sectors, which could help reduce overall antropogenic GHG emissions.

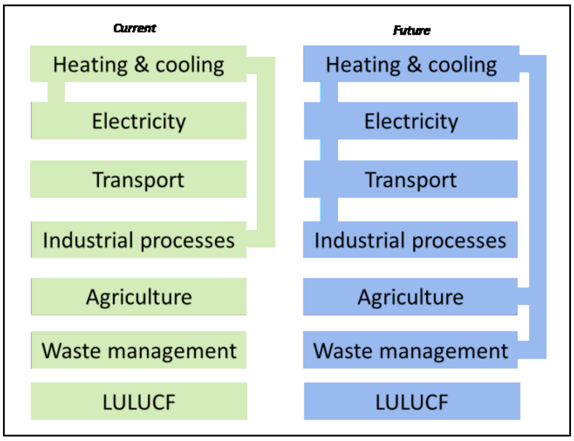

Figure 2. All GHG emitting sectors and their current and future technical coupling. The LULUCF secor is strongly connected to the other sectors in political terms.

In Figure 2 the sectors agriculture and waste management are connected to the heat and power sectors in the future energy systems, while industrial processes are further integrated in the future to also interact with the transport sector. The further integration of industrial processes with the three energy sectors can happen for instance through the production of synthetic fuels from flue gases in industry. The coupling of agriculture happens through recycling of excess heat from other sectors in the heating of greenhouses, as well as by integrating the production of fertilisers further. The LULUCF sector is politically connected to the other sectors by emissions abatement through the development of forest carbon sinks, but there is no technical integration.

In order to reduce emissions and mitigate climate change, measures must be taken in all GHG emitting sectors, but reducing emissions in the power and heat sectors is technically easier than doing so in transport, industry and agriculture. Studies carried out for different regions by different institutions and researchers have found that fully renewable energy systems as a rule are highly electrified and also utilise some synthetic fuel or gasified biomass, which means energy is lost in the conversion process. The result is overall larger electricity consumption and a larger primary energy consumption in relation to final energy consumption than in the current energy system; i.e. more primary energy must be used to produce clean energy to meet demand, even though energy efficiency measures are employed to lower demand in the first place. Figure 3 illustrates this decreased efficiency in an electrified, fully renewable energy system.

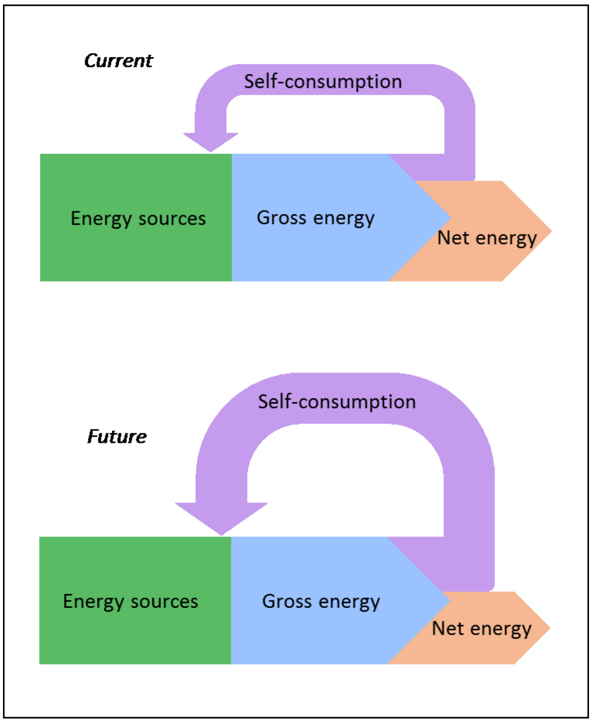

Figure 3. More energy is lost in conversion processes to produce biofuels or synthetic fuels in future clean energy systems than what is lost in today's fossil-based energy system.

All the scenarios analysed in this thesis are explorative and not predictive by nature; they illustrate possible future energy system configurations, which lead to very low or zero emissions either from the energy sector or, for the countries where such scenarios were available, for the entire society in 2050. These energy system changes take place in countries where all citizens already have access to affordable energy; the emphasis can be put on shrinking the domestic primary energy consumption through energy efficiency measures and on making energy production more sustainable while still ensuring security of supply and the functioning of the system.

While developed countries can focus on the sustainability of their energy consumption the emerging and developing economies are forced to concentrate on the costs and security of supply –sides of the energy trilemma[6] as they are deploying their energy systems or expanding them. In 2016 1.2 billion people -16% of the world population- were still without access to electricity (IEA, 2016), representing the very different energy system challenge facing the developeding countries. However these simultaneously happening energy system overhauls are connected in that many structural changes which cost much and are slow to implement in industrialised countires, such as electrifying transport or shifting energy production from large-scale generation using fossil fuels to distributed generation from intermittent renewable energy sources, can be much more easily implemented in areas where the energy system is only now being built out and expanded to reach all citizens and income levels. Many of the low-emission technologies are also otherwise suitable for deployment in emerging economies; good examples are solar PV lighting in rural areas and microgrids to supply entire villages with power –these solutions are modular and do not require expensive fuels.

Industrialised countries are encouraged to fund emission-reducing projects in emerging economies through the Joint Implementation[7] (JI) and Clean Development Mechanism[8]

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[6] https://trilemma.worldenergy.org/

[7] http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php

(CDM) tools under the Kyoto Protocol. Different regions are expected to contribute in varying magnitude, and although the projected increase in global energy demand is due to the demand growth in emerging economies, the solutions researched and tested in industrialised countries can still bring about large climate benefits since these regions are already large energy consumers and since the solutions can be readily applied to the emerging economies.

2.2 An uncertain future

The imperative to reduce GHG emissions is strong and there are both national and international policies and economical instruments in place to steer the development of today's energy systems toward a more sustainable energy supply. In addition to this, there are clear indicators that the cost of renewable energy will continue to decrease (WEC, 2016). However, the future is never certain and even small changes in the economy or political landscape can have large, unprecedented impacts that ultimately change the course of development. Many of the technologies that could, once commercialised, have a large impact on the emissions from energy systems are still in need of research and development; examples range from wave power to CCS, PtL and PtG technologies, and fusion technology. In addition to cost effectiveness social and political acceptance is a critical success factor for energy technologies. (WEC, 2016)

Although variable renewable energy sources are abundant the availability of raw materials used in the production of PV panels, CSP (concentrated solar power) plants and batteries could be a critical factor to the future global expansion of these technologies. The availability of biomass is limited and there is large uncertainty both as to the amount of energy that can be sustainably generated from biomass and as to the scientific and political definition of sustainable biomass. Biofuels produced from wood and food waste, from crops not suitable for human consumption otherwise or from algae (i.e. so-called second and third generation biofuels) are in principle considered sustainable while production that competes with food production, diminishes carbon sinks or reduces biodiversity pose a risk –but the discussion on sustainability of biomass is still ongoing with new perspectives such as LCA (life cycle analysis) being taken into use. The total climate effect of utilising biomass in energy production is not unambiguous and policies might change in the future due to the ongoing discussion. (Koponen et al., 2013; Soimakallio et al., 2011)

Biomass gasification as well as high temperature electrolysers which could be used in the production of synthetic fuel from renewable electricity still need more development before commercialisation. PtG and PtL technologies are recognised as presenting new business opportunities when integrated with industrial processes or waste management; (Breyer et al., 2015) find that "PtG systems can be applied in a broad variety of input and output conditions, mainly determined by prices for electricity, hydrogen, oxygen, heat, natural gas, bio-methane, fossil CO_2 emissions, bio-CO_2 and grid services, but also full load hours and industrial scaling". The many variables determining the profitability of PtG or PtL systems highlight the uncertainty of commercialisation. A risk of PtG and PtL technology is also the availability of renewable electricity; if sufficient renewable generation capacity is not deployed in time, the large electrolyser investments will not

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[8] http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php

pay off or the produced fuel could even be made with electricity that is not emission-free, removing the climate benefit of the technology altogether. (Breyer et al., 2016).

The future surprises and brings in aspects we did not forsee, and taking this into consideration in energy system planning and in individual investment decisions related to future energy systems enables decision-making that is not as vulnerable to future uncertainty. Bonzanigo & Kalra (2014) found that when a new coal plant to be funded by the World Bank was planned in Turkey some 10 years ago the critera weighed were cost of energy production and energy security for Turkey. Environmental aspects such as carbon pricing and climate change mitigation were not even discussed; this showcases how criteria considered marginal in some cases can become a priority over a relatively short period of time. There might be aspects linked to a system-level change in energy supply, which currently are not discussed at all.

Exploring the future energy visions of other countries provides a framework in which to insert the expectations for the national energy system transitions. The common climate and energy policy in Europe creates a larger market for commercialisation as well as for research and development. However, different member states also have their own national policies and as subsidies and other support mechanisms affect the installations of renewable energy generation capacity drastically, there is inherent political risk to a transition toward 100% renewable energy systems. In addition to political and economical national policies such a transition can also be steered by social aspects such as the need for affordable energy to avoid energy poverty or simply the social acceptance of a large energy system overhaul.

The pending energy system overhaul is a sum of many parts and new technical solutions for decarbonising the transport- and industry sectors are needed. In particular cement and steel industries are large emitters of GHG emissions; the two industries were the source of 8% and 6.6% respectively of global emissions in 2015[9] and in Finland steel production is the largest point emitter of CO_2-emissions both nationally and in Nordics. As a result of the research conducted in the Neo-Carbon Energy (NCE) project a business case that both reduces emissions from the steel industry and integrates PtL production in a steel mill is found. This business case, documented along with other options for reducing GHG emissions from steel production[10], is studied in this thesis and evaluated with the RDM method to account for the large uncertainties which are inherent to transformative energy system changes such as moving to a 100% renewable energy supply.

2.3 Decision making under uncertainty

Many energy-related policy and investment decisions have long-term effects on society as they can either steer development in some certain direction or lock it in on the current path for several decades to come (Kalra et al. 2014). Examples are decisions on subsidies, the passing of new laws, technology investments, or the favouring of one infrastructure investment over another. While these choices have to be made today, policy makers and firm leaders can not be certain of what type of future they are planning for.

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[9] Process and energy-related emissions combined; process related emissions make up approximately half of the emissions. Source: (PBL Netherlands Environmental Assessment Agency, 2016) and sustainability indicators at www.worldsteel.org

[10] Documented by VTT researchers Kärki and Vakkilainen, Internal unpublished document, produced in 2016

Complex decision-making problems such as the aforementioned farreaching decisions can benefit from the use of formal decision models. Formal decision models organise the available facts, which highlights any possible missing information as well as distinguishes between objective and subjective information. Using a model also prevents the cognitive and motivational biases[11] of decision makers from influencing the decision too much. Some of the benefits of formal processes and decision modelling are:

- The modelling process forces the decision makers to think more and from several perspectives, which contributes to decision quality
- All alternatives will be treated on equal terms in a formal process
- The decision model serves as a communication tool and can in some cases reveal differing underlying assumptions (decision makers may have differing world views)
- The model provides defensible decision recommendations
- The model eliminates some, but not all, of the incidents where bias could affect the decision makers' judgement
- The decision outcome(s) can be better (but not necessarily)

Probability is the dominant way of capturing uncertainty in decision models: an uncertain factor is assigned a range of values and some probability for each value within the given range. In energy system analysis the uncertainty is often handled by creating alternative future scenarios with the help of quantitative models and performing a sensitivity analysis where the assumptions of some selected parameters are varied. This means that decisions are made by *first assessing what sort of future the decision is to serve or serve in*, and *then using some form of optimisation to elicit a strategy that best fits this best-guess future*. These approaches are often called "Predict-then-Act" approaches, or "Agree-on-Assumptions" processes. (Vilkkumaa, 2015; Eisenführ, 2010 Bonzanigo & Kalra, 2014)

Fully renewable energy systems are however transformative by nature, and this increases the number of uncertainties and the range of directions in which society and the technoeconomical constriants for energy systems could evolve. When the future is hard to predict, it is hard to know whether decisions that are based on predictions of the future are robust. For this reason, an alternative approach to decision making under uncertainty is utilised and demonstrated here with a case study in the Finnish steel industries. Robust Decision Making (RDM) is an "Agree-on-Decisions" approach to decision making under uncertianty, and as such strives to help decision makers make good decisions without trying to predict the future.

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[11] *Cognitive bias*: systematic "thought errors"; e.g. the assessment of conditional probablility differs from the correct value given by Bayes' rule, for example assuming a long male is a basketball player even though this is, in fact, not probable at all; or assuming events that are more often reported in the media or easier for us to relate to are more probable than other events.
Motivational bias: letting the desireability or undesireability of events affect our judgement; e.g. overoptimism about success probabilities and strategic underestimation of failure probabilities.
Different strategies to prevent these biases from affecting decision results are summoning multiple experts with differing points of view, using decomposition and realistic assessment of partial probabilities and not providing anchors as to avoid anchoring bias. (Montibeller, 2015)

2.3.1 “Agree-on-assumptions” – approach

Complicated decisions are often tackled by gathering available information and making a best-estimate prediction of the future, whereafter an optimal solution is sought given the future prediction. The use of optimisation provides a formal solution which hedges against the proposed solution being largely influenced by the decision maker’s beliefs and it provides a least-cost-solution, should the future turn out to match the best-estimate prediction. These approaches thus work well when the predictions are accurate and uncontroversial. However, problems arise in situations of *deep uncertainty*; Lempert et al. (2003) define *deep uncertainty* as occurring when “the parties to a decision do not know—or do not agree on— the likelihood of future events, the best model for relating actions to outcomes, or the value of potential outcomes”. (Bonzanigo & Kalra, 2014; Lempert et al., 2003)

If the future is very uncertain, a decision based on a best-estimate prediction is in fact based on overconfidence in our ability to predict the future. In addition to this, situations in which decision makers do not agree on assumptions arise easily when there are different vested interests present since different objectives lead to different hopes and beliefs about the future. This puts a gridlock on the process and a decision cannot be made without efforts to persuade decision makers to believe in the same kind of future. In a situation where modelling efforts in combination with a best-estimate prediction of the future yield solutions that do not feel desireable to the decision makers, there is the additional risk of rejection of the results. If the process is too much of a black box, decision makers will not understand why one option won over the others or what the risks are should they choose one option over another. (Lempert et al., 2003; 2013)

2.3.2 “Agree-on-Decisions” –approach: Robust Decision Making

The “Agree-on-decisions” –approach runs the traditional process backwards: Instead of starting by attempting to predict the future, decision makers start by listing the different choices they have available. These choices (plans of action) are then tested in hundreds or thousands of plausible futures, which creates a database with information on how the plans fare in different types of futures. Robust Decision Making (RDM) uses data mining and statistical analysis to identify interesting futures in this database: Which are the futures in which plans fail? Examining these futures offers insights into the risks associated with choosing a certain plan over the others. The method can also tell us in which futures plans fare well, or in how many of the modelled futures a certain plan performs poorly. The information can be used to pick a plan that performs well over a wide range of futures –that is, a robust plan.

RDM focuses the decision makers´attention on the relevant question: Which plan of action is most robust to surprises? Since we cannot know the future, focusing on which plan fares the best in a simulation of plan performance in just one –to us plausible- future easily misguides decision makers to feel confident that the future will, in fact, look much like the one future scenario which was picked and thus the decision process is focused on which future is chosen and not on which plan decision makers prefer. Even when plans are tested in the commonly used 3 or 4 alternative future scenarios or a sensitivity analysis is performed, this method guides decision makers to focus on the best performing plans in each simulated future instead of paying attention to which plan fares “the least badly” across all simulated futures. A plan which outperforms all alternatives in a few futures might still be a much riskier choice than the plan which is always the second best performer.

RDM has been researched and developed for more than a decade; the method was developed by the RAND corporation[12] (Bryant et al., 2009; Lempert et al., 2003) and has since been used in several case studies, for example (Hallegatte et. al., 2012; The World Bank, 2013; Ranger, 2013), see Lempert et al. (2013) for a summary of applications. The RDM approach is interactive and iterative, engaging decision makers in several different phases of the analysis and the goal is to inform rather than replace the deliberations of the decision makers. One RDM study was performed to compare future energy system scenarios in NCE (Forsström, 2016).

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[12] RAND is a nonprofit institution that helps improve policy and decisionmaking through research and analysis. RAND® is a registered trademark.

3 Renewable energy system in Finland

3.1 The Finnish energy system today

Finland is a sparsely populated country situated far north, and thus has long distances and high heating demand. Due to this and to the fact that the country's most important industries are very energy intensive, Finland has comparatively high annual energy consumption per capita; 257.5 GJ/capita (6.2 toe/capita) per person –much higher than the OECD average 173 GJ/capita (4.16 toe/capita) and roughly double that of some southern European countries. GHG emissions per capita are however lower than the OECD average (9.36 tonnes/capita) at 8.28 tonnes of carbon dioxide equivalent per capita[13].

The target level of renewables out of total primary energy supply set for Finland in the Renewable Energy Directive from 2009 is 38% by 2020. This level has already been reached and surpassed; in 2014 38.7% of gross final energy consumption came from renewable sources, out of which bioenergy constituted the largest part (Tilastokeskus, 2015a). Finland had the third highest renewable energy share in the EU after Sweden and Latvia. Electricity consumption per capita is similarily high at 15.2 MWh although electricity in Finland is fairly decarbonised; in 2015 45% of electricity was renewable (39% in 2014) and a further 35% came from nuclear power plants (unchanged between 2014 and 2015). The 2014 share in Finland breaks down as renewable energy providing 52% of the heating and cooling sector, 31.4% of the electricity sector and 21.6% of the transport sector. (Energiateollisuus, 2016).

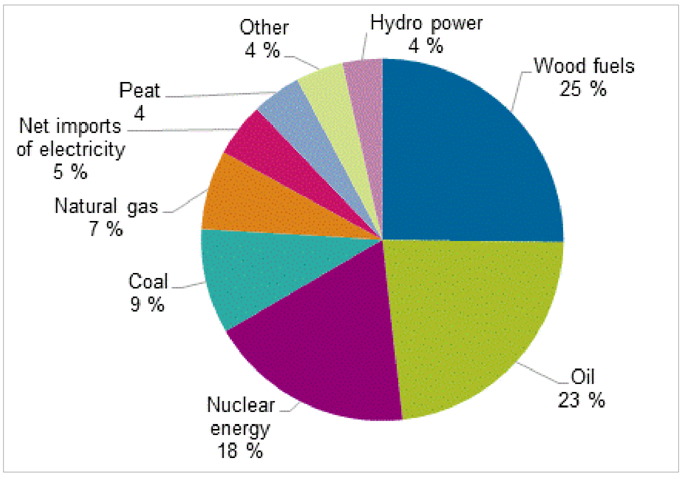

Figure 4. Energy source shares of total Finnsih energy consumption in 2014. (Tilastokeskus, 2015a)

The large heating demand in Finland is met in part by combined heat and power (CHP) plants producing both electricity and heat with an overall higher efficiency than when the two are produced separately. CHP is also widely used in the industrial sector, which makes Finland's energy system even more efficient. Finland's large forest industry and in particular the production of pulp and paper has brought with it several technological innovations and the efficient use of natural resources; much of the forest-based biomass used for energy production is in fact side products, such as spent liquors and residue materials from the pulp and paper industry. The large proportion of the CHP production that is not fuelled with biomass is, however, run on fossil fuels which means that the

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[13] http://www.iea.org/statistics/statisticssearch/

heating sector relies heavily on fossil fuels, as does the transport sector (Tilastokeskus, 2015c).

By far the largest share of the renewable energy used in Finland stems from the forests; biomass is about 80% (2015) of the total primary renewable energy. In power production the amount of forest-based biomass (both in the form of wood residue and residue products form the pulp and paper industry) accounts for 40% of renewable power production. Hydropower is the most important renewable power source in Finland, accounting for more than half of the renewable power produced in Finland. A small share of renewable power is produced with wind (4% of renewable power produced in Finland in 2014, amounting to around 1.7% of total electricity production) and heat pumps stand for a small share of the renewable heat production. Recently, electricity imports have risen considerably from the Nordic market region and in 2014 they were 22% of electricty supply in Finland. Finnish electricity generation is very distributed compared to other countries what with several CHP and small hydro power plants strewn out across the country. (Tilastokeskus, 2015a; Energiateollisuus, 2016)

3.2 Political backdrop and agreed upon policies and targets

Finland has historically been a frontrunner in enabling clean energy and introducing low carbon policies, with both ambitious current legislation and early action such as the introduction of a carbon tax already in 1990. In 2015 the Finnish Parliament approved the National Climate Change Act, committing to a law-bound emissions reduction of 80% by 2050 compared to 1990, and allowing an increase in the target if later climate science should indicate it necessary. The emissions reductions in question are for all Finnish emissions covering both emissions covered by the EU ETS (Emission Trading System) directive (electricity production, energy-intensive industry, part of chemical industries, a large share of district heat production and aviation) and those not (transport, agriculture, waste management, residential and commercial sectors, part of industries and small scale power and heat production). Approximately half of the current Finnish GHG emissions are covered by the EU ETS. The Climate Change Act further stipulates that Finland shall have its own National Climate Panel, which brings together experts from different disciplinaries to support political decision-making. (LSE, 2016a; Ministry of the Environment, 2015; The Ministry of the Environment, 2016)

In addition to the 38% renewable energy target for 2020, Finland abides by the other targets set by the EU in the so called *Climate and Energy Package 2020*: a GHG reduction of 20% compared to 1990 and a 20% increase in energy efficiency as compared to 2007, all to 2020. For the share of renewable energy in transport Finland has a national higher target of 20% for the year 2020, in contrast to the 10% target set by the EU. In the *2030 Climate & Energy Framework* adopted in 2014 the proposed Finnish target for non-ETS (e.g. sectors not covered in the ETS) emissions reductions is 39%, up from 16% in the 2020 package. Due to the multitude of domestic targets and measures, Finland will meet its targets for 2020. (EC, 2009; EC, 2014a; LSE, 2016a; Ministry of Employment and the Economy, 2013)

Noteworthy in the case of Finland is that the country is currently increasing its nuclear power capacity in an effort to increase domestic carbon-neutral electricity production. To that same end, increased use of forest-based biomass is planned for the future, but because there is currently great uncertainty as to LULUCF policy the exact consequences in terms of GHG emissions are not yet clear.

The energy-related targets of the current Finnish government are, amongst others, raising the share of renewable energy to more than 50% during the 2020s and the self-sufficiency in renewable energy to more than 55%; phasing out the use of coal in energy production during the 2020s; cutting the use of imported oil for domestic needs in half during the 2020s; raising the share of renewable transport fuels to 40 per cent by 2030 and ensuring that Finland has achieved the 2020 climate objectives already during the government term, which ends in 2019. These targets, along with EU 2030 targets, are considered in the newest version of the national energy and climate strategy (TEM, 2017). The strategy also includes a review of what a 100% renewable energy system could look like in Finland in 2050. The national energy and climate strategy is renewed regularily and there are already four previous versions (from the years 2001, 2005, 2008 and 2013). In addition to this, the semi-long term plan for climate policy, KAISU, which focuses on the non-ETS sector in particular is under preparation and due to be published in late spring 2017. Finland also has an Energy and Climate Roadmap for 2050 and a Climate Change Adaptation Plan, both from 2014. (Ministry of the Environment, 2017; Ministry of Employment and the Economy, 2015; 2017)

3.3 Future energy system: Neo-Carbon Energy

Neo-Carbon Energy (NCE) is a research project funded by the Finnish Funding Agency for Innovation's (Tekes) new strategic openings. The Technical Research Centre of Finland VTT Ltd, Lappeenranta University of Technology (LUT) and Finland Future Research Centre (FFRC) at the University of Turku conduct the research. The NCE project draws up a completely transformed energy system for the year 2050; one in which the entire energy demand is met by renewable energy sources, the different energy sectors are highly integrated and the entire society potentially is driven by other values than profit maximisation.

The NCE project entails socio-economical research on how society could evolve to the year 2050 as well as techno-economical energy system modelling with the help of four different energy system models. The four different future scenarios which describe different cultural and socio-economic workings of society in 2050 and named Radical Startups, Value-Driven Techemoths[14], Green DIY engineers and New Counciousness. These scenarios are all classified as transformative, and moreover they are explorative by nature; the research focuses on what *could be* and not on what is *probable to come*.

In the **Radical Startups** future, there are no clear lines between work and leisure, and the workplaces are communities that form a network of startup enterprises. These companies drive the economy, and some of them are specialised in energy and energy services. The **Value-Driven Techemoth** future has an economy dominated by a few technology giants or "techemoths" which have a central role in forming and developing the energy infrastructure. These companies offer their employees more than work; they are a platform for self-organising employees and also provide education, housing and leisure. In the **Green DIY Engineers** future a Do-It-Yourself economy has arisen to sur-

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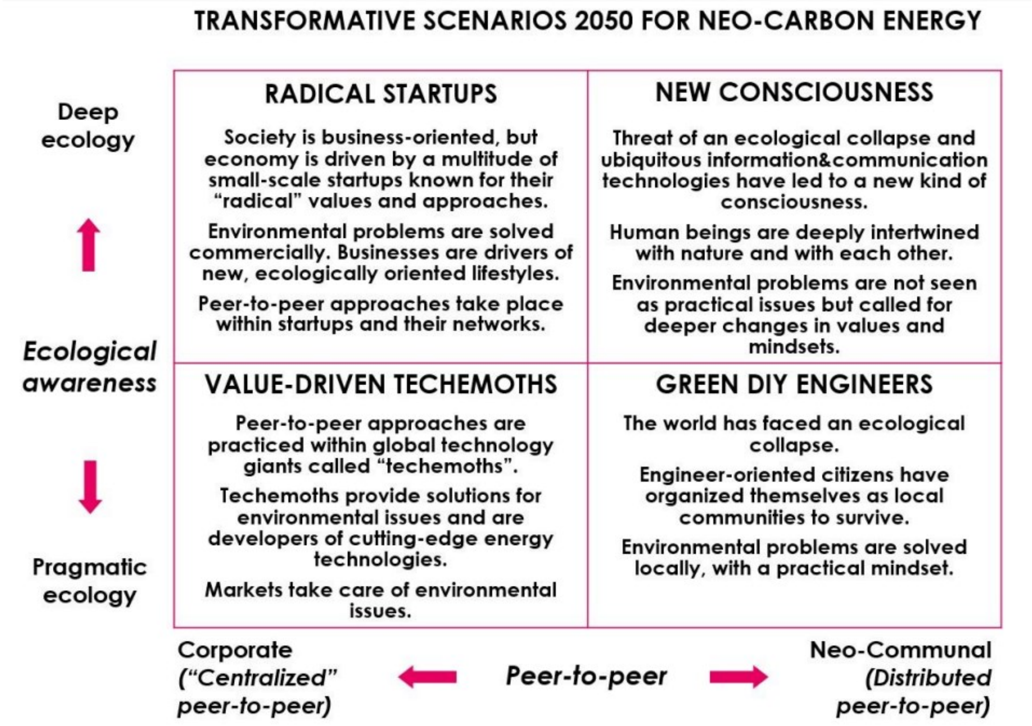
[14] Techemoth is a new construction from the words Technology and Behemoth, meaning a giant technological company which has grown to offer its employees more than just work and salary.

vive an ecological collapse. Energy is produced locally in smaller communities and smart scarcity has ensured many communities a relative abundance and self-sufficiency. (Heinonen, Karjalainen, & Ruotsalainen, 2016)

In the fourth future scenario, **New Consciousness**, global collaboration, robotisation and ICT have developed the farthest and both resources and information are shared in a world where a new consciousness involving greater respect for nature has arisen with the help of brain-to-brain communications and virtual reality. In this reality growth is environmentally sustaibale "neogrowth" which emphasises immaterial and cultural growth. The fully sustainable energy systems are both distributed and centralised. Figure 5 shows the four different scenarios and their characteristics on two scales: ecological awareness and a corporate versus communal scale dubbed "peer-to-peer". (Breyer, Heinonen, & Ruotsalainen, 2016; Heinonen et al., 2016)



RADICAL STARTUPS

Society is business-oriented, but economy is driven by a multitude of small-scale startups known for their "radical" values and approaches.

Environmental problems are solved commercially. Businesses are drivers of new, ecologically oriented lifestyles.

Peer-to-peer approaches take place within startups and their networks.

NEW CONSCIOUSNESS

Threat of an ecological collapse and ubiquitous information&communication technologies have led to a new kind of consciousness.

Human beings are deeply intertwined with nature and with each other.

Environmental problems are not seen as practical issues but called for deeper changes in values and mindsets.

VALUE-DRIVEN TECHEMOTHS

Peer-to-peer approaches are practiced within global technology giants called "techemoths".

Techemoths provide solutions for environmental issues and are developers of cutting-edge energy technologies.

Markets take care of environmental issues.

GREEN DIY ENGINEERS

The world has faced an ecological collapse.

Engineer-oriented citizens have organized themselves as local communities to survive.

Environmental problems are solved locally, with a practical mindset.

Figure 5. The four different socio-economical scenarios in NCE (www.neocarbonenergy.org)

The FFRC research highlights the change in attitude towards energy use and production in the four future scenarios and in line with the forecast of energy production being more distributed also the ownership of energy generation capacity is expected to be more diverse in 2050. Currently around 70% of Finnish electricity generation capacity is owned by large utilities –in the future it is expected that for instance also private persons, farmers and municipalities as well as funds and banks own electricity generation capacity. (Heinonen et al., 2015)

In addition to the FFRC's research on how society functions in 2050 and what drives the transformation of the energy system, LUT has modelled the Finnish energy system in 2050 using EnergyPLAN energy system model (Child & Breyer, 2015, 2016) and VTT has modelled the possible pathways to a 100% renewable energy system in 2050 using TIMES-VTT[15] energy system model (Pursiheimo et al., 2017) as well as with electricity system planning tool WILMAR and electricity system model BALMOREL[16] (Ikäheimo et al., 2015). The EnergyPLAN energy system analysis depicts Finland as an island without energy trade, models the supply and demand for one calendar year set in 2050 and thus assumes that technology investments happen overnight, not taking into consideration the already existing infrastructure or power plants. The hourly resolution makes the model suitable for analysises where a large amount of varieable renewable energy (VRE) is integrated in the system. The 100% renewable electricity system of 2050 has been analysed with electricity system models BALMOREL and WILMAR to study the consequences of intermittency and the optimal operation of the electricity system. The input data for these simulations came from the outputs of the modelling done with TIMES-VTT. The results from the analysis with TIMES-VTT are discussed here.

The modelling done with TIMES-VTT studies both the energy supply and total energy demand (e.g. also industry, agriculture and transport) in 2050 and the possible pathways to such an energy system. The Nordic electricity market is embedded in the TIMES-VTT model and the results of the analysis cover the development of energy supply in Denmark, Sweden and Norway in addition to that of Finland. The global energy markets are also modelled in TIMES-VTT and thus part of the simulations, but these are not analysed in the NCE project. In addition to emissions from energy, TIMES-VTT also includes emissions from industry, waste, agriculture and LULUCF and thus a cost-effective pathway to large societal GHG emissions reductions in parallel with a 100% renewable energy system is modelled. On the other hand, the TIMES-VTT model is very large, which constrains detailed modelling of energy systems with very high shares of VRE. (Pursiheimo et al., 2017; Child & Breyer, 2015, 2016)

Although the FFRC's research for NCE depicts four different socio-economical future scenarios, only one 100% renewable energy system is modelled in EnergyPLAN and in TIMES-VTT three scenarios are modelled, but these differ merely in technoeconomical constraints and do not mirror the four different socioeconomical futures described by FFRC. The three scenarios modelled in TIMES-VTT are named BASE, LO-HH2 and LO-BIO. The definitions for these are presented in Table 1 below.

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[15] The TIMES-VTT optimisation model used in this study is based on the TIMES (The Integrated Markal Efom System) model framework, described in detail in Loulou et al., (2005)

[16] See http://www.energyplan.eu/othertools/global/wilmar-planning-tool/ and http://www.balmorel.com/

Table 1. Definitions of scenarios in NCE inTIMES-VTT (Pursiheimo et al., 2017)

Scenario	Definition
BASE	Scenario aiming at 100% renewable share of primary energy supply in Nordic Countries. In 2050 high tax for all non-renewable energy sources (including nuclear). Demand value on end-use based on drivers of population and economic growth. Average annual GDP growth from 2010 to 2050 within 1.8-2.3% and annual population growth within 0.1-0.5%. Industrial volumes based on official estimates in Finland (with blast furnace based steel production phased out until 2050). In other countries development of industrial volumes is based on demand drivers. Techno-economic data on all technologies based on existing TIMES-VTT model library comprised from numerous sources, investment cost data updated for PV and P2G in accordance with Child et al., (2017)
LO-HH2	Similar to BASE with following exceptions Transport related use of hydrogen disabled. Import of biodiesel from outside Nordic Countries limited annually to 30 PJ in 2030-2050 for each country.
LO-BIO	Similar to LO-HH2 with following additions. Potential for energy use of forest biomass and bio crops significantly limited to lower levels.

Biomass[17] together with electricity produced from wind, solar and hydropower constitute the backbone of the transformative future energy system modelled with TIMES-VTT, with the demand for energy intensive fuel in transport and industry met in roughly equal proportions by synthesised fuels and biofuels. There is also electrification in the transport sector, and in the BASE scenario part of transport demand is met by hydrogen. The modelling done with TIMES-VTT yields that the main drivers for the introduction of PtG and PtL technologies are in fact the transport sector and the industrial sector along with the heating sector in the form of district heat demand –and not the need for energy storage due to added intermittency of electricity supply as previously suggested in other studies (for instance in (Connolly & Mathiesen, 2014)). This finding is in line with those of Breyer et al. (Breyer et al., 2015) and Kärki et al. (Kärki & Vakkilainen, 2016) which were both conducted as part of the NCE research project.

According to the TIMES-VTT modelling results the total primary energy supply in Finland falls from more than 1500 PJ in 2010 to around 1200 PJ in 2050, depending on the scenario. This decline coincides with a growing end-use of energy and is explained by increased electrification (and higher efficiencies of electric technologies) as well as by the phase-out of nuclear power, for which energy supply is calculated using a theoretical efficiency of 30% as opposed to 100% efficiencies of wind and solar power. Electricity consumption goes up from around 80 TWh in 2010 to ca. 125 TWh (450 PJ) in 2050, while energy end-use in the transport sector falls to 140 – 160 TWh (540 PJ) from about 215 TWh in 2010. The results show that ICE based vehicles utilising mainly liquid but also gaseous biofuels still play an important role in the transport sector in 2050. The disabling of the use of hydrogen in the transport sector in the LO-HH2 and LO-BIO scenarios increases the use of synthetic gas and electricity in transport and, generally,

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[17] In large part side products from the forest industry.

decreased potential of biomass in LO-BIO increases P2G utilisation in all nordic countries.

Because Finland and Sweden use substantial amounts of coal in steel production, blast furnace based steel production is phased out during 2030-2050 in all three scenarios to avoid coal consumption. It must be noted that some natural gas and oil products are utilised as raw material in the industry sector and as input in international bunkers. It is suggested that further research into the supply of carbon dioxide to PtG production plants could find symbiotic links to industry or other energy production, as for instance the CO_2 sequestration process of biomass combustion could improve cost-efficiency of the PtG process. (Pursiheimo, Holttinen, & Koljonen, 2017)

Transforming the primary energy supply to renewable in 2050 requires a high level of electrification in the energy system, and in addition to this the utilisation of biomass for energy production is essential for Finland and Sweden to become 100% renewable. The findings from TIMES-VTT show that Nordic countries can balance the variable supply of renewable energy through crossborder trading of electricity and the modeling done with EnergyPLAN (Child et al., 2017) shows that the hour-to-hour power and heat balances work. With the cost reduction assumptions for renewables and PtG used in Pursiheimo et al. (2017), the future energy system could be based on renewables with similar costs as today's energy system. The costs for converting the finnish energy system to 100% renewable rise due to the phasing out of 1600 MW of nuclear power capacity prior to it's end-of-lifetime. The differences between the three scenarios are not dramatic, suggesting that the energy system can adapt to the more difficult conditions in scenarios LO-HH2 and LO-BIO. Table 2 lists the assumptions made in the NCE scenarios and Table 3 summarises their technical content. (Pursiheimo, Holttinen, & Koljonen, 2017)

Table 2. Assumptions in the Neo-Carbon Energy scenarios

Assumptions table	
Energy demand	TPES falls by approximately 20%, energy end use also decreases but not by as much
Socioeconomic	In the modelling efforts the course of societal evolution is not expected to change. The FFRC scenarios assume large changes in social behaviour and economical drivers
Political and economical	The FFRC scenarios present large changes to the political, cultural and economical system, while the TIMES-VTT modelling effort creates an economically feasible path from today's energy system to that of 2050. To reach 100% RES nuclear power must be phased out by political decision.
Energy sources and GHG mitigation	100% RES (with small exceptions) In the modelling efforts GHG emissions are mitigated mainly from the energy sector, in the FFRC scenarios society undergoes large cultural changes and emissions are mitigated in many sectors –but this is not quantified.
Emissions accounted for	All GHG emitting sectors are modelled in TIMES-VTT, but mitigation measures are only simulated for the energy sector

Table 3. Summary of the NCE scenarios

Finland -NCE	
Sectors accounted for	All GHG emitting sectors
Sector coupling	Within the energy sector there is coupling of all subsectors, the waste sector is coupled to the energy sector and the industry sector is partially coupled to the energy sector.
Infrastructure	The substitution of infrastructure in place today with infrastructure needed for 100% RES is modelled in TIMES-VTT
Model used	EnergyPLAN, WILMAR, BALMOREL, TIMES-VTT
Modelling time step	1 hour and in TIMES-VTT 1 year with seasons and day-night variations accounted for within the year
Inclusion of international trade	In TIMES-VTT international trade of electricity and fuels is modelled. Analysis is also made with EnergyPLAN where international trade is not part of the analysis.
Energy carriers	Electricity, methane, liquid synthesized fuel, biofuel, hydrogen and methanol

4 Current and future energy systems elsewhere

Several other countries have conducted research on what a future renewable system might look like. The countries chosen for analysis alongside Finland in this thesis are Sweden, Denmark and Germany. Sweden is of interest as a point of comparison for Finland as the countries are neighbouring and similar in size, political establishment and socio-economical status. Denmark is chosen as a third Nordic country both for its recent rapid deployment of wind power and for its difference form Sweden and Finland; the country is far smaller, has a milder climate and possesses a different palette of natural resources while still being part of the Nordic electricity market. Germany is a recognized world leader in both renewable energy deployment and policy, yet German emissions have increased due to the closing of nuclear power plants and the consequential increased use of fossil fuels along with renewables. Since the German Energiewende has been in motion for years now, it is to be expected that German future plans are both detailed and well informed, which makes them an interesting comparison to the Finnish analysis carried out in the NCE project.

The main assumptions in most of the compared scenarios are very similar, but there are differences in technical approach and in the number of sectors covered. Each of the compared scenarios also naturally caters for a different set of needs as each country has its own starting point in terms of natural resources, earlier implemented efforts to reduce emissions and accumulated know-how in selected areas. All five countries analysed in this thesis do however share a set of characteristics:

- The population in these countries has increased only moderately during the period of 2010 – 2014: these are rich industrialised countries where population growth is not strong and some nations even project a decline in population size until 2050.
- All studied countries have managed to decouple economic growth and energy consumption, i.e. total primary energy supply (TPES) per GDP has decreased steadily during the period 2010 – 2014.
- Carbon intensity in energy production has also come down for all countries except Germany, where the closing of nuclear power plants has led to an increase of lignite combustion.
- Carbon instensity (or GHG emissions) per GDP has come down for all countries including Germany, meaning energy efficiency in Germnay has increased more than the carbon intensity of energy production.

Adapted from (IEA, 2012, 2015, 2016b)

In addition to the above listed socio-economical common denominators, the five countries are all situated in Europe and part of the European Union. This means that EU legislation on emissions reductions, shares of renewable energy and more is binding in all five countries, in addition to any possible national targets and laws. Prior to the COP21 negotiations, countires were invited to communicate their intended nationally determined contributions (INDCs) outlining targets and actions for the post 2020-period. In its INDC the EU committed to a binding target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990, to be fulfilled jointly by all member states. At the same time renewable energy is to constitute 27% of final energy consumption in the EU and energy efficiency is to increase by 27% between 1990 and 2030. (EC, 2015)

All four countries analysed in this thesis have some renewable energy already in their domestic energy mix, see Figure 6. Sweden leads the way with more than 50% of gross final energy consumption (abbreviated GFEC in Figure 6 below) stemming from renewable energy sources in 2014, while Germany only has roughly 13% renewables out of both TPES and gross final energy consumption. TPES figures do not include electricity trade. In Finland and Sweden the series "Geothermal / solar / wind" is in practise the share of wind energy in TPES, since solar PV and geothermal production is very small. Germany and Denmark have larger shares of solar PV generation but wind power still stands for the lion's share of the percentages shown in Figure 6.

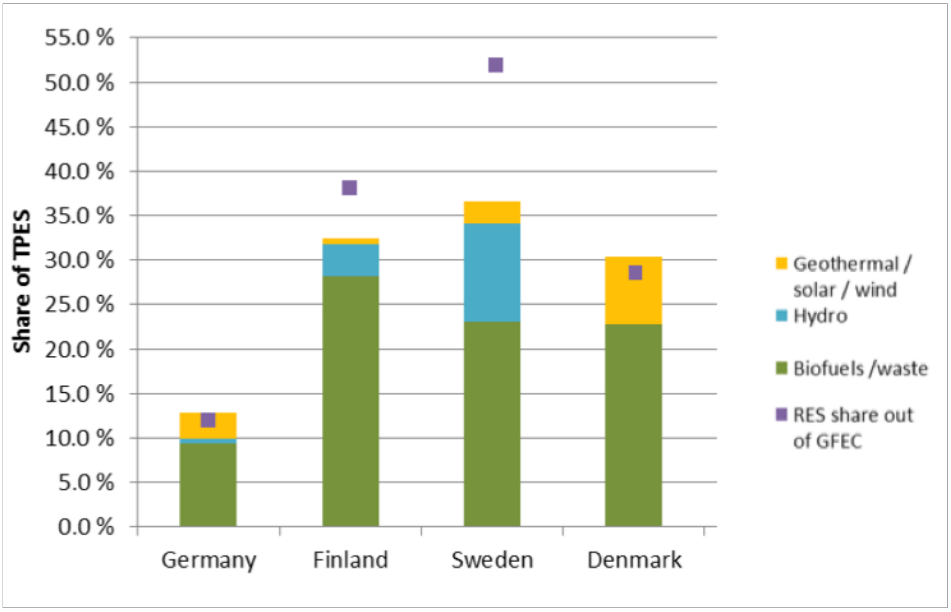

Figure 6. Share of renewable energy in the reviewed countries, 2014. Source: TPES figures IEA country statistics[18]; GFEC figures (Eurostat, 2016a)

In addition to reviewing the current share of renewables in the energy mix in each country, it is noteworthy that Finland is currently investing in new nuclear power plants. Since the lifetime of a new nuclear power plant extends to around 40 years, these power plants will still be in operation in 2050 if not by political decision decommissioned earlier. Denmark has no nuclear power plants and no plans on commissioning new ones, while Germany has decided to phase out nuclear power completely by 2022 (BMUB, 2017). Sweden has long debated the future of domestic nuclear energy, first deciding to phase it out but recently revoking that decision and stating that current research and visions on increasing renewable energy in the energy mix are not contra-nuclear but pro-renewable energy. Sweden will thus most probably also still rely partially on nuclear power in 2050. (Energikommissionen, 2017; Swedish Government, 2016a)

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[18] http://www.iea.org/statistics/statisticssearch/

4.1 Sweden

4.1.1 The Swedish energy system today

As a Nordic country with both high heating demand during wintertime and energy-intensive industries such as iron ore and pulp and paper constituting a considerable part of the economy, Sweden has high energy consumption per capita. The country however has abundant hydroresources and biomass, and coupled with nuclear power and the recent rapid deployment of new wind power parks this allows Sweden to produce more than half of primary energy supply from renewable energy sources. Out of the 2014 electricity production 50% was renewable and 91% CO_2 free. Figure 7 shows the Swedish electricity consumption and its origin. (Eurostat, 2016a; IEA, 2016b)

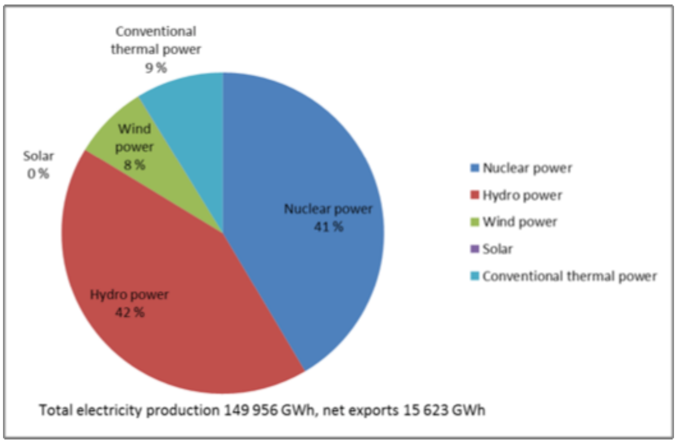

Figure 7. Swedish electricity consumption and RES share. Data from (Energimyndigheten, 2016)

Sweden has the third highest share of renewable energy out of all European countries, and the highest out of EU countries. The EU 2020 target of 49% RES has already been surpassed and in 2014 the amount of renewable energy in the Swedish energy mix was 52.6% (Eurostat, 2016a). Some of the renewable energy is imported in the form of electricity from the Nordic electricity market Nordpool where Norwegian hydro power resources keep the RES share high –thus domestic TPES figures do not show as high a RES share. The electricity and heating sectors are already highly decarbinised, but the transport sector still relies heavily on oil. Distances in Sweden are long and thus decarbonisation of the transport sector is of utmost importance to reduce GHG emissions. In 2014 total GHG emissions in Sweden amounted to 54 Mton CO_{2eq} per year which yields 4.6 tonnes per capita per year (OECD average is 9.9 tonnes per capita per year) out of which 3.86 tonnes of CO_{2eq} per capita was energy related. (IEA, 2016b; UNFCCC, 2016)

4.1.2 Political backdrop and agreed upon policies

The Swedish government recently reached a new Energy agreement (Swedish Government, 2016a) in which the main direction for the country's future energy and climate policy is outlined. The agreement is a next step after the "National policy framework" from 2009 (Swedish Government, 2009) in which it was outlined that Sweden aims to have zero net GHG emissions in 2050 and that the transport sector is set to be "independent of fossil fuels" by 2030. The new agreement tightens the timeline for GHG neutrality stating that this should happen already in 2045, with negative GHG emissions after that. The new agreement also states that Sweden will have 100% renewable electricity in 2040, but there is room for uncertainty in this since it is stressed that the goal is not a political decision to phase out nuclear power, but a target for renewable energy genetration (Swedish Government, 2016a). Sweden earlier decided to phase out nuclear power by 2020, but the decision has been taken back and ten nuclear reactors are now allowed to operate also after 2020. One reactor (Ringhals 2) is to close in June 2019 and another (Ringhals 1) in 2020. (SRSA, 2016a, 2016b)

The objective for the transport sector from the 2009 agreement is not mentioned in the new Energy agreement and neither are the various objectives defined in 2009 for 2020, such as a fossil fuel-free heating sector, but biofuels seem to play the most important role in reaching these goals (Svensk Energi, 2016; Swedish Government, 2016a). The Swedish government agreements reflect the political ambition and public debate in Sweden, but neither of them cites any calculations or scenario modelling results. The Swedish policy framework from 2009 has been followed up by a strategic plan for the future called "Uppdrag Framtid", which loosely translates into "The future mission". The strategic plan contains a review of the goals set in 2009, a seris of proposals for further measures and tightened targets as well as a broad-term plan for how to reach these targets (Swedish Government, 2016b).

Running up to the 21st Climate Summit in Paris in late 2015 and hence, not only Swedish government but also companies, municipalities and citizens have shown great interest and dedication toward energy and climate issues. The public debate is geared toward creating a more sustainable society and there are concrete examples such as a plan to deploy another 30 TWh worth of wind power until 2020 (counting from the base year 2002) or the newly built sustainable neighbourhoods in the vicinity of Stockholm. In the electricity sector decarbonisation is driven primarily by a green certificate system and a mandate for power producers to provide a certain share of renewable electricity. Emission reductions from industrial processes are being researched; an example is Swedish-Finnsih steel company SSAB's project to reduce emissions from steel production by using hydrogen as reducing agent in the production process[19]. (Svensk Energi, 2016)

No 100% renewable total primary energy supply goal has been set in Sweden, but the World Wildlife Fund (WWF) and the Swedish Environmental Protection Agency (IVL) as well as Greenpeace in collaboration with the European Renewable Energy Council (EREC) have conducted studies on how a 100% renewable energy system in Sweden could be acheived. There are several studies for how Sweden could achieve a 100% renewable electricity supply and which policies should be employed to achieve this goal most efficiently: "Vägval" conducted by the Royal Swedisg Academy of Engineering Sciences (IVA, 2016) and "Kraftsamling" by the Swedish Energy Commission (Energikommissionen, 2017) both studies take other energy sectors into account but offer future recommendations only on electricity system configuration.

4.1.3 Future energy system: Fyra framtider

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[19] https://www.ssab.com/globaldata/news-center/2017/02/27/08/01/the-swedish-energy-agency-is-investing-heavily-in-a-carbon-dioxide-free-steel-industry

An explorative future energy system study produced by the Swedish Energy Agency called “Four futures” (Fyra framtider) contains two scenarios, Legato and Vivace, with a nearly 100% renewable[20] energy system and in Legato Swedish society is GHG neutral[21] with total emissions in 2050 amounting to less than 5 Mton $CO_{2\text{-eq}}$ per annuum (Statens energimyndighet, 2016a).

The study is comparable to the Finnish futures research done by FFRC with the NCE project in that it draws up four future scenarios in which energy consumption is intertwined with the way society has evolved and in sync with social and cultural aspects. The future scenarios were drawn up without the use of models, but the electricity supply was analysed with the help of energy and electricity system models Markal[22] and Apollo[23]. Both models include the Nordic electricity market and thus include the cross-border trade of electricity. Heating demand is quantified and the energy sources for heat production are specified for the different future scenarios, and the transport and industry sectors have been analysed in separate reports as part of the same project[24] but not modelled. Waste is incinerated for heat and thus coupled with the energy sector, while emissions from industrial processes and LULUCF are only briefly discussed and emissions from agriculture are not part of the study.

In all scenarios the electrification of the energy system increases, and export of electricity from Sweden to the neighbouring countries also takes place in all four scenarios. Biomass dependence increases in all scenarios and the possible import of biomass is discussed as a measure to counterfeit shrinking of the domestic carbon sink. The four scenarios represent different prioritisations in society; in **Forte** economic growth is the strongest driver and society uses large amounts of energy, in **Legato** energy is seen as a scarce resource and focus is on sustainability and fairness in the distribution of resources globally, while energy consumption in **Espressivo** is determined by individual consumer choices reflecting lifestyles and **Vivace** utilises energy and climate solutions as a path toward economic growth by making Sweden a global leader in technological solutions related to this. In Legato final energy demand is 243 TWh/a and in Vivace it is 326 TWh/a. Figure 8 shows an overview of the energy sources in use in the modelled energy sectors in the four futures.

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[20] The only fossil -based contributions to the energy system in the Legato scenario are from fossil fuel use in the mining industry, from international transport and from incineration of waste containing fossil raw materials. (Statens energimyndighet, 2016a)

[21] With Sweden's current population of 9.7 million not set to change drastically this equates to less than 1 Mton of $CO_{2\text{-eq}}$ per capita per year.

[22] Markal is a Nordic energy system model with interconnections to Poland and Germany. The model optimises the electricity production mix according to the assumptions given.

[23] Apollo is an electricity market model that simulates the European power market on an hourly time step and a previously defined energy mix. It also gives electricity prices.

[24] https://www.energimyndigheten.se/contentassets/7409d428db1a4fe18a9a15dca681a218/vagval-energisystem-2020_20150219.pdf and https://www.energimyndigheten.se/globalassets/klimat--miljo/fyra-framtider/38764_industrins-langsiktiga-utveckling-och-samspel-med-energisystemet_webb.pdf

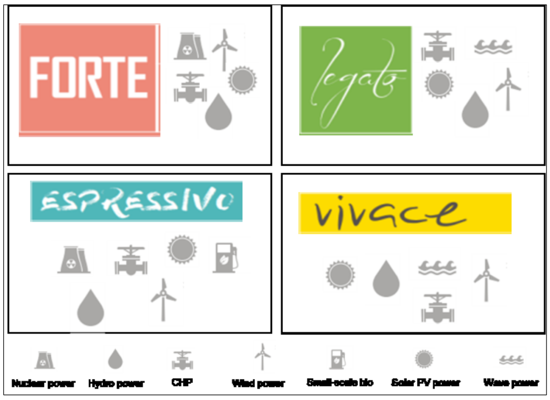

Figure 8. Energy sources and production methods in use in the electricity sector in the four Swedish scenarios in 2050. Figure content from (Statens energimyndighet, 2016a) **own compilation.**

Two out of the four scenarios use nuclear and fossil energy in 2050. It is noted that the increased electrification of society means utilities and households must become more resilient to disruptions in electricity supply and that the addition of distributed small-scale production minimises the risk of disruptions. The GHG emissions decline in all four scenarios in comparison to 2014 levels, but Forte and Espressivo do not reduce emissions enough to meet the goals set out in the Paris Agreement. Legato has the lowest GHG emissions in 2050 and Forte the highest, and in Forte these stem foremost from the industry and the transport sector. Biomass consumption increases in all scenarios, and as can be seen from Figure 9 most of it is used in the transport sector in the form of biofuel. (Statens energimyndighet, 2016a, 2016b)

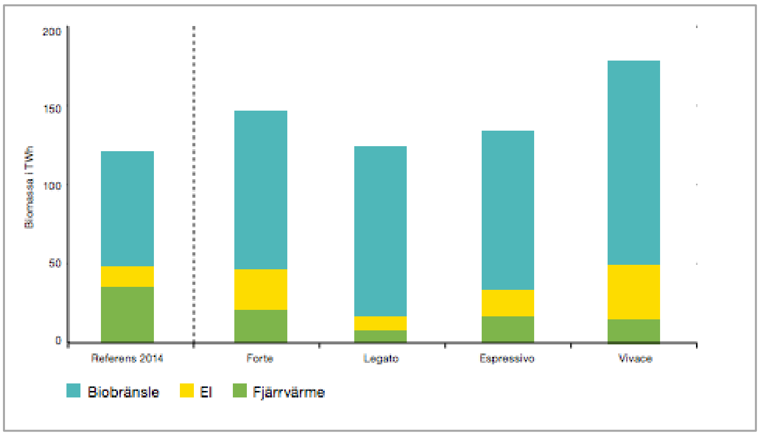

Figure 9. Biomass consumption in the four scenarios in Fyra Framtider and in 2014. Biobränsle = biofuel, El = electricity, Fjärrvärme = district heating. (Statens energimyndighet, 2016b)

To achieve zero net emissions in 2050 in Sweden the Swedish energy sector needs to reduce emissions to a maximum of 10 Mton CO_{2eq} per annuum, according to the study. This goal is met in both 100% renewable scenarios Vivace and Legato, in Vivace emissions are just below the limit and in Legato they are below 5 Mton CO_{2eq} per annuum. The technologies in use in Legato are biomass gasification and biofuel production from cellulose as well as Bio-CCS and possibly CCS (perhaps for the mining industry where small amounts of fossil fuels are used, there is room for uncertainty here). Demand response and behavioural changes are also set to play a large role in Legato as transport demand diminishes and consumers are expected to make choices partially based on environmental factors. The Legato scenario is used as reference in the comparison to other country plans with either 100% RES energy systems or GHG neutrality by 2050, and

Table 4 shows a summary of the assumptions in Legato, with Table 5 summarising the technical aspects of the scenario.

Table 4. Assumptions in the Swedish future energy scenario Legato (part of "Fyra framtider")

Assumptions table	
Energy demand	Decreases to 243 TWh/a out of which 148 TWh is in the form of electricity.
Socioeconomic	The 100% RES scenario is assumed to be tightly connected with new values such as global fairness. Circular economy and behavioural changes are emphasised
Political and economical	The future scenario which both reaches GHG neutrality and has 100% RES experiences little economic growth in comparison to other scenarios
Energy sources and GHG mitigation	100% RES (with small exceptions) CCS and bio-CCS are mentioned
Emissions	Emissions from electricity, heat and transport are quantified, and emissions from LULUCF and industrial processes are discussed. Agricultural emissions not mentioned.

Table 5. Summary of the Swedish future scenario

Sweden – Legato, Fyra Framtider	
Sectors accounted for	The electricity sector is modelled, heat and transport quantified
Sector coupling	Within the energy sector there is coupling of all subsectors, but the transport sector is not modelled as a whole. The waste sector is coupled to the energy sector.
Infrastructure	Only briefly discussed
Model used	Markal, Apollo
Modelling time step	1 hour for electricity
Inclusion of international energy trade	International electricity trade is modelled and trade of other energy commodities is discussed but not modelled.
Energy carriers	Electricity, biofuels, DH (sources: waste and even in a few scenarios fossil fuels, nuclear)
Remarks	Power-to-gas mentioned only once, not modelled

4.2 Denmark

4.2.1 The Danish energy system today

The climate in Denmark is milder than in the other Nordic countries and the Danish industry is also less energy intensive, yielding a much lower per capita consumption of energy than in neighbouring Nordic countries (IEA, 2016b). In 2014 total primary energy consumption in Denmark amounted to 188.4 TWh, and out of this 29.2% came from renewable energy sources (Eurostat, 2016a). Although the deployment of wind turbines has been rapid during the past five years and new records for the share of Danish electricity produced with wind power are being set continuously, the overall share of wind power in total energy consumption is only around 5% and the most important renewable energy source is biomass (DEA, 2016)[25].

The Danish GHG emissions from fuel combustion are larger per consumed energy unit than in the neighbouring Nordic countries, primarily due to the fact that the Danish percentage of renewables in the energy mix is lower than those in other Nordic countries, but also because Denmark has no nuclear power plants. GHG emissions from fuel combustion amounted to 6.12 tonnes of CO_{2eq} per capita in 2014. Figure 10 shows the amount of renewable electricity and energy in Denmark in 2014.

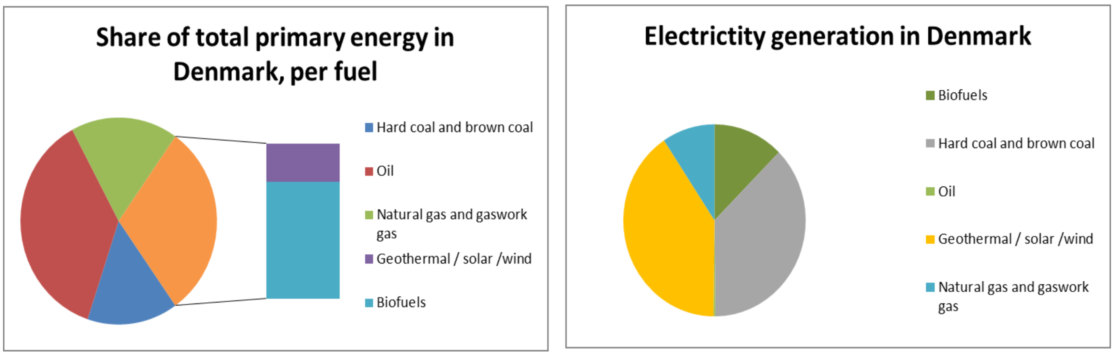

Figure 10. Shares of energy sources in TPES and in electricity generation in 2014. Own rendition of data from http://www.iea.org/statistics/statisticssearch/

Denmark has a large agricultural industry including meat and dairy production. GHG emissions from the agricultural sector thus account for almost one fifth of total Danish emissions (excluding the LULUCF sector) (UNFCCC[26]). Windmills are one of the main exports alongside processed foods and agricultural and industrial machinery, further emphasizing Denmark's role as a leader in wind energy. The country also has its own oil and gas reserves in the North Sea and was until recent years a net exporter of energy (DEA, 2016; IEA, 2016b). Denmark estimates that the country's oil reserves will run out during the following 20 years, and the depleted oil fields could potentially be suitable for CO_2 storage. A handful of research projects for CCS were ongoing in 2009 when the IDA Climate Plan 2050 was published. The LULUCF sector in Denmark constitutes a small sink (in 2012 approximately 900 kt CO_{2eq}, which is less than 2% of emissions (UNFCCC data, see footnote). (IDA, 2009b)

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[25] Total energy consumed and TPES are not the same, but in this case wind power is around 5% out of both.

[26] http://unfccc.int/di/FlexibleQueries/Event.do?event=go

In addition to fossil fuel resources Denmark has ample wind resources with possibility for both onshore and offshore wind power plants, and the first projects utilising solar thermal power for the widespread district heating network have recently been successfully implemented. Denmark also has a considerable wave power resource along the country's long coastal line. As much as 55% of the heating demand in Denmark is covered by district heating. (IDA, 2015)

4.2.2 Political backdrop and agreed upon policies

The Danish government's long-term goal to make Denmark 100% renewable by 2050 was set in 2006. The energy policy instruments needed for this transformation are outlined in the Danish Energy Strategy 2050, which was the first of its kind both nationally and internationally when published in 2011. The Danish Energy Strategy 2050 was followed up by a Climate Policy Plan in 2012 focusing on targets for 2020, after which the Climate Act has secured monitoring of greenhouse gas emissions and regular status reports on climate change mitigation efforts to create transparency in climate policy. (DME, 2016)

The more detailed energy scenario for 2020 includes an interim greenhouse gas emissions reduction target of 40% compared to the 1990 level. This target covers all Danish GHG emissions and is more ambitious than the target of reducing emissions in the non-ETS sector by 20% compared to 2005, which is set for Denmark by the EU. In the transport sector as well as in the proportion of final energy consumption which is to come from renewables, Denmark follows the 2020 targets set out by the EU; 10% RES in transport and 30% RES out of total consumption. Denmark will most likely exceed the 2020 energy efficiency target of 4% set by the EU. (DME, 2016; EC, 2009; IDA, 2015).

The transformation towards a 100 % renewable Denmark includes oil used for heating purposes as well as all use of coal, both in heating and in electricity production, being phased out by 2030. The heating and power sectors are to be 100 % renewable in 2035. An interim goal before the total phase out of fossil fuels from electricity production by 2050 is a proportion of 70% renewable electricity in 2020. In 2014 more than half of Danish electricity consumption was produced with renewables (see Figure 10). The Danish government's goal is that all transport sector energy is to come from renewables in the year 2050, but in achieving this Denmark is highly reliant on international technological development and also on the level of ambition of international policies. Domestically ambition is high; the Danish capital Copenhagen intends to be the first carbon neutral city in the world in 2025, and several other Danish cities are following suit.

The 2050 Energy Strategy includes three different policy tracks to be promoted; initiatives with immediate effect, initiatives that set out long-term frameworks and initiatives that are to encourage future technological development. All these are pursued simultaneously, but their effects will be seen at different stages during the coming decades. The phase out from fossil fuels will happen first in the energy sector with the help of wind and biomass, whilst smaller industry and the transport sector will follow. Denmark relies highly on the interconnections to Sweden and Norway for pumped hydro storage in situations where electricity production exceeds demand, and in the future the amount of sustainably available imported biomass might also be a critical factor for the Dansih energy system. Denmark plans to replace natural gas with biogas. (IEA, 2016c; DME, 2016; IDA, 2015)

4.2.3 Future energy system: IDA Climate Plan and Energy Vision

Both the Danish Energy Agency (DEA) and the Danish Society of Engineers (IDA) have researched how the Danish energy system could run on only renewable energy sources in 2050. The DEA has produced a "DEA Wind" scenario which is compared to the "DEA Fossil" scenario and the IDA has published three reports on the matter, starting with the IDA's Energy Plan 2030 from 2006, IDA´s Climate Plan 2050 from 2009 and finally the most recent report, IDA's Energy Vision 2050, published in 2015. The DEA Wind scenario, the IDA Energy Plan 2030, the IDA Climate Plan 2050 and IDA Energy Vision 2050 all contain comprehensive energy system configurations for a 100% renewable energy system in the year 2050. The Climate Plan 2050 from 2009 also includes measures for reducing emissions in other sectors than energy. (DEA, 2014; IDA, 2009a, 2009b, 2015)

In addition to the DEA and IDA 100% renewable energy scenarios there are two Heat Plan Denmark studies (2008 and 2010) in which the future heating system in Denmark has been studied in detail. The issues of how to deal with limited biomass resources and differentiated transport needs were studied in the CEESA (Comprehensive Energy and Environmental Systems Analysis) project in 2011. The most recent IDA future energy system scenario, IDA Energy Vision 2050, builds on the findings from these research projects and on the same principles and methodologies and the previous IDA scenarios. This most recent scenario is reviewed here, alongside the IDA Climate Plan 2050 in which emission reduction measures for all GHG emitting sectors are discussed. (CEESA, 2011; Ramboll, 2008, 2010)

IDA Climate Plan 2050

The IDA Climate Plan 2050 describes measures for a 90% reduction of total Danish GHG emissions in 2050 compared to the year 2000. There are no emissions from the 100% renewable energy sector in which nearly 65% of energy demand is met by biomass and the rest by wind power, PV power, wave power, geothermal power and solar thermal power. Electrolysis is used to produce hydrogen, which is used as a fuel in fuel cell CHP plants and in the transport sector for those cars that are not battery electric vehicles. Neither large-scale batteries nor CCS is included in the Climate Plan due to too high costs.

In addition to emission reductions in the energy sector, the IDA Climate Plan 2050 proposes measures for decreasing emissions from the agricultural sector and the industry sector. All waste is incinerated and thus part of the energy sector, the biodegradeable part of waste being counted as biomass and with the consideration that the energy sector might produce some emissions if fossil fuel based waste is not considered to be CO_2 neutral. All in all emissions are reduced to 5.2 Mt of CO_2-eq in 2050 when not counting extra emissions from aviation due to fuel discharges at high altitudes[27]. This equals

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[27] These emissions are not included in the scenarios of other countries. What is meant is aircraft greenhouse gas effects due to high altitude fuel discharges to empty fuel tanks before landing. "There is no

7.2% of Danish emissions in 2000, and when counting the extra emissions from aviation the emissions in 2050 amount to 10.2% of the emissions in 2000. The proposed mitigation along with the reference scenario used in IDA Climate Plan 2050 is presented in Figure 11. Danish emissions in 2000 including LULUCF and excluding the extra emissions from aviation fuel discharge were 72 Mt CO_2-eq (UNFCCC). The reference case used in IDA Climate Plan 2050 is the Danish Energy Authority's basic forecast for energy consumption, dated 30th of April 2009. It contains some reductions in energy consumption of the transport sector but as can be seen in Figure 11 there is no decarbonisation of the energy sector.[28] (IDA, 2009a, 2009b)

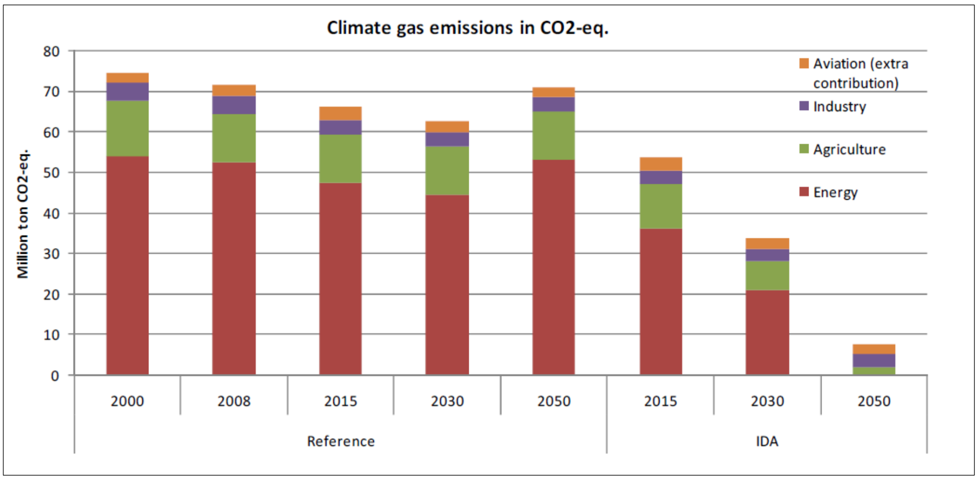

Figure 11. Greenhouse gas emissions in the IDA Climate Plan 2050 Scenario. (IDA, 2009a)

The IDA Climate Plan scenario estimates the emissions from industrial processes (including emissions from waste disposal sites) in 2000 to 4.2 Mt CO_2-eq/a and suggests a 25% reduction of emissions in this sector by, amongst other measures, changing the materials and production methods for cement and through the incineration of waste. The annual GHG emissions from agriculture were estimated at 19 Mt CO_2-eq in 2008, which includes energy-related emissions from the agriculture sector of 7 Mt CO_2-eq per year. It is suggested that the total emissions from the agricultural sector can be reduced to 2 Mt CO_2-eq/a in 2050 through the decarbonisation of energy (a reduction of 7 Mt CO_2-eq/a), improved agricultural practise and conversions (a reduction of 7 Mt CO_2-eq/a) as well as savings in arable land due to changed dietary habits and reduced amount of food waste (a reduction of 3 Mt CO_2-eq/a). The emissions from agriculture had at the time of writing of the IDA Climate Plan 2050 report already fallen slightly from 20.8 Mt CO_2-eq/a in 2000. The different GHG emitting sectors and their total emissions in 2050 according to the IDA Climate Plan 2050 scenario are presented in Table 6 below. The LULUCF sector is not mentioned in the scenario except for in a consideration of international LULUCF emissions due to dietary changes. The LULUCF sector in Denmark currently acts as a small net sink (UNPCCC). (IDA, 2009b)

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widespread consensus on the magnitude of this increase, with multiplication factors varying from 1.7 up to 5 proposed for ordinary aviation fuel on top of the CO2 emissions directly related to the fuel." (IDA, 2015)

[28] Danish Energy Authority, "Notat Energistyrelsens basisfremskrivning, april 2009 (Forecast the Danish energy system)," Energistyrelsen (Danish Energy Authority), Copenhagen, Apr.2009

Table 6. Total Danish emissions per sector in 2050, as in the IDA Climate Plan 2050 scenario

Sector	GHG emissions, 2000 Mt $CO_{2\text{-eq}}$	GHG emissions, 2050 Mt $CO_{2\text{-eq}}$
Energy	54.0	0.0
Agriculture	13.8	2.1
Industry	4.2	3.1
Extra emissions from aviation	2.5	2.4
Total	**74.5**	**7.6**

Source: (IDA, 2009b)

The 100% renewable energy system configuration in the IDA Climate Plan 2050 scenario represents a cheaper overall solution for supplying the Danish energy needs in 2050 than the fossil fuel utilising reference scenario in IDA Climate Plan 2050. The more recent IDA Energy Vision 2050 (published in 2015) discusses the energy system in greater detail and is more relevant for analysis here since it is an iteration of the earlier configuration. The findings from the energy system analysis in IDA Climate Plan 2050 are the same as in IDA Energy Vision 2050 and in other similar energy system analyses: the 100% RES scenario entaials a larger share of investment costs and a smaller share of fuel costs, and no CO_2-allowance costs. Operation and maintenance costs also increase, and the result is that a larger share of the total expenditure is spent domestically, which results in more Danish jobs than in the reference scenario.

IDA Energy Vision 2050

The IDA Energy Vision 2050 does not include other sectors than energy; total Danish emissions in 2050 are described as in the IDA Climate Plan 2050, presented in Table 6 above. The IDA Energy Vision 2050 takes a closer look at the energy system design and introduces ”The Smart Energy System” concept, which is built around three grid infrastructures; the electricity grid, the thermal grid and a gas (or liquid) grid distributing synthesised fuel. The electricity, thermal and synthesised fuel sectors are tightly integrated to create flexibility in the system as a whole and possibility for cheap energy storage across the three grids. The entire energy system including the transport sector is modelled with EnergyPLAN with a 1-hour timestep. The modelling does not include cross-border electricity trade. Figure 12 shows the sector coupling and energy flows between sectors as well as the different technologies in use in the Energy Vision 2050 scenario. (IDA, 2015)

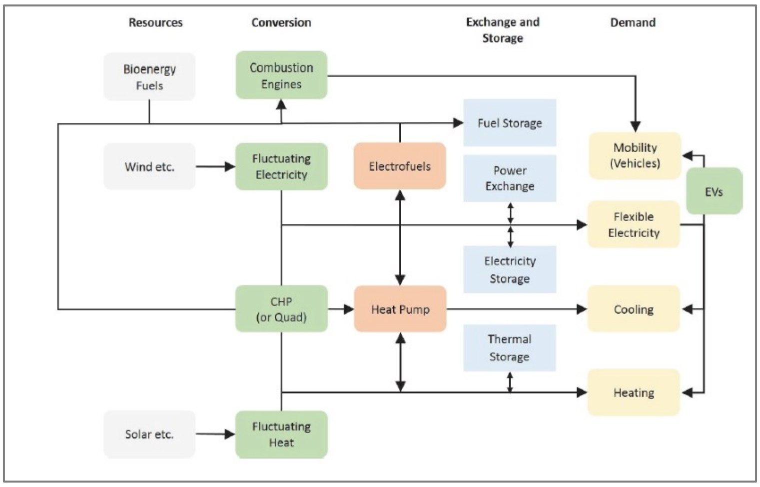

Figure 12. Interaction between sectors and technologies in a future smart energy system, as modelled with EnergyPLAN. (EV's: Electric Vehicles, Quad: production of four outputs) (IDA, 2015)

In the IDA Energy Vision 2050 scenario the growth assumption for industrial production is 0.61 – 1.17 % annually, in line with the Dansih Energy Agency's scenarios[29]. Industry and service including agriculture and construction are assumed to grow in total by 40 % between 2015 and 2050. The net energy consumption of industry and service however decreases from 54 TWh/year in 2015 to 42 TWh/year in 2050. The demand for transport increases by 42 % between the years 2015 and 2050; total transport fuel demand in 2050 is 133 PJ (36.9 TWh). Most of the increase in transport demand is assumed to happen in freight transport, which is largely shifted from road transport to marine transport. Rail transport also increases significantly and there is a modal shift toward more cycling and walking. Although there is a larger number of personal vehicles in 2050 than in 2015, these are in general electric vehicles which helps decrease the energy consumption of the transport sector. (IDA, 2015)

Infrastructure investment needed for the changes to come in the transport sector are assessed and the annual transport system costs in the IDA Energy Vision scenario are lower in 2050 than in the scenarios put forward for Denmark by the Danish Energy Agency[30]. The part of transport demand not suitable for electrification (100 PJ out of 133 PJ) is fuelled by electrofuels. The scenario uses two different carbon sources for the electrofuel; carbon dioxide taken from the air to produce fuels labelled as "electrofuels" and when gasified biomass is used as carbon source the produce is labelled "bioelectrofuel"[31]. These two are used in equal proportion, and a sensitivity analysis reveals that an increase in the ratio of bioelectrofuel lowers the electricity demand, but increases the biomass consumption. IDA Energy Vision adjusts the biomass availability forecast somewhat downward in relation to the numbers put forward in IDA Climate Plan, and it is emphasised that biomass resources should be used with care. The biomass share of fuel production is 47 PJ. (IDA, 2015)

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[29] Energistyrelsen. Energistyrelsen notat: Forbrugsmodel: Fremskrivning af nettoenergiforbruget – metoder, forudsætninger og resultater. n.d.

[30] The DEA has both a fossil and a renewable scenario; the IDA scenario has cheaper annual costs for the transport system than both. However, this takes time to achieve; in 2035 the IDA scenario has higher costs than both DEA scenarios.

[31] The principal difference between bioelectrofuels and CO2 electrofuels is the carbon source originating either from biomass gasification or from stationary sources of CO2 emissions such as power plants or industrial plants. In case of bioelectrofuels, biomass is first gasified and the produced syngas is upgraded with hydrogen in the hydrogenation process

Total primary energy consumption in the IDA Energy Vision 2050 scenario declines from the 2015 level of approximately 820 PJ (228 TWh) to about 575 PJ (160 TWh) in 2050. This is done through energy efficiency measures, installing of heat pumps and electrical boilers, introducing net zero energy buildings and fourth generation district heating, creating flexibility in electricity demand, electrifying transport and making technical improvements to CHP plants as well as introducing PtG, in this scenario specifically power-to-methanol ar to dimethyl ether (DME). More than 60% of primary energy consumption in Denmark in 2050 comes from intermittent renewable energy sources, with an additional 8 % from solar thermal and geothermal. The remaining part of energy consumption is covered by biomass; in total approximately 230 PJ (64 TWh) –a significantly smaller amount than suggested in the IDA Climate Plan 2050 scenario (284 PJ, corresponding to 63 % of the there projected smaller total energy consumption of 450 PJ). Figure 13 shows the primary energy supply in TWh for the years 2015, 2035 and 2050 with both the IDA scenario and a comparison to the DEA fossil and wind scenarios. As can be seen in the figure, the IDA scenario is an iteration of the DEA wind scenario; a finetuning of the energy system configuration to include less biomass and more IRES.

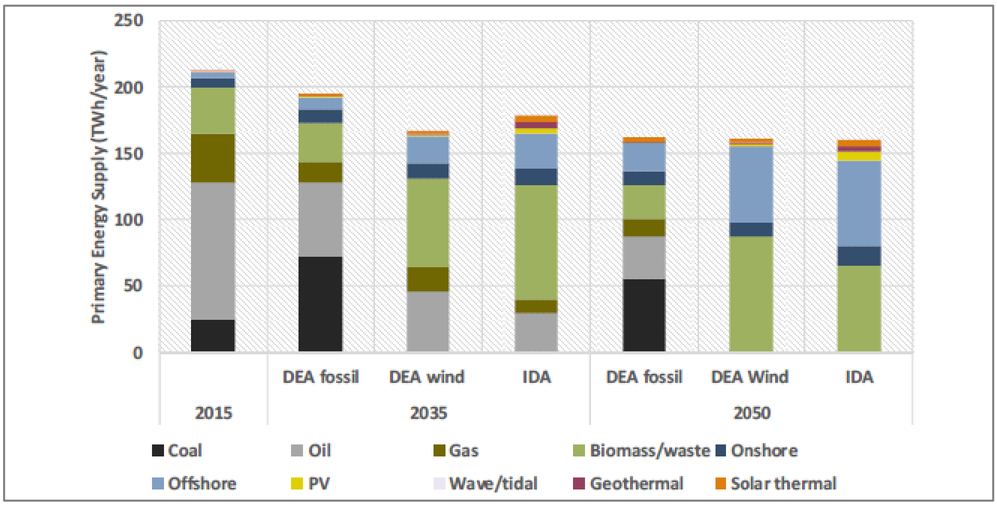

Figure 13. Primary energy supply in 2035 and 2050 in the IDA Energy Vision 2050, in 2015 and in the DEA scenarios (using the medium fuel price assumptions corresponding to the oil price of $ 105 / barrel). (IDA, 2015)

The IDA Energy Vision 2050 concludes that Denmark's energy needs in 2050 can be satisfied with only renewables, and that this is most feasibly done by increasing the share of electrification and enabling sector coupling while implementing energy efficiency measures to decrease energy demand.

4.2.3.1 Summary of the two scenarios

It is significant that there already existed several comprehensive scenarios for how the Dansih energy system could be fully functional while producing zero emissions before the IDA Energy Vision 2050 scenario was published in 2015. The conclusion from the IDA Climate Plan (IDA, 2009a) is that total GHG emissions in Denmark can be reduced to less than 8 Mt of CO_2-eq in 2050, and that a fully renewable energy system is cheaper and prodces more domestic jobs than the reference scenario. This conclusion holds in the more recent Energy Vision, which is based on the same economic growth assumptions as the energy system in Climate Plan. IDA Energy Vision adjusts the biomass availability forecast somewhat downward in relation to the numbers put forward in IDA Climate Plan, and it is emphasised that biomass resources should be used with care.

The decline in total primary energy supply in the Energy Vision scenario is smaller than in Climate Plan, and this is due to two things: firstly, the IDA Energy Vision scenario utilises less biomass than the IDA Climate Plan, meaning the gap has to be filled with more intermittent energy sources and a larger share of synthesised fuel for storage and use in areas where intermittent electricity is not a suitable energy source. The energy-intensive synthetisation of fuels increases the overall energy needs of the energy system in IDA Enery Vision. The second reason is that the energy carrier in the synthesised fuel grid is not hydrogen as in the IDA Climate Plan, but either methanol or dimethyl ether (DME), which are both more energy intensive to produce.

The fuel and CO_2 allowance prices utilised in the IDA Climate Plan 2050 and IDA Energy Vision 2050 scenarios are based on the DEA's assumptions. The prices in IDA Energy Vision 2050 differ from those in IDA Climate Plan 2050 since the DEA updated their assumptions in December 2014[32]. Table 7 summarises the assumptions in the two scenarios and Table 8 is a summary of the proposed energy system as per IDA Energy Vision 2050, including the emission mitigations for other sectors presented in IDA Climate Plan 2050.

Table 7. Summary of assumptions in the Danish future scenarios

Assumptions table	
Energy demand	Primary energy supply decreases by approximately 23 % from 2015 to 2050.
Socioeconomic	Citizens are expected to shift eating habits towards a more plant-based diet
Political and economical	The economic growth rate for industrial production and services is the same in the 100 % RES scenario as in the BAU cases
Energy sources and GHG mitigation	The most important energy source is wind, followed by biomass. GHG emissions are mitigated to a total of 8 Mt CO_2-eq in 2050.
Emissions accounted for	All GHG emitting sectors, but LULUCF only as part of agricultural sector.

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[32] Agency DE. Forudsætninger for samfundsøkonomiske analyser på energiområdet, december 2014. Copenhagen: 2014.

Table 8. Summary of the Danish future scenario

Denmark –IDA Climate Plan 2050 and IDA Energy Vision 2050	
Sectors accounted for	Energy (electricity, heat, waste, transport) and, in the IDA Climate Plan 2050, also agriculture and industry. LULUCF is discussed as part of emissions from agriculture and food production.
Sector coupling	Within the energy sector there is coupling of all subsectors.
Infrastructure	The IDA Energy Vision 2050 outlines a plan for three interconnected smart grids: heat, electricity and gas (or liquid). Costs are calculated but not modelled.
Model used	EnergyPLAN
Modelling time step	1 hour
Inclusion of international electricity trade	The system is modelled without international trade but separate analyses are done to examine the effect of international trade.
Energy carriers	Electricity, water (DH) and two synthesized fuels defined as “electrofuel” (CO_2 taken from air) and “bioelectrofuel” (CO_2 originates from gasified biomass): methanol and DME

4.3 Germany

4.3.1 The German energy system today

Germany has a large energy-intensive industry sector including steel and metal production, building and construction as well as an automobile industry. Final energy consumption in 2014 was 3 560 TWh (306 Mtoe) out of which 570 TWh was in the form of electricity. In 2014 energy consumption per capita was 44 MWh (3.78 toe/capita) and GHG emissions from the burning of fossil fuels amounted to 8.93 tonnes of CO_2-eq per capita. Figure 14 shows the German primary energy consumption mix in 2014, thus including the consumption of the energy sector itself. 13 077 PJ is equal to 3632 TWh. (IEA, 2016b)

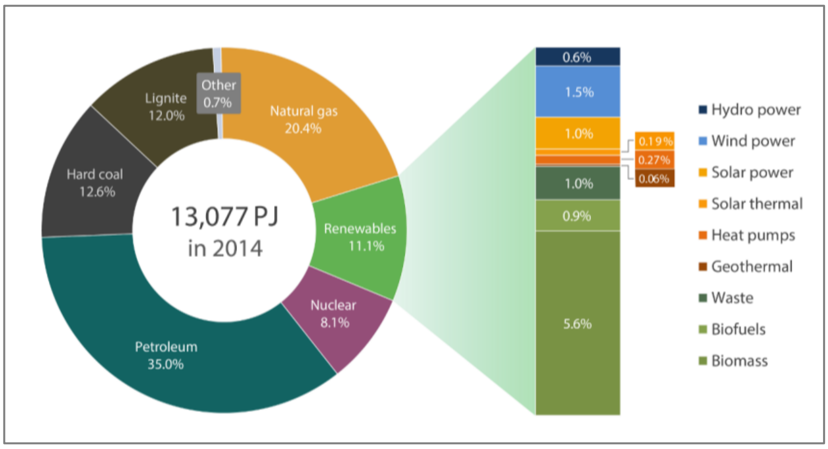

Figure 14. Primary energy consumption mix in Germany 2014. 13 077 PJ equals 3632 TWh. (Energytransition.de, 2017; data from AGEB, 2017)

As can be seen in Figure 14, renewables made up only 11.1% of primary energy consumption (13.8% of TPES as calculated with a different method used by Eurostat) in 2014 –even as renewable energy and in particular renewable power production capacity has grown rapidly in Germany during the past 10 years (AGEB, 2017; Eurostat, 2016a, 2016b). In electricity production the share of renewables was higher at 28.2% of TPES (Eurostat, 2016a, 2016b). Wind power is the most important renewable electricity source, with wind and solar PV power providing the lion's share of renewable electricity and biomass being the most important renewable energy source. Germany is a net exporter of electricity but imports uranium, petroleum (oil) and natural gas. The country has more than 400 000 km of gas grid for transport of natural gas, and this infrastructure can also be used as storage –the thermal energy storage capacity of the gas grid is approximately 220 TWh. (UBA, 2014)

Before March 2011 nuclear power stood for about one fourth of German electricity, and after the closing of reactors it has gone down to around 15%. The shift away from nuclear power has lead to an increase in the use of coal in power production in the short term; in particular lignite makes up a large share (44% in 2015) of electricity production, and coal in total (hard coal and lignite combined) was the second largest energy source in Germany in 2014. Renewable energy production capacity is to replace the fossil capacity in the long run, but biomass capacity as well as hydropower capacity are largely built out (BMUB, 2014; Energytransition.de, 2017), meaning the increased share of renewables in electricity production is to come from solar PV and wind power. Germany has large wind resources in the north especially along the coastline, while the southern part of the country has good solar resources. In the heating sector geothermal, solar thermal, heat pumps and incineration and gasification of waste are already being used on a small scale. The growing share of renewables in electricity has brought down German wholesale electricity prices, but pushed up retail prices for electricity since the feed-in tariff payed to renewable energy producers is funded by a surcharge on electricity bills. In 2014, Germany had among the highest residential electricity prices in Europe, with an average-weighted reatail price of 35 cents/kWh. (BMUB, 2014; EIA, 2017)

Ever increasing shares of intermittent renewable energy sources has already led and will no doubt also in the future lead to power spikes both in Germany and in the neighbouring countries' electricity transmission grids –necessitating short term storage as well as resilience in the power grids. In parallel, the closing of nuclear power plants in the south where most of the electricity demand is situated has led to a deficit in transmission capacity between the large coal power stations and wind parks in the north and the consumption in the south. These two issues form the infrastructural problem facing the German energy system; it has been recognised that 3800 km of new transmission lines is needed to balance the supply and demand between northern and southern Germany, and integration of power markets with neighbouring countries is to help aid the momentary overcapacity in the grid. Germany currently has a 6.8 GW capacity of pumped hydro storage (IHA, 2017), which could, just as compressed-air storage, provide more flexibility to the electricity grid and thus help alleviate power spikes. (AGEB, 2017; EIA, 2017)

4.3.2 Political backdrop and agreed upon policies

Germany is a recognized leader in matters of renewable energy deployment and GHG mitigation. The country's national targets are more ambitious than those of the EU; Germany has pledged to have a 100% renewable electricity supply by 2050, and to mitigate total GHG emissions at a rate of 40% by 2020, 60% by 2030 and 80 – 95% by 2050 in comparison to 1990 (LSE, 2016b). However, the rate at which GHG emissions are reduced has slowed after the Fukushima disaster in 2011, after which Germany made a formal commitment to accelerate its phase-out from nuclear power (BMUB, 2017). The decision meant shutting down the oldest 8 nuclear power plants right away and establishing a timeline for the shutdown of the remaining nine plants by 2022. The phased-out power production capacity has largely been replaced by coal (BMUB, 2014). The ninth nuclear power plant was shut down in June 2015 and the next shutdown is planned to take place before the end of 2017. Public opinion in Germany was long since opposed to nuclear power, and thus a phase-out would have taken place either way, only not as swiftly as decided upon in response to the disaster.

Renewable power generation capacity in Germany has grown at an increasing rate over the past two decades, and the amount of electricity produced from renewables tripled during 2004 – 2014 (AGEB, 2017). This is in large part a result of energy policy; in 1991 Germany introduced a feed-in-tariff as part of a law called "*Stromeinspeisungsgesetz*"; the law of feeding electricity to the grid. The law gives renewable energy priority to the grid and guarantees that it is bought at an above-market price. The law from 1991 has been revised several times (most notably in 1998, 2000, 2004 and 2014) and since the year 2000 it is often referred to as the EEG ("*Erneuerbare-Energien-Gesetz"*) the law of renewable energy. Up until the year 2000 the FIT was dependant on the market price of electricity, but in 2000 the political will was to strengthen the incentives for investors further by introducing set FITs for a period as long as 20 years. The German FIT today depends on the year of installation, the size of the capacity being installed and on the technology. (Energytransition.de, 2016; Salo, 2015)

The installation of PV solar capacity started growing after 2004 when the technology was approved for FITs, and between the years 2011 and 2014 grew unexpectedly fast. The rapid deployment of renewables has decreased wholesale electricity prices but increased consumer electricity prices in Germany (BMUB, 2014; EIA, 2017; LSE, 2016b). The FITs are payed by electricity consumers in the form of an EEG surcharge as part of the household electricity bill, and energy-intensive industries are exempt of the fee to ensure their competitiveness internationally and prevent utilities from moving production to other countries with cheaper electricity prices. This increases the burden put on households; between the years 2012 and 2014 the EEG surcharge paid by German electricity consumers almost doubled from 3.59 cents/kWh to 6.26 cents/kWh as a consequence of more utilities being relieved of the surcharge and, increasingly, more households buying less electricity from the grid due to rooftop solar PV installations, which further decreases the amount of electricity sold on which the levy can be distributed. All in all, the German FIT system has succeeded in incentivising investment in renewable power production capacity, but the costs of the system are currently not on a sustainable level. (BEE, 2015; Salo, 2015)

Due to the long prevalent strong political will to reduce GHG emissions and combat climate change, there are numerous studies and reports on how to make the German electricity supply 100 % renewable and how to decarbonise the German society. The German government’s energy concept contains guidelines for an overall strategy to 2050 outlining how the country’s energy supply is to be developed. The guidelines are based on a fundamental decision that the majority of Germany’s energy requirements should be met from renewable sources. The following key targets are defined for 2050:

- Increase the proportion of electricity generated from renewable sources to at least 80%
- Reduce electricity consumption by 25%
- Reduce primary energy consumption by 50%
- Redevelop the building stock with the aim of achieving climate neutrality
- Reduce final energy consumption in transport by 40%.

4.3.3 Future energy system: THGND 2050 Scenario

The research that is assessed to be most relevant for comparison with that in the Neocarbon Energy project is the *Treibhausgasneutrales Deutschland 2050*[33] (THGND 2050) scenario published by the German Federal Environment Agency, UBA (Umwelt Bundesamt), in 2013. The THGND 2050 Scenario is part of an interdisciplinary process, which started with investigating the possibility of 100% renewable electricity in 2010 and was expanded to include first all emissions from energy and then all emissions from German society.

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[33] *Treibhausgasneutrales Deutschland means “Greenhouse gas-neutral Germany”. The scenario name is abbreviated THGND 2050.*

The THGND 2050 Scenario demonstrates a future in which total GHG emissions in Germany have been reduced by as much as 95% by 2050 compared to the base year 1990, meaning total per capita emissions are lowered from the current 11 tonnes of $CO_{2\text{-eq}}$ per capita to less than 1 tonne of $CO_{2\text{-eq}}$ per capita. The objective is to show that a virtually carbon-neutral German society is technoeconomically achievable, and no predictions are made as to how probable such a future is. The term *carbon-neutral* is in this context relaxed to allow GHG emissions of 1 tonne of $CO_{2\text{-eq}}$ per capita (referred to as a "climate compatible" level of emissions), and it is mentioned that the final emissions could be offset abroad through Joint Implementation (JI) or Clean Development Mechanisms (CDM).

More than 80% of all German GHG emissions came from the energy sector during the years 1990 - 2014, and thus decarbonising energy supply is the most important step in German GHG emissions reduction. Figure 15 shows the assumed German emissions by sector in 2050 and in the reference years 1990 and 2010. In Figure 15 it can be seen that a renewable energy sector alone is not sufficient for achieving a reduction of 95% of German emissions. The THGND 2050 project consists of several parts and one of the first points of action was showing, in 2010, that it is possible to supply Germany's power demand from renewable energy sources only (UBA, 2010). The approach of starting by decarbonising electricity supply is in line with the methods used in other studies of 100% renewable energy systems, such as (Connolly et al., 2014; Lund et al., 2009; Mathiesen et al., 2011). Following the research on a 100% renewable power sector that integrates with the transport and heating sectors, emissions reductions in agriculture as well as coupling of the waste and industry sectors with the energy sector is introduced in the THGND 2050 Scenario –report, (UBA, 2014).

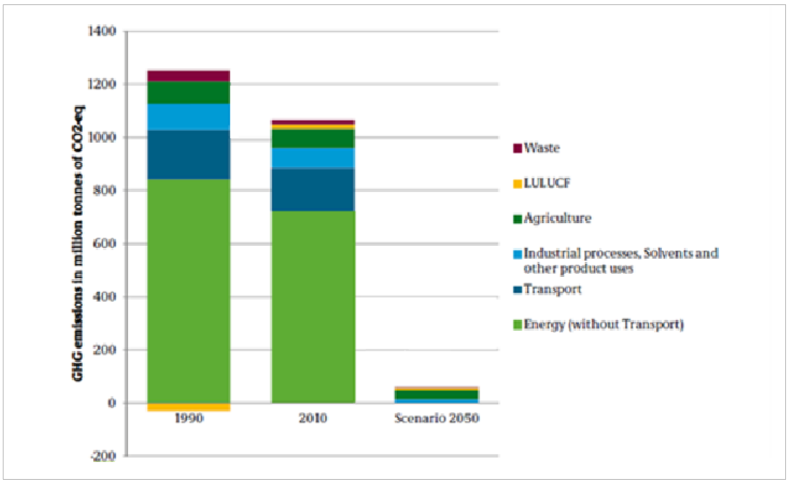

Figure 15. Total GHG emissions in Germany by sector, the years 1990 and 2010 as recorded and the year 2050 as envisioned in the THGND 2050 Scenario. (UBA, 2014)

In order to achieve a 95% reduction of emissions in comparison to 1990, the THGND 2050 scenario looks at emissions from industry[34], from waste disposal, agriculture and from land use, land use change and forestry (LULUCF) in addition to emissions from complete energy supply. Underlying assumptions for the year 2050 are that the average annual growth of GDP in Germany is 0.7% and that the country is still an exporting

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[34] The reporting of GHG emissions from the industry sector deviates from the NIR categories and assigns all industrial processes (Sector 2 in the Common Reporting Format (CRF) for international climate reporting), solvents and other product applications (CRF Sector 3) to one single category, "industry".

industrial country. It is assumed that those industry sectors that are currently in Germany will remain there, emphasising that structural changes in the industry sector could lead to unwanted carbon leakage. The study handles German emissions as those that are produced in Germany, meaning that there is an inherent possibility for carbon leakage through the import of goods from other countries –but simultaneously carbon leakage from other countries to Germany is prevented by counting the emissions from exported goods and energy.

Further assumptions made are that the population is expected to decrese to 72.2 million (from 81 million in 2014 and 82.5 million in 2005), and as a result of this coupled with energy efficiency, technology development and behavourial changes the final energy consumption in Germany is assumed to drop by almost 50% compared to 2010, from aound 2600 TWh to 1323 TWh. Three requirements are set for the future emission-free energy system:

- Nuclear power is excluded as it is no longer an option after the political decision to shut down the existing reactors and refrain from building more
- Biomass produced from crops is excluded as Germany does not consider it sustainable to use land for biomass production. Biomass from waste and residues is accepted as an energy source
- Carbon capture and storage (CCS) is considered unsustainable and is thus not included as an option in the future energy system in THGND 2050

Furthermore the scenario assumes the use of current (2013) best available technology and the progress of energy efficiency and GHG mitigation technologies in pilot status in 2013 into widespread use in 2050. However no new inventions are assumed to emerge. Table 9 shows a summary of the assumptions in the THGND 2050 Scenario.

Table 9. Assumptions in the German future energy scenario THGND 2050

Assumptions table	
Energy demand[35]	Final energy consumption decreases by almost 50% compared to 2010. TPES decreases by approximately 20%.
Socioeconomic[36,37]	Population decreases by 12.5% compared to 2005 Germany is still in 2050 an exporting country with annual GDP growth of 0.7%
Political and economical	Industry structure is unchanged Political decision on nuclear power holds
Energy sources and GHG mitigation	Nuclear not allowed Crop based biomass not allowed CCS not allowed
Emissions accounted for	All GHG emitting sectors. German emissions are those produced in Germany, including exports

In the THGND 2050 scenario all energy production is based on renewable energy sources. The backbone of the energy system is electricity produced mainly from wind

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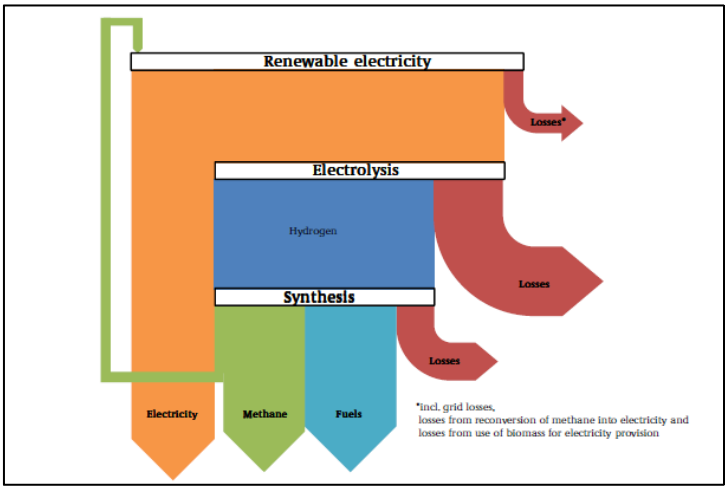
[35] Final energy demand in 2050 is based on UBA's own calculations, results are documented in (UBA, 2010)

[36] Data for the socioeconomic model used in the analysis was taken from the Prognos[2] reference scenario, referred to in (UBA, 2010).

[37] GDP was estimated to increase to EUR_{2000} 2,981 billion (EUR_{2000} 41 301 per capita) (UBA, 2010)

and solar, and from this both renwable methane and renewable liquid fuels are synthesised. Although energy consumption is halved compared to 2010, energy supply decreases by less, since the energy system losses increase as a consequence of the introduction of PtG and PtL. The main energy carrier in terms of terawatt hours is liquid renewable fuels (“motor fuels”, 552 TWh), followed by electricity (457 TWh) and methane (306 TWh as energy and 282 TWh worth of raw material for industry). The methane used as raw material is mainly used in the chemical industry processes requiring a carbon source –this would reduce process-related GHG emissions in many areas, for example ammonia production, to almost zero. The energy flow of the energy system in 2050 with the larger losses due to conversion from electricity to synthetic fuels is shown in Figure 16.



*incl. grid losses,
losses from reconversion of methane into electricity and
losses from use of biomass for electricity provision

Figure 16. Energy flow in the THGND 2050 scenario (UBA, 2014).

The final energy consumption and raw material needs in Germany in 2050 are assessed to add up to 1605 TWh per year, out of which 1323 TWh is energy demand. Due to the system losses annual total primary energy supply in 2050 will, however, be close to 3000 TWh. The transport sector[38] uses mostly[39] liquid synthesised fuels and some electricity, while the industrial sector makes use of synthesised methane and electricity, but uses no liquid fuels. The scenario leaves room for the use of hydrogen as an energy source in industry, since this is less energy intensive than synthesising methane. The use of hydrogen as a fuel is however not part of the final THGND 2050 report, although it was part of the initial energy system simulation carried out earlier by the UBA (2010), on which the THGND 2050 report builds. This leaves room for uncertainty as to how important hydrogen could be as an energy source in industrial processes.

The current German gas grid has a considerable storage capacity of 220 TWh thermal or 128 TWh electrical power[40], and this infrastructure could be readily used to transport and store methane. In the earlier energy system simulations by UBA (2010) the energy system simulations are run with the assumption of hydrogen being used instead of methane[41], but a comparison between the two cases is also made. In the energy system

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[38] Transport excludes the international part of shipping and aviation.

[39] More than 80%

[40] Based on efficiency of 58%

[41] The assumed electric system efficiencies of utilising hydrogen and methane as chemical energy storage are 42% and 35%, respectively. (Electric system efficiency here means the total efficiency of the electrolysis and reconversion processes in the case of hydrogen, and in the case of methane it means the efficiency of electrolysis, methanation and reconversion.)

simulation carried out with the SimEE Energy System Model it is assumed that the German power transmission grid will have been sufficiently upgraded for there not to be a problem of lacking grid infrastructure for the distribution of renewable electricity. The entire German area is thus simulated as a “coherent copper plate” within which feed-in and load is balanced. One central finding is that PtG technology is important for balancing IRES and that the technology is the key to sector coupling.

The scenario introduces sector coupling not not only between different energy sectors such as heating, electricity and transport but also between industry and energy, as well as between industry and waste through increased recycling which produces raw materials for the industry. The waste sector is also coupled with the energy sector through waste inceneration for heat production: the only non-renewable energy sources is the proportion of fossil-based waste being burned. Renewable energy (photovoltaic, onshore wind, offshore wind, geothermal energy, hydropower and biomass) potentials were assessed by first determining the area potentially available for deployment of each technology, and then reducing that area based on a) ecological considerations such as nature conservation areas, b) competing land uses such as transport routes and c) settlement areas. It is stated that the applied constraint ciriteria where ambitious in order to avoid overestimations.

The emissions reductions for each sector are presented in Table 10, from which we can see that GHG emissions from the energy sector are reduced to almost zero in 2050, to be compared to 1028 million tonnes in 1990. The remaining emissions would be 60 million tonnes of CO_{2eq}, equal to about 1 tonne of CO_{2eq} per capita. Table 11 summarises the THGND 2050 scenario and the methods used in the research.

Table 10. Distribution of GHG emissions in the UBA THGND 2050 Scenario. (UBA, 2014)

Emission Source	**CO_2-eq in Mt**
Energy[I]	0
Industrial processes, solvents and other product applications	14
Agriculture	35
LULUCF	8
Waste	3
Total	**60**

[I] Including transport, processing industries etc.

Table 11. Summary of the THGND 2050 scenario

Germany –THGND2050	
Sectors accounted for	All GHG emitting sectors including LULUCF
Sector coupling	There is integration between all GHG emitting sectors.
Infrastructure	Infrastructure is discussed and costs are calculated but not modelled
Model used	SimEE Energy System Model.
Modelling time step	1 hour, run over four years to accommodate for different weather patterns.
Inclusion of international trade	International electricity trade is modelled.
Energy carriers	Electricity, synthesized methane (both as fuel and as raw material in industry), liquid synthesized fuels and hydrogen

5 Comparison of future renewable energy system scenarios

The first research question in this thesis concerned how the scenarios with very low GHG emissions or 100% RE systems of selected three other EU countries compare with each other and with the 100% RE systems portraited as part of the NCE project.

5.1 Overview

The four country scenarios reviewed in this thesis each represent different approaches to a future fully renewable energy system. All scenarios are explorative, but they reflect long-term political goals to a varying extent and the level of technical detail varies greatly. The Finnish NCE project is a state funded research effort analysing the role of PtG in a 100% renewable future energy system. Finland will phase out the use of coal for energy production by 2030 and aims to increase the amount of energy stemming from renewables (TEM, 2017), but simultaneously new investment into nuclear power is being made –this emphasises the explorative and informative nature of the NCE study; it is not a government plan for how to reach specific political targets.

The Swedish Fyra Framtider project is produced and published by the Swedish Energy Agency and it is an exploration of how society as a political and socioeconomical energy consuming entity could evolve. It offers two options for how a fully renewable energy system could be formed: one where economical growth slows and societal values change radically, and one where investment into renewable energy is a source for economic growth and national competitiveness. Neither of the Swedish scenarios clearly reflects the current political course, although Vivace does offer many “sellable” points such as the creation of new jobs and industries through the pursuit of a 100% RES system. The Swedish study is strictly qualitative, with modelling done only for the electricity sector and no presentation of the exact energy consumption of sectors other than electricity or of shares of energy sources out of TPES.

The Danish future scenario is published by the Dansih association of engineers and is an iteration of previous work that partially builds upon research by Danish universities, the DEA and other institutions (IDA, 2015). This study too is explorative, while it is a reflection of the current Danish political will[42]. The IDA Energy Vision includes both a revisited assessment of sustainably available biomass as well as modelling efforts and calculations of infrastructure investment; something the Swedish scenario, which also assumes a high dependency on biomass, does not. IDA Energy Vision builds upon the IDA Climate Plan in which measures for reducing GHG emissions in all sectors are analysied; the scenario presents measures for reducing overall GHG emissions by 90% by 2050 compared to levels in the year 2000.

The German Environment Agency UBA is the publisher of the German future energy system scenario, which simultaneously is a scenario for a GHG neutral[43] society. The THGND scenario is the study that most closely reflects national politics: it explores the possibility of reducing GHG emissions by 80-95% in comparison to 1990, which is the

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[42] In 2006 Denmark set the goal to be 100% renewable by 2050, several Danish cities have pledged to be either 100% renewable or carbon-neutral already before that (see chapter 4.2.2).

[43] The term *carbon-neutral* here allows GHG emissions of 1t $CO_{2\text{-eq}}$ per capita, see chapter 4.3.3 for more

German political decision, along with having a 100% renewable electricity supply by 2050. The design of a 100% renewable electricity supply has been studied for years by both the UBA and by other institutions, (UBA, 2014) and this is iterated upon to model a 100% RES energy system and integrate all GHG emitting sectors as well as suggest measures for reducing non energy-related emissions from industry and agriculture.

5.2 Energy system models and technical assumptions

A central differentiating factor is to which extent scenarios are based on energy system modelling. All four future renewable energy system research efforts (NCE, Fyra Framtider, IDA Energy Vision and THGND) are qualitative as a whole, but they contain quantitative analysises; all four projects model at least the national electricity system. In the German scenario this translates to modelling almost the entire energy system as all fuel and some heat is produced with renewable electricity, and as geothermal heat and solar thermal are coupled to the modelling of the electricity system –while the Swedish modelling of the electricity sector leaves out fuel and heat production completely. Table 12 shows a summary of the four future scenarios reviewed in chapter 4, listing the energy system models used, central technical findings and research methodologies.

Table 12. Summary of the four country scenarios

	Finland	Sweden	Germany	Denmark
Scenario or project name	Neo-Carbon Energy	Fyra framtider	THGND 2050	Energy Vision 2050, Climate Plan 2050
Publisher	VTT, LUT, FFRC	Swedish Energy Agency	Umweltbundesamt (UBA)	DEA[44], IDA[45]
Scenario type	Explorative 100% RE system plan, GHG reduction mainly in energy	Explorative future e. system plan, includes GHG reduction	Explorative scenario of a GHG neutral society, 100% RE energy	Explorative 100% RE system, GHG reduction in all sectors
Sectors accounted for	All GHG emitting sectors	Energy, waste, industry	All GHG emitting sectors	All GHG emitting sectors
Sectors modelled	All GHG emitting sectors	Electricity	Electricity (including PtG process)	Electricity, heat and transport
Models used	TIMES-VTT, EnergyPLAN, BALMOREL, WILMAR	Markal, Apollo	SimEE	EnergyPLAN
Modelling time step	1 hour, 1 year	1 hour	1 hour	1 hour
International trade modelled	In TIMES yes, in EnergyPLAN no	Yes (electricity)	Yes (electricity)	Dicussed, not modelled
Consideration of energy infrastructure	All are modelled (costs calculated)	None	Discussed, costs calculated	Discussed, costs calculated
Central technologies	PtG, biofuels	Biofuels	PtG, PtL	PtG
Central energy sources	Biomass, wind, PV, hydropower geothermal	Hydropower, biomass, wind, PV	Wind, PV, solar thermal, geothermal	Biomass, wind, PV, wave, geothermal, solar thermal
Central energy carriers	Electricity, biofuels, methane, hydrogen	Electricity, biofuels	Electricity, methanol, methane, hydrogen	Electricity, hydrogen
Remarks	Models the path from today to 2050	Does not include TPES calculations.	Share of biomass in TPES not reported. Share of hydrogen as energy carrier unclear	Adapts methane & DME as energy carriers in favour of previously modelled hydrogen

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[44] DEA is the Danish Energy Administration

[45] IDA is the Danish association of engineers

As can been seen in Table 12 different models are employed in the four scenarios or scenario groups, with the exception of the EnergyPLAN[46] energy system model which is used in one of the modelling efforts in NCE in addition to that in IDA Energy Vision. EnergyPLAN is a disaggregated simulation model for analysis and design of energy systems with high penetration of intermittent renewable energy sources; the model simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University in Denmark. In NCE EnergyPLAN is used to analyse a 100% RES electricity system in Finalnd in 2050, while the Danish modeling effort includes heat and transport sectors (as well as waste, through the incineration of waste).

In NCE the entire energy system as well as all GHG emitting sectors are modelled in TIMES-VTT[47], which is a global multi-region partial equilibrium energy system model based on the IEA TIMES modelling framework. TIMES-VTT is a bottom-up model that finds a cost-optimal path to a set year. In the modelling effort in NCE the 100% renewable share of primary energy supply is reached by setting a high penalty tax on non-renewable energy sources for the year 2050, thus allowing utilisation of non-renewable fuels in 2050, but letting cost optimality guide investments towards a 100% renewable energy system. The results from TIMES-VTT are used in analysises performed with electricity system model BALMOREL and electricity system planning tool WILMAR to further analyse the electricity sector in the 100% RES energy system in 2050. BALMOREL[48] is a disaggregated partial equilibrium model with emphasis on the electricity and combined heat and power sectors. It is implemented as a mainly linear programming optimisation problem. The WILMAR[49] planning tool is used to analyse the optimal operation of power systems. It contains a mixed integer, stochastic optimization model that minimises the expected value of the system operation costs, treating wind power production forecasts and load forecasts as stochastic input parameters. (Pursiheimo, 2017)

In the Swedish Fyra Framtider project energy and electricity system models Markal and Apollo were used. Markal[46] or *MARKet ALlocation – The Integrated MARKAL EFOM System* was developed under the IEA ETSAP framework and is a partial equilibrium model representing the Nordic energy system with interconnections to Poland and Germany. The model optimises the electricity production mix according to the assumptions given. Apollo[50] is a European electricity market model that simulates the European power market, including prices, on an hourly time step. Apollo was developed by Swedish consultant company Sweco Energy Markets and it requires a previously defined energy mix. The SimEE model used in the THGND scenario simulates renewable electricity production, the load curve and flexible load over several years in an hourly resolution. The model was developed by the Franhofer institute in Germany, and through the coupling of transport, heating and electricity sectors in THGND a large part of[51]

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[46] http://energy.plan.aau.dk/links and http://www.energyplan.eu/

[47] http://iea-etsap.org/

[48] http://www.balmorel.com/

[49] http://www.energyplan.eu/othertools/global/wilmar-planning-tool/

[50] The APOLLO power market model –brochure (2015), available for download at www.sweco.se

[51] It is not entirely clear to what extent synthetic fuel use in transport was modelled; the production of synthetic fuel is however modeled, as is reconversion to electricity in case of electricity deficit. Also, waste incineration does not seem to be part of the SimEE simulations. Heat production is simulated with solar thermal and geothermal, but any heat production in CHP plants is left out. Based on the biomass

energy production and consumption can be modelled with the electricity system model. (Statens energimyndighet, 2016a; UBA, 2010)

The largest difference in modelling methods is that the TIMES-VTT modelling in NCE models a consistent, cost-optimal path from today's energy system to that of 2050, while other models simulate a 100% RES system in 2050. The latter approach does not take existing infrastructure into account, although it must be stated that both IDA Energy Vision and THGND discuss and calculate costs for infrastructure investments separately, taking time horizons for the shutting down of old power plants into consideration as well as discussing the possible future applications of already existing infrastructure (e.g. gas grids). Another fundamental difference is which sectors are modelled and in which sectors the modelling effort (or other scenario calculations) aims to reduce emissions. In TIMES-VTT all GHG emitting sectors are modelled, but the target of a 100% renewable energy system only incentivises the model to reduce emissions from energy (and waste, in the form of waste incineration or biogas production). This approach differs from that in THGND, where the focus lies on reducing emissions; the 100% RES energy system is only one part of the solution in the scenario, in which emissions from industrial processes are brought down by producing large amounts of synthetic methane to be used as raw material in the industry[52]. This shift in focus increases energy demand and affects the design of the energy system greatly. In the NCE TIMES-VTT scenarios industry is assumed to use some fossil fuels as raw material for processes.

5.3 Scenario purpose and role of PtG, PtL technology

In IDA Climate Plan GHG emissios from industry are reduced by more than 25% and those from agriculture by almost 85% by 2050 comared to levels in 2000. Also the THGND scenario contains measures for how to reduce emissions from agriculture and industry by introducing carbon neutral synthetic methane for use as raw material in industry and connecting to the energy sector for instance through changes in the production methods of ammonia. In both of these scenarios PtG/PtL technology has a more prominent role than it does in the NCE or the Fyra Framtider scenarios, suggesting that the purpose of the scenario (to design a 100% RES energy system, or to reduce emissions from society as a whole) strongly affects the design of the energy system and in particular the role of PtG/PtL.

In addition to difference in scope in terms of GHG reduction the inclusion of cross-boarder trade of electricity and other energy goods in the modelling effort should affect the findings in the four different scenarios. For example, in the Finnsih and Swedish scenarios cross-boarder trade (and the access to large hydropower resources in Sweden and Norway) is found to be sufficient for smoothing the effects of large amounts of IRES in the energy (in the case of Sweden electricity) system, i.e. need for storage capacity is not a driver of investment in PtG technology. The Danish modelling effort does not include international trade, and PtG plays a larger role in the energy system than it does in the Finnsih and Swedish energy systems. In THGND PtG is found to play a key role in balancing electricity supply to the grid although cross-boarder trade is modelled.

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criteria in THGND heat production with CHP is however either not an option or very marginal. (UBA, 2014)

[52] Nearly half of methane production in THGND is used as raw material for the industry. (Chapter 4.3.3)

Regardless of modelling framework or sector scope, all future scenarios assume a decrease in total primary energy supply and an increase in electrification in the energy system. The order of magnitude in TPES decline is similar in the scenarios for Finland, Denmark and Germany: the Finnish and German future scenarios both assume a drop in TPES by approximately 20% til the year 2050 in comparison with 2010, the Danish scenario assumes a 23% decrease in somparsion to 2015. Interestingly, the Finnish scenarios reflect a decrease in final energy consumption of only around 10%, while the German THGND 2050 scenario assumes final energy consumption decreases by 50%. This difference points to a structural difference in the two energy systems; in THGND 2050 roughly two thirds of consumed energy is in the form of electrofuels (approximately half of which is methane and half of which is liquid electrofuel: half of the methane is used as raw material in industry), while the role of PtG is much smaller – ranging between 10 and 15% of TPES– in the NCE scenarios modelled with TIMES-VTT. The energy losses in THGND are thus larger than those in NCE, where biofuels play a large role in powering the transport and heating sectors and where industry raw material is not produced with the PtG process.

In the Danish scenario *IDA Energy Vision* the share of electrofuels out of TPES is approximately 17%, and it is all used in the transport sector. Half of the electrofuel is produced with carbon dioxide taken from stationary sources such as industrial flue gases, and half is so-called "bio-electrofuel", produced by upgrading gasified biomass with hydrogen. The produced electrofuel is in the form of methanol or dimethyl ether, as opposed to the prevous scenario by IDA (IDA, 2009b) in which the end-use fuel for transport was hydrogen. Room is left for the use of hydrogen in both NCE and in THGND, but in both scenarios mainly in the industry sector. In NCE the PtG production capacity is not large and it is, with the exception of certain times in winter when unusually large amounts of electricity is needed, used fully all the time. This reflects one of the key findings of the TIMES-VTT modelling effort: in the NCE scenario PtG is not used to balance fluctuating electricity production, as opposed to the case in THGND. The main drivers for PtG investment in NCE are the transport- and industry sectors' need for energy intensive fuel; not the need to store electricity in chemical form. In THGND, PtG and PtL technology is found to be key for sector coupling in the long run, as it both stabilises the supply of electricity and provides transport and industry with energy-intensive fuel and chemicals.

The Swedish future scenarios with 100% RES both assume that final energy consumption decreases –in Vivace by 13% and in Legato by 35% in comparison to 2015[53]– but effects on TPES are not discussed. Neither of the scenarios encompasses use of PtG or PtL technology, powering the transport sector with biofuels and electricity instead and balancing fluctuating electricity production with abundant hydropower resources and with cross-boarder trade. This suggests energy losses in the system will not grow in proportion to energy consumption, but the Swedish scenarios do not contain sufficient information on the technical details of the different future energy systems to draw this conclusion[54]. The role of data centers as controllers of fluctuating energy supply[55] is dicussed for all scenarios in Fyra Framtider, and in the Vivace scenario state-aided battery storage installation in the order of magnitude of 10 MWh is suggested as part of the

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[53] Calculations based on (Statens energimyndighet, 2016a) and the Swedish Energy Agency's publication *Energiläget 2015*, available at https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=5521

[54] For instance, the phasing out of nuclear power affects the ratio of energy consumption to TPES.

[55] Internationally distributed data centers could re-route computing power to countries with excess electricity, moving electricity load across boarders and thus reducing the need for balancing power.

solution to intermittent renewable energy supply. Electrification of the energy system increases in both 100% RES scenarios in the Swedish Fyra Framtider explorative study, in line with the findings from all other country scenarios compared in this thesis.

5.4 Uncertainties: Biomass, CCS and social behaviour

The Swedish scenario offers no numbers on energy use in transport, but it is clear that the personal vehicle fleet is not fully electrified and that biofuels are the most important energy source for transport. In the Vivace scenario Sweden is an exporter of biofuels, and biomass is also used in the production of heat and electricity. In 2015 biomass stood for 22% of TPES in Sweden[56] and the use of biomass is set to increase in all four scenarios on Fyra Framtider (see Figure 9). Whithout figures for TPES in 2050 it is not clear how large a share out of Swedish primary energy biomass will supply, but it can, with fair certainty, be said that it is larger than 22%[57]. For Denmark biomass availability assumptions were adjusted downward in the Energy Vision 2050 –scenario (in relation to earlier assessments by the IDA) and the share in 2050 in Energy Vision is 32% out of TPES. The Finnish NCE scenarios modelled with TIMES-VTT have an even greater dependency on biomass; the share ranges between 40 and 50% out of TPES. In the TIMES-VTT modelling biofuels were found to compete with PtG, whilst a sensitivity analysis performed in the IDA Energy Vision scenario found that an increase in the ratio of bioelectrofuel (in relation to electrofuel produced from flue gases) lowers the electricity demand while increasing the biomass consumption.

In the German scenario the share of biomass out of TPES is not reported, but the use of biomass is limited to that which can be extracted form waste and residues and biomass dependency is thus very low. A recent study (Szarka et al., 2017) of the role of bioenergy in long-term energy scenarios for Germany found that the sustainable domestic biomass potential varies greatly between scenarios, ranging from 350 to 1700 PJ and from 5 to 28% out of final energy consumption. This highlights the large uncertainties in predicting transformative changes in the energy system: even with a multitude of scenarios and simulations the future conditions cannot be certainly predicted. One result of the modelling with TIMES-VTT in NCE was that in the LO-BIO scenario where biomass resources are reduced, the amount of synthetic gas produced with PtG increases even with relatively high investment costs for PtG. This suggests that in addition to technology cost and demand factors for PtG technology, the importance of PtG in a 100% RES energy system in 2050 depends on the availability –physical, economic or political- of biomass.

Another case for differing assumptions in the four analysed future renewable energy systems is the use of carbon capture and storage. In Fyra Framtider the option of CCS and in particular bio-CCS to create negative emissions is discussed as a solution for reducing emissions from industry and from non-energy sectors. The Danish future scenarios IDA Energy Vision and IDA Climate Plan do not discuss the option of CCS, athough Denmark in principal has offshore areas suitable for carbon storage (IDA, 2009b; 2015). NCE does not include the option of CCS and neither does THGND, due

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[56] Statens energimyndighet: online statistics used for the calculation. Available at: http://www.energimyndigheten.se/statistik/energilaget/?currentTab=0#mainheading

[57] Final energy consumption decreases in both 100% RES scenarios in Fyra Framtider, and in all other country scenarios TPES decreases with 20% or more in comparison to 2010 (Denmark with 23% in comparison to 2015).

to reported limited storage capacity and assessment of CCS as unsustainable. Currently the future use of CCS is uncertain internationally, with several operational and coming sites in North America but none in mainland Europe, and the UK's 1 billion pund research grant for CCS cancelled in 2015[58].

In addition to uncertainty regarding energy resources and technology available in 2050, a central aspect for the reduction of GHG emissions is wether or not socio-economic aspects and human behaviour are expected to change over the course of the next 3 decades. The Swedish Fyra Framtider paints one future scenario in which global fairness and environmental protection are new, stronger values than profit maximisation for society. The Finnish NCE project has a socio-economic, cultural explorative view of what the futurtre could bring where some of the scenarios, just like Swedish Legato, show a completely transformed value ground for society. The TIMES-VTT modelling in NCE however depicts what is an economically feasible way of transforming the current Finnish energy system to one of 100% RES in 2050 –without any assumptions of changed behaviour or alternative driving forces to replace cost minimisation. The scenarios including social change can thus be seen as an exploration, while the 100% renewable energy system is demonstrated to be achieveable also with today's norms.

The Dansih scenario assumes increased demand flexibility and modal shifts and, for the minimisation of emissions from agriculture Danes are assumed to alter their diets to be more vegetable-based. However, the transformation to a 100% RES energy system is not built on radical changes in behaviour or the adoption of new societal values. In THGND, final energy consumption is assumed to halve by 2050 in comparison to 2010. Much of this comes from increased efficiency and electrification of the energy system, but vast modal shifts in transport and the emergence of large demand flexibility from consumers are expected.

5.5 Main results of the comparison

The comparison of scenarios shows that in all country scenarios the hardest sectors to decarbonise are transport and industry. The industry sector inherently emits greenhouse gases even when energy supply is completely renewable: in the form of process emissions, most noteably in steel and cement production (IEA, 2016). Much of the transport sector can be electrified, but air travel and some of heavy freight transport still require energy-intensive fuels in gaseous or liquid form. In the four scenarios analysed in this thesis such fuels are provided either from biomass or through a PtG or PtL process. A result of analysing the different scopes of the scenarios is that the role of PtG/PtL technology seems to depend on whether the scenario objective is to reduce emissions also from industry and other non-energy sectors, or if it is merely to design a 100% energy system.

Germany, Denmark and Finland rely on a combination of electrification of transport and the introduction of synthetic fuels produced with PtG or PtL technology. In the German THGND scenario synthesised gas produced with a PtG process makes up more than half of final energy consumption. In the scenario electricity conversion to methane and dimethyl ether is key to coupling sectors and for balancing electricity supply in the grid

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[58] http://www.ccsassociation.org/why-ccs/ccs-projects/current-projects/; www.carbonbrief.org; (BBC, 2016)

by producing synthesised gas with any surplus electricity. In addition to the syngas used for energy, almost 300 TWh wort of methane is produced for the indutry to use as raw material. None of the other scenarios simulate the use of synthetic gas as a raw material in industry, and the in the German scenario the role of PtG/PtL technology is more prominent than in other scenarios. The production methods and integration possibilities of the PtG process with existing industrial processes is discussed but not modelled in THGND.

In the Danish IDA Energy Vision scenario synthetic gas makes up 17% of TPES, and it is all used in transport. The Swedish and Finnish studies do not find PtG to be essential for load management purposes; the NCE study, in which syngas makes up between 10 to 15% of TPES, finds that the main drivers for PtG investment are the transport- and industry sectors' need for energy intensive fuel. The 100% reneable scenarios in Swedish Fyra Framtider do not utilise PtG at all, relying instead on biofuels. Sensitivity analyses in the NCE and Energy Vision projects as well as comparison between results in the four different projects show that in the case of a shortage of biomass PtG/PtL is utilised regardless of high costs and increased electricity consumption. One result of the comparison made in this thesis is thus that the role of PtG in future high RES scenarios in part depends on the assumptions made regarding biomass availability.

The challenge of reducing GHG emissions in the industry sector is proposed to be solved with PtG only in the German scenario: the Swedish scenario refers to novel technologies (e.g. hydrogen reduction in steel making) and the German, Danish and Finnish scenarios emphasize energy efficiency, and in the case of THGND, the use of synthetic fuels in industry. In NCE scenarios blast furnace steel making is phased out, as this process is extremely emission intensive. If CO_2 emissions from industrial processes could be captured and turned into synthetic fuels, this would reduce emissions of the overall system as well as provide beneficial integrations of industrial side streams or increased production of district heat. (Kärki et al., 2016; Onarheim et al., 2016)

Within the NCE project, it has been researched how different residual streams from both the agriculture sector and the industry sector could be utilised in the production of synthetic gas in a PtG process. In THGND such integration possibilities are discussed, but real-life business cases do not yet abound and there are no large-scale demonstrations of the technology. The first profitable cases for the production of synthetic fuel could be in an environment where both excess process heat and a carbon source are present. (Kärki et al., 2016)

The Swedish scenarios' reference to novel technologies for reducing emissions in industry well as the vastly differing assumptions on biomass availability (in NCE biomass dependence ranges between 40 and 50% out of TPES, in THGND biomass dependency is very low) highlight the large uncertainty related to transformative future scenarios. Some of the technologies that will enable the transformation are not yet commercialised, and thus it is uncertain which these are, or if new breakthroughs are just around the corner. The deep uncertainty that characterises simulations and scenario studies in such circumstances is often overlooked; as NCE and Fyra Framtider suggest it is, after all, possible that large cultural or societal changes happen before 2050 as a result of an ecological or political collapse. Such unpredictable changes in the course of development leading to completely new circumstances are hard to predict or imagine –which makes it hard to assess the success of novel technologies.

A result of comparing the four scenarios is that plans for the utilisation of PtG in a future renewable energy system abound, but uncertainty as to how big a role the technology plays is large. The role of PtG seems to depend on demand for energy intensive fuel, carbon neutral raw material for industry and on biomass availability in addition to PtG technology cost. Biomass availability along with many other factors affecting future energy systems, such as energy commodity prices, the availability of CCS and even societal values are subject to deep uncertainty, and to avoid restricting ideas about what the future may bring, business case studies of the integration of PtG in a future renewable energy system could be more informative if studied with an Agree-upon-decisions approach, as opposed to the more commonly used Agree-upon-assumptions approach.

6 Business Case Study with RDM

In this thesis a business case related to the Finnish NCE project is evaluated through the Robust Decision Making (RDM) process to offer a new perspective on dealing with the deep uncertainty associated with transformative energy system changes. The RDM method turns the decision-making process upside down by comprising a stress test on the options available, informing decision makers about the robustness of different options instead of simply optimising a solution for a best-guess future. The RDM process description, results and deliberation on the analysis performed in this thesis are provided in this chapter. First, a suitable business case is selected out of 16 reviewed cases, which were part of the first funding period of the NCE project. Second, the RDM analysis with its different phases is described and thirdly the results of the business case study are presented, followed by a discussion of the analysis performed.

6.1 Case selection

For the Robust Decision Making analysis to be meaningful, the case should be one that contains many plausible strategies whose performance can be compared in a vast number of simulated futures. Several different energy production- and industrial processes as well as applications within waste management and agriculture have been analysed as part of the NCE project to study where the integration of PtG or PtL could be integrated profitably first. The integrated processes analysed are power-to -hydrogen, -synthetic natural gas, -methanol (MeOH), -gasoline, -Fischer Tropsch-wax and olefins, and the sectors range from energy production to the pulp & paper industry, the cement-, iron- and steel industries, wastewater treatment and fertiliser production. A summary of the business cases researched during the 1st funding phase of NCE (June 2014 – June 2016) is presented in Appendix I. The steel industry business case studied in this thesis was picked from this list and is an analysis of performance-enhancing and GHG emission -mitigating investments in the SSAB steel mill in Raahe, Finland. (Breyer et al., 2015; Kärki & Vakkilainen, 2016; Lempert et al., 2003)

The selected business case was chosen based on three criteria; i) the partner company, here representing the primary decision-makers, was interested in participating in the research to demonstrate the validity of the RDM method; ii) the different decision options were previously well defined and linked to both uncertainties and performance metrics through an existing quantitative model or analysis tool; iii) the relevance of the particular case is high since GHG emissions from the steel industry amount to almost 7% of global emissions and this particular steel mill is the largest point emitter of CO_2 in the Nordic countries. The Raahe steel mill business case consists of 8 different emission mitigation options and one reference option describing the status of the mill prior to investment. (IEA, 2016; SSAB, (Kärki & Vakkilainen, 2016))

The selected case:
GHG emission mitigating investment at SSAB steel mill in Raahe, Finland

The SSAB steel mill in Raahe, Finland had an annual crude steel production of 2.8 Mt and GHG emissions of approximately 4 Mt CO_2-eq in 2015[59]. The mill produces hot rolled coils and plates and there is an on-site coking facility. In addition to steel, the factory produces some of its own electricity need on-site and it is connected to the local district heating network to make use of the excess process heat. The Raahe factory is very well integrated and has relatively low GHG emissions per produced ton of steel in international comparison. SSAB however wants to be a frontrunner in low-emission steel production and is working toward this goal also at other mills[60]. The eight investment options considered for the Raahe plant in this thesis are listed and briefly explained below. These were analysed and compared by VTT researchers[61] prior to the analysis with RDM in this thesis. A more detailed explanation of the technologies can be found in Appendix III along with sources for all assumptions and technical data. A description of the basic steel production process is given in Appendix II.

The furnace is the central component in a steel factory and any changes made to it require the shutting down of production for the duration of the maintenance. Steel production in Raahe happenes via the blast furnace route and the next planned furnace maintenance, which is when any changes to the furnace could be made without additional breaks in production, is in 2030. For this reason, the investment options are divided into two groups: five of them concern changes to the furnace, while the other three investment options utilise side-streams and could thus be added on without making changes to the furnace. These three processes are called “add-on” –processes in the case study that follows. (Arasto, 2015; Kärki & Vakkilainen, 2016; SSAB[62])

Investments that require changes to the furnace:

a) Oxygen Blast Furnace (OBF)
b) Oxygen Blast Furnace with CCS (OBF CCS)
c) Increased PCI and GTCC (BF Plus)
d) BF Plus with CCS (with Selexol)
e) BF Plus with CCS (with MEA)

“Add-on” –investments:

f) Post Combustion CCS (PC CCS)
g) Replacing PCI with torrefied biomass (Bio coke)
h) Power to methanol integration (PtMeOH)

All investments except for the BF Plus concept without CCS (option c) mitigate the greenhouse gas emissions of the steel mill. The BF Plus concept without CCS however uses less purchased electricity than the business as usual case since on-site electricity production increases, which means that GHG emissions are reduced *relative to the steel, heat and electricity output*. It is also noteworthy that the Power-to-liquid option does not lower the mills’ documented emissions even though carbon dioxide and carbon

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[59] Annual steel production and emissions vary year to year based on orders and operational activities at the mill. The annual crude steel production for 2015 was calculated from the hot metal production in 2015 given in (Arasto, 2015)

[60] https://www.ssab.com/globaldata/news-center/2017/02/27/08/01/the-swedish-energy-agency-is-investing-heavily-in-a-carbon-dioxide-free-steel-industry

[61] Onarheim, Tsupari, Kärki and Arasto, unpublished working papers, some results are presented in (Onarheim et al., 2016)

[62] From communication with SSAB officials

monoxide are removed from the flue gases. This is because the current accounting rules class the produced fuel as emission-free and thus the Emission Trading Scheme (ETS) credits have to be bought by the fuel producer to avoid double counting. The hydrocarbons captured and converted into methanol in the steel facoty are released again in the form of carbon dioxide once the synthetic fuel is utilised as energy in some other sector. In the bio coke investment option emissions are reduced because carbon dioxide produced from combustion of biomass are accounted for as net zero emissions analogically to the EU ETS (Directive 2003/87/EC[63]) (EC, 2014b)[64]. The yearly emission reductions achieved by each investment option are shown in Figure 17, with the physical emission reduction for the power to methanol case shown even though it is not accounted for as a reduction in the ETS and thus causes no cost savings.[65]

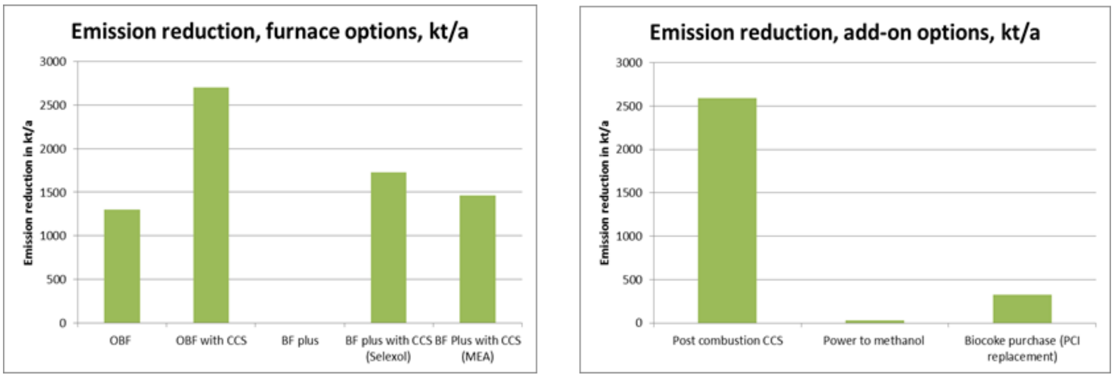

Figure 17. Emission reductions for the"furnace options" and the"add-on options"

In general, the carbon capture and storage (CCS) options offer the greatest reduction in emissions. These investments are however large and the future availability of CCS technology (storage sites, political favour, and more) is uncertain[66]. The application of power-to-liquid technology in the steel industry could offer an interesting alternative to CCS; in essence, the PtL option means utilising the carbon instead of storing it -which in some cases bares a lower economical and political risk than CCS. Because large-scale electrolysers are not yet available, the case modelled here utilises only the converter gases and consequently produces much less methanol than theoretically possible if all the flue gases from the steel mill would be captured –or even 65% such as in the post-combustion CCS investment option. This choice is related to the investment costs in addition to the technical aspect of electrolyser availability; assessing the cost of an electrolyser several hundred times larger than the largest currently existing one is challenging and produced estimates could potentially be misleading in a case study where other costs can be assessed with moderate confidence. The size of the electrolyser modelled in this case is 17.6 MW, and the theoretical emission reduction (see explanation above) shown in Figure 17 is calculated based on this and data from Table 1 in article 1 in Arasto (2015). Costs for electrolysers are expected to come down in the future as the technology is further developed and deployed.

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[63] Directive 2003/87/EC: https://ec.europa.eu/clima/policies/ets_en#tab-0-1
http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02003L0087-20140430&from=EN

[64] The discussion of differences between real and accounted emissions reductions is beyond the scope of this thesis.

[65] The emissions reduction for PtMeOH is shown in Figure 17 to illustrate the scale difference of the investments. The emissions are reduced from the flue gasses, but not counted as emission reductions in the case as explained above.

[66] See chapter 5.4

The costs for all eight investment options are presented in Figure 18, showing the bio coke investment option as the clear exception in terms of costs: a 30 % share of the pulverised coal used in the plant currently can readily be substituted with biocoke, meaning GHG emissions from the mill are reduced without any technical changes or additions to the steel plant. Modelling the investment expenditure as zero is a simplification, as some transaction costs assumably occur when making changes in contracts for PCI coal. However, the option differs greatly from the others in that no technical alterations are made to the plant. It is also noteworthy that the investment costs for the PtMeOH case and the four CCS cases assumed in this case study are not as such applicable to the steel mill in Raahe because they are based on the assumption that converter gases are already captured at the mill, as is done in many steel mills today. The assessment of the validity of previously researched and documented data input for the eight investment options is beyond the scope of this thesis. All assumptions and input variables are listed in Appendix III.

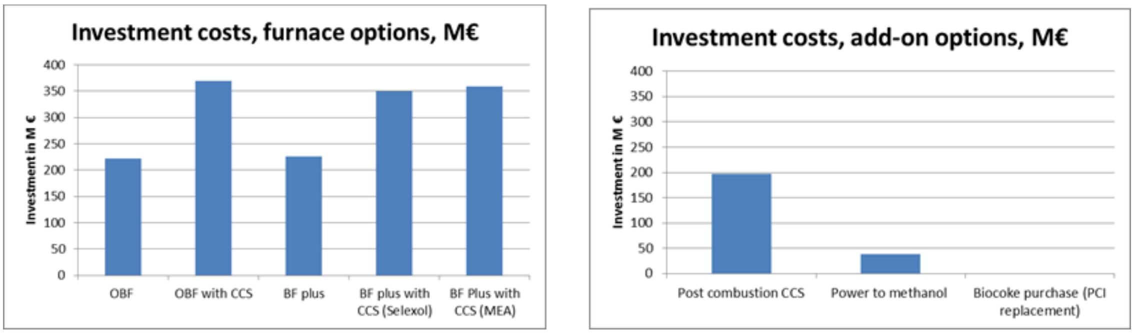

Figure 18. Investment expenditures for the"furnace options" and the"add-on options"

In the group of investment plans which include changes to the furnace the CCS options are the most expensive, with little variation between the three different options. The two modifications to the furnace not including installation of CCS (that is, OBF and BF plus) have similar investment costs, which are clearly lower, but these two options also reduce emissions by far less than the CCS options. In the "add-on" group of investment options the spread in investment expenditure is far larger; as can be seen in Figure 18 the post combustion CCS option costs nearly 200 million €, which is cheaper than any of the options in the furnace group but more than 5 times as expensive as the PtL option, when that is realised in the order of magnitude proposed here. It is good to note already prior to the analysis that the three options in the add-on group are of different magnitude both in terms of investment expenditure and in terms of emission reductions.

The previous analysises by VTT researchers compared the economic profitability of the eight investment options under different electricity- and ETS credit prices. The technical specifications for each optionn along with assumptions on investment costs for different components, achieved reductions in emissions as well as differences in fuel input and output between each plan and the business as usual case are the same in this thesis as in Onarheim et al. (2016). One addition was made to the modelling of the options; where applicable, the possibility of not running the emission reducing process in years when the variable costs of the added technology would be positive, i.e. incur a loss (or an increased loss) for the mill was added. This added option should closer resemble reality; in a year when it is not profitable to reduce emissions at the mill (due to low ETS credit prices, high electricity prices or high CO_2 storage prices, etc.) the capital expenditure incurred by the investment is paid but the variable costs of running the additional emissions reducing process are not incurred. This option is added to all three "add-on" processes (Post combustion CCS, Power to methanol and Bio coke processes) as these can be turned off without affecting steel production at the mill[67].

6.2 RDM analysis

Decision support with the Robust Decision Making approach requires decision makers (DMs) who provide data input and deliberation, and analysts who perform the data mining and the visualisation of the results of the statistical analysis. In the steel mill case study performed in this thesis the decision makers are four SSAB and two VTT representatives. There are two analysts from VTT, including the thesis author.

The implementation of RDM has four steps:

1. DMs define the objectives of the decision, the exogenous future uncertainties and the plans under consideration
2. Analysts construct a large number of plausible futures using computer models and the previously defined exogenous future uncertainties. Each considered plan is then tested in each of the futures, generating a database with data on how the plans perform in different futures.
3. Data visualisation and statistical analysis of the data help DMs identify clusters of futures that highlight the vulnerabilities of different plans.
    - ➢ If these scenarios help DMs identify potential new ways to address those vulnerabilities (i.e. new plans), then DMs go back to Step 1. Otherwise the process continues to Step 4.
4. DMs use trade-off analysis to evaluate whether these plans are worth adopting. If not, they go back to Step 1.

The process continues until decision makers agree on a robust strategy. Figure 19 shows a visualisation of the process.

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[67] The OBF and BF Plus investment options are changes to the furnace which reduces emissions, but means that the emissions reducing process must be run at all times since it is part of the steel production process. The OBF and BF plus CCS options [OBF with CCS, BF Plus with CCS (Selexol) and BF Plus with CCS (MEA)] could in principle be modelled with the running of CCS as optional, but the technical details of such an option are not known and researching them are beyond the scope of this thesis. It is thus only the ”add-on” processes which are modelled to include the option not to run the emission reducing process.

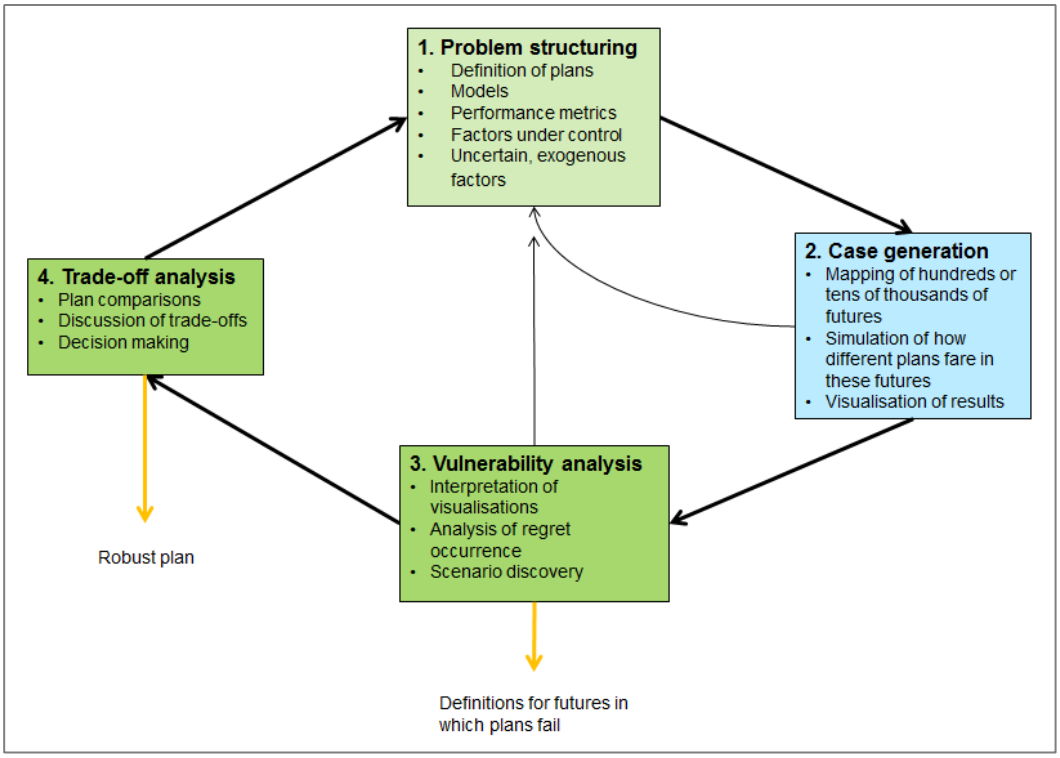

Figure 19. Visualisation of the iterative RDM process. Adapted from (Forsström, 2016)

6.2.1 Problem Structuring

In the first step of the RDM analysis the available plans, the uncertain factors comprising the possible futures and the decision criteria are defined by the decision makers. This basic data collection happens in Decision Maker Workshop 1. The workshop was held in Raahe, Finland on 28.11.2016 and the questions to which the Workshop sought answers were:

A. Defining the options: which different investment options are being compared? Describe them / offer previously constructed models that define the characteristics of them. These are the so-called Issues under control (C).
B. Identifying the components that define the future: which factors do, in the DMs' opinions, define the environment in which the investment is supposed to thrive? In other words, which factors are important when constructing a model of the future? Examples are the oil price, the CO_2 –allowance price, political stability, sustainable biomass supply etc. These are the so-called Uncertain factors (U).
C. Defining the goal: what are the objectives of the investment decision and how is success measured? Examples are profitability, low economic risk, long life time, good energy security etc. These are the so-called Performance metrics (P).

Table 13 lists the answers to the above three questions as elicited in Decision Maker Workshop 1. The fourth basic RDM analysis component is the model (M), which links the uncertain factors (U) to the performance metrics (P) with the help of the issues under control (C) for each strategy. The model is based on the model used by VTT researchers Onarheim, Tsupari, Kärki and Arasto in the previous techno-economic analysises and it is implemented in Excel. The new model is constructed to produce a data set readable to R, a prerequisite for the RDM analysis.

Table 13. List of RDM components as defined in the Decision Maker Workshop 1

Issues under control (C)	Uncertain factors (U)
• The definitions of 8 investment options + 1 reference case • Steel production is kept constant • Option to run the emission recuction process only in years when it is profitable (applicable only to “add-on” cases, see chapter 5.1 for explanation)	• Price of electricity • Price of CO_2 allowance (EU ETS) • Price of LNG • Price of coal • Price of coke • Price of biocoke • Price of carbon neutral liquid fuel • Price of oxygen • Price of transport and storage of CO_2 • Investment price level[68]
Models (M)	**Performance metrics (P)**
• Excel model based on (Arasto, 2015) simulates 5000 futures	• Total cost • CO_2 emissions • Financial risk[69]

In Decision Maker Workshop 1 the current situation at the steel mill (the business as usual case) as well as the 8 considered investment options were first defined to verify that all DMs were aware of the technical details of the investment options and of the assumptions in them, such as steel production being kept constant in all cases. A list of the technical data provided for each investment option is given below (List 1), and a complete list of input data along with a detailed technical description of the options can be found in Appendix III. The performance metrics (P) of the investment were decided prior to discussing the uncertain factors (U); Decision Makers agree that costs and emission reduction are the two most important measures of success in this case, and that high confidence that the steel production can continute uninterrupted also after the changes to the factory is a prerequisite for the investment.

The constructed model (M) calculates total costs for each investment option in each simulated future, translating GHG emission reductions into economical profits via the diminished costs for EU ETS credits. However, it is agreed that emissions reductions might in some years be worth more that their equivalent EU ETS price; hence CO_2 emissions are listed as a performance metric of its own in Table 13. Financial risk is selected as a third performance criteria, and defined as the spread in costs over the simulated futures; i.e. how large is the risk that real costs differ greatly from the expected value (based solely on simulated futures and the outcomes in these; no probabilities are assigned to any certain type of future).

The technical input data listed in Appendix III for the technical properties in List 1 are given as differences between the investment option in question and the BAU case. This is due to limited access to technical information on the BAU case, and due to the fact that the new model is based on that by researchers Onarheim, Tsupari, Kärki and

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[68] By *investment cost level* the realised cost of investment is meant; investment cost is set to vary between 75 % and 167 % of the initially assumed cost of investment, and is thus different in different future simulations.

[69] By Financial risk the spread of simulated costs is meant; the larger the spread of expected costs of an investment option, the greater the risk that costs differ greatly from an expected value.

Arasto. Thus a BAU case is not implicitly modelled, but instead a selection of one option infers the difference in outcome related to the BAU case.

List 1. Technical data used to define each investment option

List of technical properties modelled in the Excel model (M)
Direct CO_2 emissions of the factory (Mt/a)
Electricity consumption on site (GWh/a)
Capital expenditure (M€/a)
Need for biomass (GWh/a)
Need for coke (kt/a)
Need for PCI –coal (GWh/a)
Need for liquid or gaseus fuels (GWh/a)
O&M costs (M€/a)

On the issue of certainty of the continuous production of steel an addition to the Excel model is discussed. An additional variable could describe the risk of interruptions as assessed by the decision makers at this point, and a penalty cost for the undelivered product could be incurred on those plans or those plans in certain typers of futures. This model feature is constructed and tested after the workshop, but it is found that the cost of delayed, lower quality or left out steel production is very hard to assess as it is highly circumstantial and as any longer interruptions in normal production will cause the costs to SSAB to increase exponentially in ways that are hard to quantify; lowered quality might lead to customers moving to other suppliers, left out production might cause breaches in contracts and so on. It is also hard to say whether these uncertainties are connected to the differences in future circumstances at all, as the successful implementation of a new technology is mainly dependent on the maturity of the technology and not on exogenous uncertainties such as the oil price. It is thus decided that uncertainty in the ability to deliver steel uninterruptedly will not be included in the model, but rather considered by the DMs separately in the trade-off analysis done toward the end of the RDM process when settling for the preferred investment plan.

Lastly, the uncertain factors that define the futures and thus affect the success of the investments are identified. For this step in the process, DMs are asked to first discuss in pairs and write down a list of variables, which, in their opinion, affect the future outcome of an investment like the one being analysed. When all pairs are done, the contents of the lists are shared to form one exhaustive list of variables whose value are uncertain in the future and which are assumed (by this group of decision makers) to affect the success of the pending investment. Applying this method to elicit the information increases the chances of all decision makers' thoughts being heard and reduces the risk of missing out on alternative perspectives due to social conformity[70] in the group. The resulting list of all uncertain factors listed by the pairs of decision makers is part of Table 13.

One variable, which was treated as uncertain in the previous analysis by Onarheim et al. (2016), was the payback time of the investment. In this analysis it was agreed that 20 years is the payback time for all investments, regardless of the size of the initial investment. Due to lack of time the value ranges DMs find plausible for the uncertain variables were not discussed in the workshop, but sent afterwards in the form of a filled-in Excel sheet. This method actually resembles the one used for eliciting the uncertain variables in the first place, as it means each DM decides on a value range he or she finds

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[70] Social conformity: feeling the need to augment our own answer to be closer to that of others

plausible –without being affected by the reasoning of others. The value ranges were compiled so that the minimum and maximum answers within the entire group of DMs became the minimum and maximum of the final value ranges. These are shown in Figure 20.

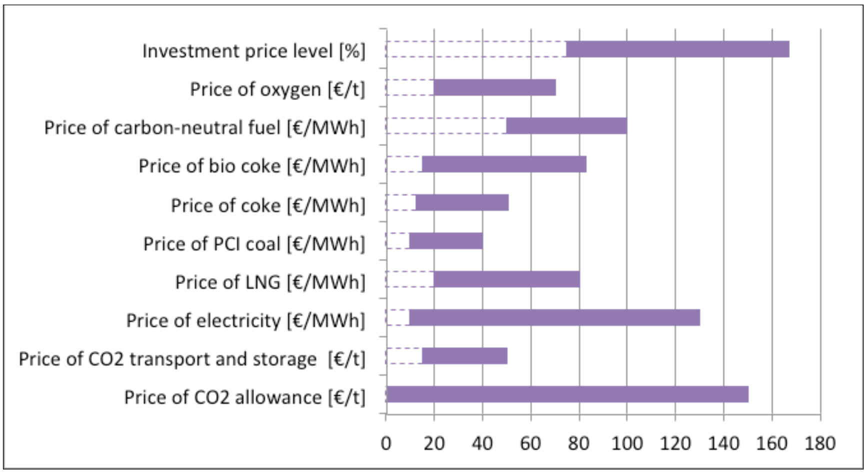

Figure 20. Value ranges for the uncertain factors as elicitated in combination with Decision Maker Workshop 1.

6.2.2 Case generation

Based on the information gathered in Decision Maker Workshop 1, a total of 5000 futures are simulated by the analysts using the Excel model, and costs for all 8 investment options are calculated in each future. The result of testing each investment option in each future is a series of 8x5000 total yearly costs, showing how profitable (or unprofitable) the options are in each simulated future. The yearly costs are calculated as the additional profit stemming from the added process, minus the annual capital expenditure resulting from the investment. All input data is retrieved from previous analysises by VTT researchers; values and assumptions along with their sources are listed in Appendix III, but the verification of this data is beyond the scope of this thesis. Thus the Bio coke investment option is modelled as a zero-investment option although this is recognised to be a simplification, and technical data on emissions reductions, fuel consumption and so on are taken straight from (or calculated based on) the sources listed in Appendix III. Additions made to the model are: 1) addition of an "investment price level" depicting the uncertainty of investment costs; this factor varies the investment costs (by the same factor for all cases in one future, from 0.67 – 1.67) for cases in different futures; 2) coupling of the electricity and oxygen prices, since the cost of oxygen production via electrolysis depends on the price of electricity entirely; 3) the option to not run emission reducing processes in years when it is not profitable to do so, for the cases to which this is applicable.

To the extent that the investments add some side stream to the steel production process or otherwise have running costs that are not linked to the production of steel, it is assumed that these processes (production of methanol from flue gases; carbon capture, transport and storage; the use of bio coke instead of PCI coal) can be "turned off" (i.e. not run) in the years in which they are unprofitable. What this way of modelling the processes means is that the costs incurred from the investments in question only consist of the capital expenditure in the years when the running of the process would lead to a greater annual cost. The investments to which this assumption can be readily applied are the add-on options (PtMeOH, PC CCS, Bio coke). It is assumed that in the cases of OBF with CCS and BF plus with CCS (all together three investment options) the carbon capture, transport and storage part of the process could be shut down in the years when it is not profitable to run, but that doing so requires some extra technical adjustments to the mill due to the different furnace type. The investigation of the possibility of such technical measures is beyond the scope of this thesis, and so it is assumed here that the option not to run an emission reducing option applies only to the add-on investment options.

Figures 21 – 22 show the costs for each plan in all the simulated 5000 futures, ordered by magnitude. The effect of building in the option to not run the side processes in the years it is not profitable can be seen as the straightened top part of the cost curves, showing that overall costs over the 5000 futures are cut when allowing for this. This addition to the initial model was made to closer resemble the real costs, as factories will generally not run processes that incur losses. Figure 21 shows the costs of the furnace options only and Figure 22 the costs of the add-on options only.

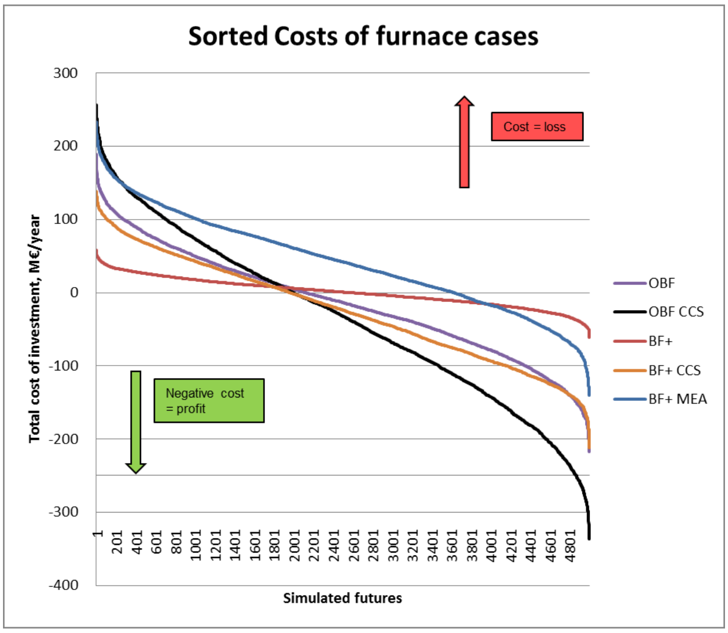

Figure 21. Spread of investment costs for the cases that involve changes to the furnace.

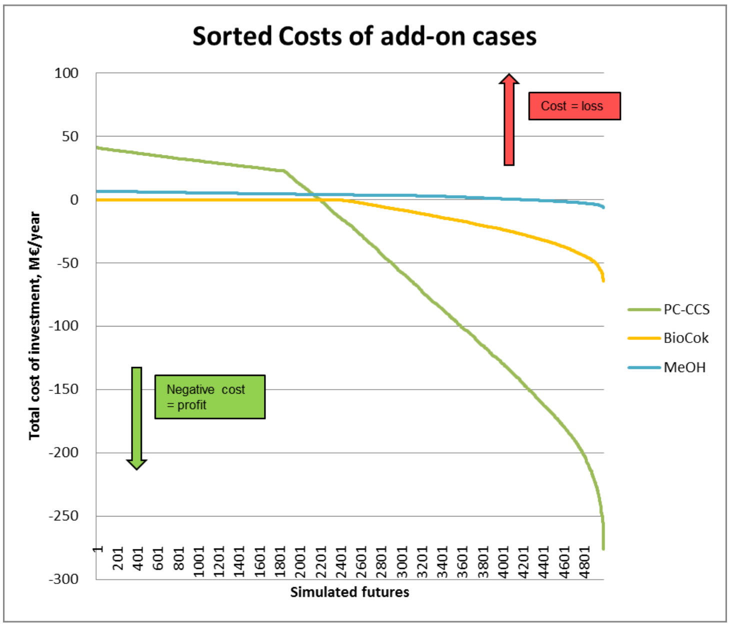

Figure 22. Spread of investment costs of the cases that utilise side streams and could be added on without changes to the furnace.

As can be seen in Figures 21 - 22, the spread of the yearly costs both between different investment plans and for the same plan in different futures is large. This is to be expected based on the different magnitudes of investment expenditure; larger investments produce both larger losses in bad years and larger profits in good years. The investment options uncluding CCS have larger capital expenditure costs than the options not including CCS, and this can be seen in Figures 21 – 22 as a larger spread in simulated costs. The costs of the investment plans in the 5000 different futures can also be described in box figures such as in Figure 23 below. This gives a comprehensive view of the spread of the simulated costs and thus sheds light on the risks associated with different investment options. It is however important not to interpret the spread as a prediction of the outcome; the 5000 costs are calculated for the 5000 simulated futures with the objective of demonstrating *possible* outcomes, not particularily *probable* or *expected* outcomes. This means that some of the simulated futures (with the corresponding costs for each investment option) are probably, upon closer inspection, higly unlikely to unfold. Because of this both the cases in which an investment option fares very well and in which it fares very badly should be further investigated before forming an opinion on whether the option probably fails or probably succeeds.

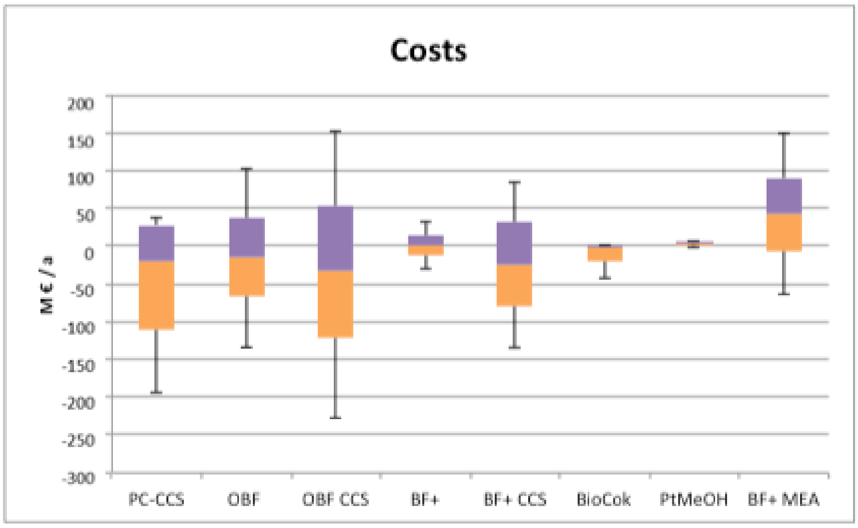

Figure 23. Here 50 % of the different simulated costs fall within the coloured box, the median is market by the colour shift, and the box in combination with the two lines cover 90 % of all the simulated costs, leaving out the outlying largest and smallest 5 %. Negative costs incur profits made.

As can be seen also in Figure 23, the spead of possible costs is in general greater for investment options including CCS (PC CCS, OBF CCS, BF+ CCS, BF+ MEA) than for options without it. As previously mentioned this is to be expected as the CCS technology, regardless of which solvent is used, has a very high investment and thus high capital expenditure (CAPEX) costs. A larger range of possible yearly costs in Figure 23 correlates well with a large investment, see Figure 18. Figure 23 however also shows the level of annual costs for each investment option; for instance OBF CCS has a large spread but the cost median is below zero, while PtMeOH has a very small spread but the median cost is positive.

6.2.3 Vulnerability analysis

The 8x5000 generated costs can be plotted to show the proportion of profitable outcomes per investment option. This gives an indicator of the robustness of an investment option (i.e. is it generally, over the 5000 simulated futures, profitable to invest int this option) –but since some of the simulated futures will be far more likely to occur than others, this representation gives no information on the probability of profitability. Figure 24 shows the relative occurrence of profitable outcomes for each investment option when 5000 futures are simulated using the value ranges presented in Figure 20. The number of times an option fails is less important than the reason it fails, i.e. the description of the type of future that renders an option vulnerable.

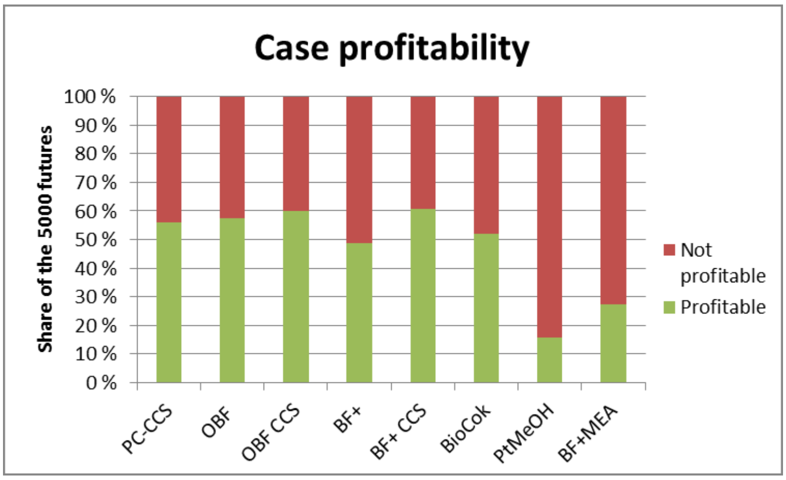

Figure 24. Futures in which cases are profitable and futures in which they are not profitable (or produce zero profit) plotted. This is for illustrative purposes only and is not to be taken as an indicator of success, see explanation above.

In addition to the number of profitable v.s. number of unprofitable outcomes regret is used as an indicative measure of robustness in RDM. The RDM method compares a set of options to each other using Regret analysis: the investment option or options with the least regret are chosen as candidate strategies and investigated further through data mining and statistical analysis to pinpoint their vulnerabilities (Lempert et al. 2003; Bonzanigo et al., 2014). The business case studied in this thesis differs from many documented use cases of RDM in that the investment options are divided into two groups within which comparison is performed, instead of comparing all eight cases to each other. Another difference is the absence of a business as usual (BAU) case in the analysis performed here; instead of comparing nine options (the 8 investment options and the BAU case) all eight investment options are defined *in relation to* the BAU case. These two anomalies were properly understood only after selecting the case and beginning the analysis performed in this thesis, and they make the analysis with RDM more complicated. The problem is solved by performing regret analysis separately for the two groups, and by performing an additional statistical analysis on the costs of the eight cases, to determine which factors render them unprofitable (i.e. a worse choice than the not implicitly modelled BAU case).

Regret is the primary measure of robustness, but in this analysis a statistical analysis of the costs (regret depicts relative costs, byt “costs” absolute costs are meant) is added to make up for the fact that an implicitly modelled BAU case is missing.

Regret is calculated for each investment option in each future as per the equation

$$R(j,f) = C(j,f) - \min_{j}[C(j,f)] \qquad (1)$$

$$\left\{\begin{matrix} j = Strategy \\ f = future \\ C(j,f) = cost \end{matrix}\right\}$$

The definitions of the futures in which a strategy is not profitable along with the definitions of the futures in which a strategy has high regret (i.e. is not successful *in comparison* to other strategies) are used to find the statistically relevant factors amongst (U) causing the success or failure of each strategy. Figures 25 – 26 show the regret of the furnace cases, and Figures 25 – 26 show the regret of the add on cases. Lower regret means the case (investment option) fares better overall, i.e. is more robust in the 5000 modelled futures.

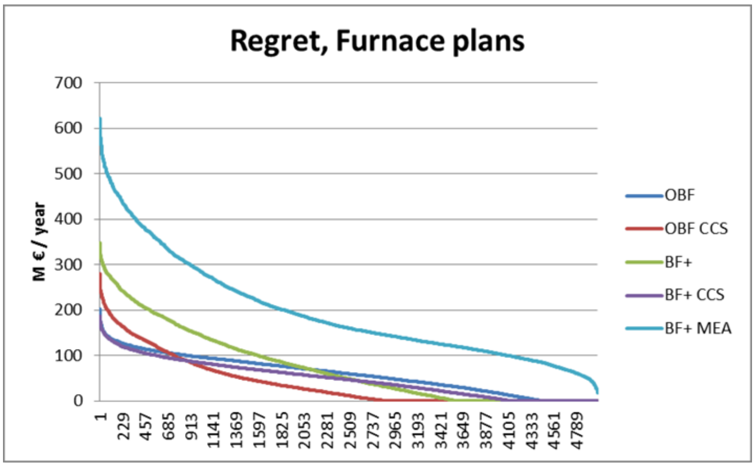

Figure 25. Regret for each furnace option in all 5000 futures, plotted from largest to smallest

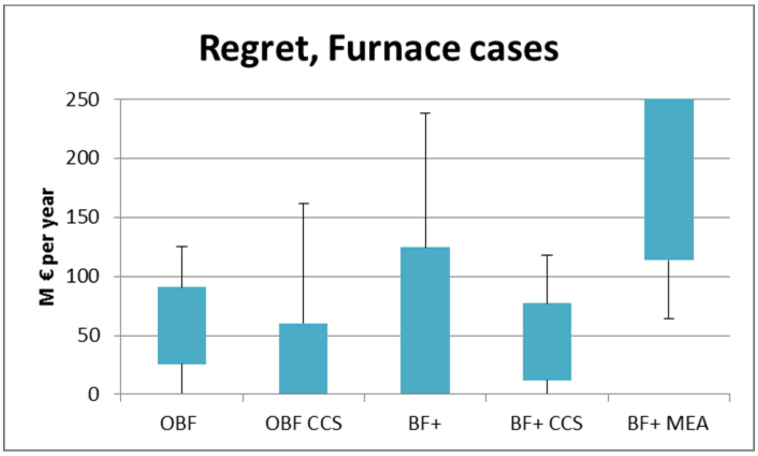

Figure 26. Box figure showing the regret for each furnace option

Figures 25 – 26 show clearly that the BF plus CCS with the MEA solvent –option has the highest regret. The options with the lowest regret are OBF CCS and BF+ CCS (with Selexol) –and out of the furnace changes that do not include CCS the OBF option fares better than the BF+ option. Since regret is a measure of how often a choice is worse than any of the other choices available, options are selected for further inspection based on their regret. Out of the furnace options, OBF CCS and BF+ CCS (Selexol) are selected as candidate strategies for further inspection.

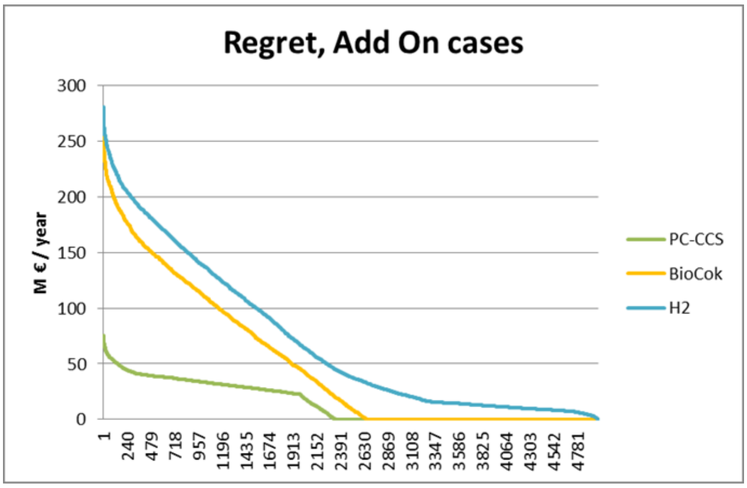

Figure 27. Regret for each add on option in all 5000 futures, plotted from largest to smallest

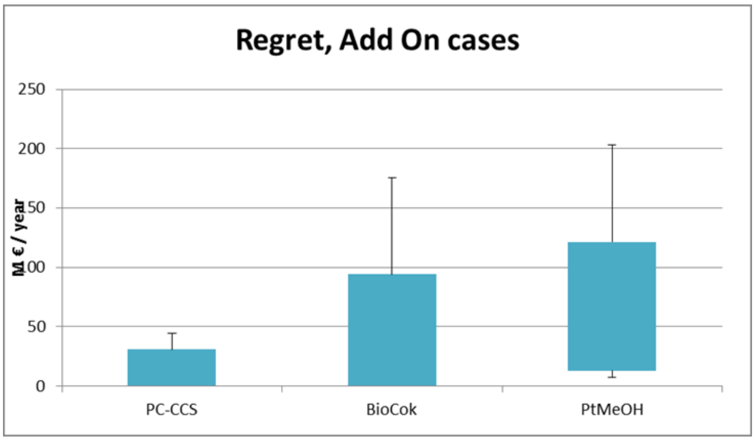

Figure 28. Box figure showing the regret for each add on option

From Figures 27 – 28 it can be seen that the PC CCS option has the least regret, while we know from the cost analysis that the Bio coke option never incurs any costs as it can be shut down in years when it is unprofitable to use bio coke instead of PCI coal. The regret showing for the Bio coke case is thus the difference between the profit (which can in some years be zero) of Bio coke and the larger profit of PC CCS. The PtMeOH case fares worse than the two aforementioned; thus PC CCS and Bio coke are chosen for further inspection. List 2 below shows the four options selected for further investigation based on their relative robustness as measured by regret.

List 2. Options with smallest regret

Investment options selected for statistical analysis	
Furnace options	OBF CCS
	BF+ CCS (Selexol)
Add-on options	PC CCS Bio coke

Four investment options have been selected as the most robust out of the two groups being compared. These options were selected because they *fail less frequently* than the other plans. The RDM analysis seeks to investigate which of the uncertain factors determine the failure of these more robust options, in order to assess the likeliness of such futures. Each simulated future consists of values for the ten (see Table 13) uncertain factors (U) –values that are randomly picked from the value range specified by the DMs and presented in **Error! Reference source not found.**. All of the ten factors are however not statistically significant for the failure or success of the investment option, and thus not relevant when describing the type of future in which the strategy fails. The next step is thus determining which of the factors (U) explain the failure of the four selected plans in question with satisfactory statistical significance.

Determining the uncertain factors (U) with the highest statistical significance for causing a plan to fail, is done by mining the produced database of 8*5000 costs using statistical analysis software R. The method used by R is the so-called Patient Rule Induction Method, PRIM. The R software package *sdtoolkit*[71] contains the function sdprim, Patient Rule Induction Method adapted for Scenario Discovery, which is designed to "discover scenarios (=futures)" i.e. elicit the factors (U) which are statistically most significant for causing some event (this event, be it plan failure or plan success, or plan failure relative to other plans' performances, is determined by the user). In the case of describing the futures in which plans fail in order to make the plans more robust, the process is called "vulnerable future discovery". This process can be divided into three steps and these are shown in Figure 29.

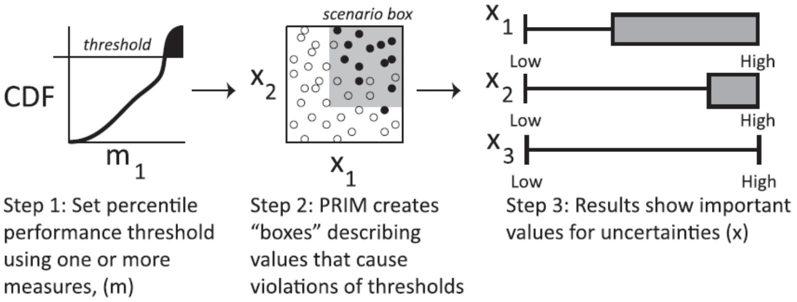

Figure 29. The scenario discovery process step-by-step. (Kasprzyk et al. 2013)

The first step of vulnerable future discovery with sdtoolkit in R is determining the numerical threshold for failure. In this business case it is done twice to reveal two different vulnerabilities; first the relative vulnerability i.e. why the option fails *in relation to the other plans*, and second, as a precaution, the absolute vulnerability (i.e. whether the option is profitable or not) is analysed to make sure that a selected investment option is not only better than its peers but also better than the BAU case. The threshold for relative failure is chosen to be the value which marks the highest 10 % of regret for each option, and the threshold for absolute failure is defined as the point where yearly costs are positive, i.e. the investment is producing a loss for the mill.

In the second step of the scenario discovery process, PRIM creates "boxes" which all consist of a number (1 or more; up to 4 or 5 is still possible to use) of uncertain factors and ranges for these which are statistically significant for the failure of the plan. The analyst selects the most informative, easily interpretable and statistically important of these boxes, which yields the result: (step 3 in Figure 29) value ranges for the uncertain factors (U) that have the highest impact in causing the plan in question to fail. A more detailed description of the PRIM algorithm and the process for performing the statistical analysis is provided in Appendix IV.

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[71] https://CRAN.R-project.org/package=sdtoolkit

The relative vulnerabilities (comparative disadvantages, i.e. the factors causing high regret) of the selected four investment plans are presented in the following figures (Figure 31 and Figure 31). The figures show the value ranges of the specific uncertain factors (U) (analogically to step 3 in Figure 29), which cause the option in question to fail in relation to the options it is being compared to; as in Chapter 6.2.2 OBF CCS and BF+ CCS are part of the furnace group of options and Bio coke and PC CCS are part of the add on group of options.

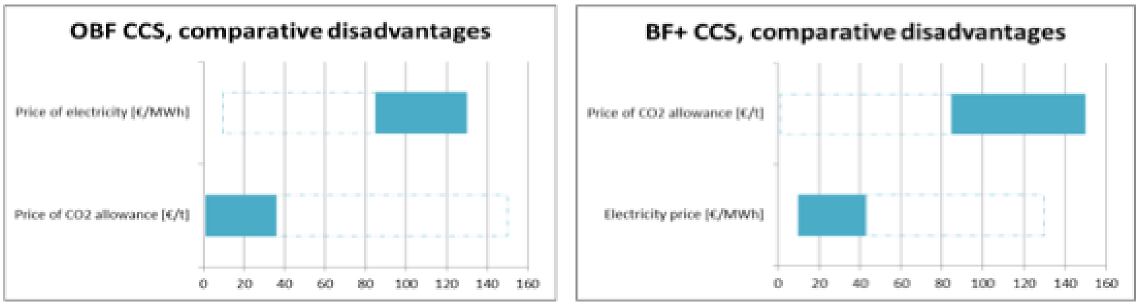

Figure 30. Results of the Vulnerable Future Discovery analysis, furnace options: uncertain factors (U) that are most significant for causing the failure of a plan in relation to others, and the critical value ranges causing failure. The filled-in area of the bar represents the price ranges to which the strategy in question is vulnerable.

For the OBF CCS and BF plus CCS (Selexol) cases two uncertain factors are sufficient for predicting the failure of the options in relation to the other furnace investment options. For both OBF CCS and for BF plus CCS these are the price of electricity and the price of the CO_2 allowance. Figure 30 shows the critical price ranges of the variables in question; OBF CCS is at its worst in relation to the other furnace options in futures where the price of electricity is higher than 84 €/MWh and the price of the CO_2 allowance is lower than 37 €/tonne, while BF plus CCS fares worse than its peers in futures where the price of the CO_2 allowance is high (more than 84 €/tonne) and electricity price is low (less than 42 €/MWh). The OBF CCS case uses far more purchased electricity (up almost 1600 GWh/a from the BAU level) than any of the other furnace options since both the Oxygen Blast Furnace concept and carbon capture are electricity intensive, and since the onsite electricity production increases by more than 400 GWh/a in all cases that involve BF plus (decreasing the amount of electricity purchased). This explains the case's vulnerability toward high electricity prices –and why low electricity prices are a threat to the relative success of BF+ CCS (in which the amount of purchased electricity decreases in relation to BAU regardless of the addition of carbon capture). The amount of CO_2 reduced is also far greater in the case of OBF CCS than in BF+ CCS (2700 kt/a compared to 1730 kt/a) explaining why OBF CCS fails -in both relative and absolute terms- when the price of CO_2 allowances is low.

It can easily be seen that the factors and factor value ranges that lead OBF CCS to fail in comparison to the other furnace cases are factors that also cause “absolute failure” i.e. unprofitability. In the case of BF+ CCS this is however not as clear; thus it should be separately checked in which types of futures the case is unprofitable to ensure that the futures in which it fares well in relation to other plans concide with the futures in which the plan makes a profit. Due to the lack of an implicitly modelled BAU case, it could be that an investment option fares well in relation to the other options available (i.e. small regret) –but that it simultaneously fares badly in relation to the BAU case (i.e. is a worse investment than not altering the mill at all). Figure 31 shows the same information as Figure 30 for the add-on cases, whereafter the cross-check with absolute vulnerabilities is done for all four candidate strategies.

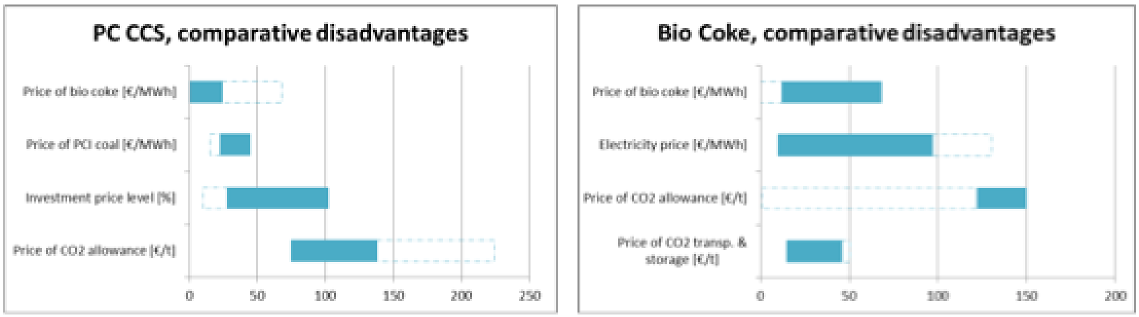

Figure 31. Results of the Vulnerable Future Discovery analysis, add-on options: uncertain factors (U) that are most significant for causing the failure of a plan in relation to others, and the critical value range for these. The filled-in area of the bar represents the price ranges to which the strategy in question is vulnerable.

As can be seen in Figure 31, more uncertain factors are needed to explain the relative failure of PC CCS and Bio coke than in the case of the two furnace cases. In the comparison of the options in the add on group of investments, the uncertain variables governing the relative failure of each option correlates with the characteristics of other options even more than in the comparison of the furnace options, since the add on group is smaller. The PC CCS case both uses more electricity and reduces emissions more than the two other options, and it also has investment expenditure several orders of magnitude larger than the PtMeOH case (and Bio coke has investment cost zero).

To extract useful information from the result it is combined with the result of the same analysis (data mining for the statistically signifcant U that define failure) performed for the absolute failure, i.e. the unprofitability of each option. For all four candidate investment options, a single uncertian factor U was sufficient for describing unprofitability with sufficient statistical significance. In the case of the Add-On processes, it is noted that the statistical analysis with R is not meaningful for the Bio coke –investment plan, as this plan has no investment costs and can be run only when it is profitable to do so; thus this plan will never (when adhering to the assumption of zero investment as modelled here; this, clearly, is not quite accurate) incur losses and thus there is no threshold for unprofitability. Table 14 below shows the numeric thresholds (ranges) for each U for each option.

Table 14. Thresholds for the most significant uncertain factor causing unprofitability

Investment option	Critical, plan-specific disadvantage	Value range
OBF CCS	Price of CO_2 allowance	< 78 € / t
BF+ CCS	Price of CO_2 allowance	< 58 € / t
PC CCS	Price of CO_2 allowance	< 73 € / t

This second data mining analysis shows which factor is statistically most significant when an option is unprofitable (and a maximum value for the "vulnerable area") –i.e. when an option fails it is very likely that the price of CO_2 allowance (which is, as Table 14 shows, the most significant uncertain facor for all the three candidate strategies that can incur losses) is within the range specified in Table 14. However, the fact that the CO_2 allowance price is within the range specified does not lead to the investment option in question being unprofitable and thus the maximum values listed in Table 14 should not be seen as an absolute threshold for unprofitability.

Table 14 provides information on under which circumstances the investment options do not break even i.e. they are a worse choice than not investing in any emission mitigation option at all. This information is combined with the information on comparative vulnerability in Figure 31 to illustrate the types of futures in which OBF CCS and BF+ CCS are vulnerable both absolutely and in relation to the other investment options in the furnace group. Figure 32 shows the threshold for the "vulnerable area" as a line with arrows in the direction of unprofitability, and the area in the 'electricity price – CO_2 allowance price' -plane where the option in question is a worse choice than some other option in the furnace group (shown as a coloured box). The success of PC CCS and Bio coke relative to each other are determined by 4 variables each and cannot be mapped in a two-dimensional coordinate system as the one in Figure 32.

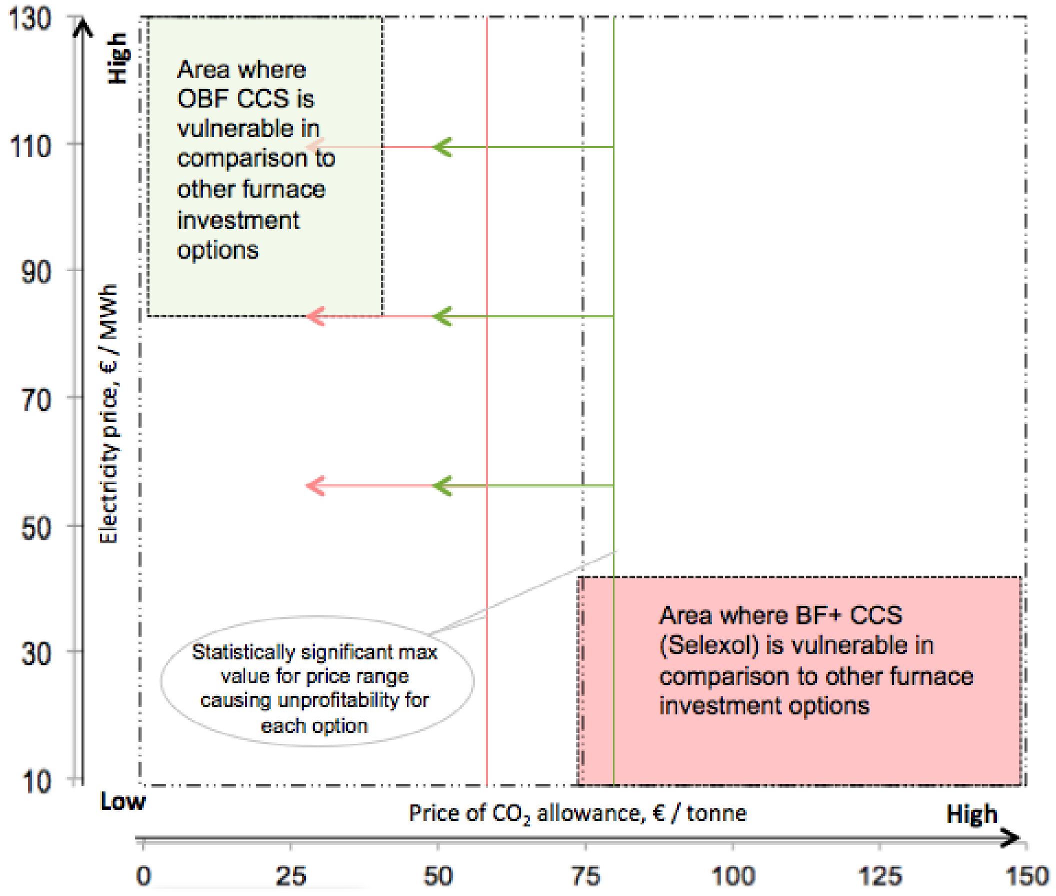

Figure 32. Visualisation showing both the areas in which OBF CCS and BF+ CCS plans have high regret (are vulnerable in comparison to other furnace cases) and the value ranges for the CO_2 allowance price which are at play when the option in question is unprofitable (i.e. vulnerable in comparison to the BAU case).

As can be seen in Figure 32, both the OBF CCS option and the BF+ CCS option are vulnerable (absolutely speaking) to low ETS prices. If emission allowance prices are high, however, OBF CCS is the best choice (not vulnerable in comparison to the other options) and BF+ CCS is the best choice if electricity prices are not expected to be very low, since that option allows for a more lax definition of "high" emission allowance prices (red line is at 58 €/t CO_2-eq. and green line at 78 €/t CO_2-eq.). In other words, (providing that emission allowance prices are high) if the Decision Makers expect the price of electricity to be low (less than approximately 45€/MWh), then OBF CCS is the more robust decision. If DMs are less certain about the very high emission alllowance prices that they are about low electricity prices, then BF+ CCS is the more robust decision. Overall, BF+ CCS is more likely to be profitable even if the emission allowance price is not very high (see Table 14 and the red and green lines in Figure 32) –while low electricity prices coupled with high ETS prices mean other furnace options would have fared even better, but investing in BF+ CCS is still better than doing no alterations at all to the mill.

The outcome of the statistical analysis and data mining done in R is in the form of definitions of groups of futures such as in Figures 30 and 31, and -in this particular analysis lacking an implicitly modelled BAU case- as in Figure 32. This information can be used to either alter a strategy so that it performs better in these futures in which it was discovered to be vulnerable; to decide to leave out a strategy completely if it cannot be altered in such a way; to come up with new strategies that by design hedge against such specific futures -or simply to determine that the strategy in question is robust already, without modifications, providing that the disvovered future (or group of futures) in which it fares badly is considered to be somehow very unlikely. This process involves the deliberation of the decision makers and is iterative, as many new analyses might be needed along the way.

In the case of the add-on investment options it is also the price of the CO_2 allowance which determines wether an investment in PC CCS is proifitable or not –while the Bio coke option (when modelled as here without any upfront investment cost) is totally risk-free as it cannot incur losses to the steel mill. In comparison to the Bio Coke case, the PC CCS case is vulnerable to high investment price levels, low bio coke prices and high prices of Pulverised Coal Injection –coal in addition to ETS prices, since the amount of PCI coal is reduced and bio coke increased in the Bio Coke case. Overall, the potential profits to be made are much greater when choosing the PC CCS option, while the risk of incurring losses is much smaller (zero) when choosing the Bio Coke option. PC CCS has the smalles regret indicating it is “most robust” according to the RDM analysis (the way it would be, were there an implicitly modelled BAU case) but this is due to the fact that PC CCS makes very large profits in many futures, while bio coke always makes either net zero or a small profit. A risk-free option is obviously very robust, even though other options might be making larger profits.

The discovering of in which types of futures the plans fare badly is called *scenario discovery*. In addition to gaining information on which factors to consider especially when determining the robustness of an investment option, the vulnerability analysis and scenario discovery open up for the formulation of new, more robust plans; if two investment options have different strengths and weaknesses, then these can perhaps be combined, or partially combined, to create a third plan that hedges against the risks to which the first two plans are vulnerable. This step was taken in one iteration of the analysis performed for this thesis, but the choice of which plans to combine was made prior to the discovery of a mistake in the model and was not valid anymore once the correction was made. New plans are analysed statistically (regret analysis and cost analysis) and compared to the initial plans to ensure that they are indeed more robust; i.e. a new iteration is done including the old plans and the new. The vulnerability analysis and scenario discovery then yield results on in which types of futures (hopefully a narrower definition, i.e. fewer futures, or a type of future which is deemed very unlikely).

6.2.4 Trade-off analysis

In Decision Maker Workshop 1, the DMs were asked to list the Performance critera (P) against which the investment options were to be assessed. The three critera, as listed in Table 13, are costs, financial risk (i.e. the relative certainty with which costs can be determined) and emissions mitigation. The cost of reducing emissions (or the profit made therefrom) is included in the cost calculations for each case in each future, but the DMs agreed that reducing emissions is a criterion in itself, which in some cases may hold more value to the DMs than the price of emission allowances in that particular future. There is thus, in this particular case study with RDM, a trade-off to be made not only about what is believed about the future (i.e. which decision is most robust when taking into account the beliefs about the future held by the DMs) but also about how much higher financial risk is acceptable in return for larger reductions in emissions, or for the chance of making larger profits.

Due to time limitations it was not possible to include the results of this deliberation in this thesis. The information to be discussed in such a decision-making workshop is however discussed here, as it is a result of the analysis performed. For the two candidate plans in the add-on group of options, PC CCS and Bio coke, the differences in scores on the three different criteria are large; the emission reductions achieved when choosing PC CCS are roughly six times greater than those achieved by choosing the Bio coke option. In terms of profits, the PC CCS case also offers the possibility of making winnings several magnitudes larger than if investment is made in Bio coke, but on the other hand the PC CCS option also holds the risk of making a large deficit if the price of CO_2-allowances falls below 70 €/tonne. The Bio coke case is, as stated before, unique in the sense that it has zero risk of being unprofitable. The spread of possible income magnitudes per year is also relatively small for the Bio coke case, i.e. the predictability of the income amount is good. In other words, if DMs want to play it safe they should choose the Bio coke option (out of the add-on processes) –if they believe the CO_2-allowance price to be well below 70 €/t in the future then they should also choose Bio coke over PC CCS, and if they believe the CO_2-allowance price to be high and are willing to take some risk in exchange for six times larger emissions reductions and the possibility of far greater profits, then they should choose PC CCS.

In the case of the investment options requiring changes to the furnace the differences between the two candidate options are smaller. The OBF CCS case however offers both larger emissions reductions (the emission reductions achieved with BF+ CCS are approximately 65 % of those achieved with OBF CCS), larger profits to be made –and a larger spread in possible incurred profits/costs, i.e. a larger financial risk as it was defined in this analysis, based on i) worse predictability of costs since the spread is larger and ii) larger deficits being possible than in the BF+ CCS case. As shown in the vulnerability analysis, OBF CCS is very robust in an environment with high CO_2-allowance prices (it causes economical losses only when CO_2-allowance prices are low and it has high regret only when CO_2-allowance prices are low *and* electricity prices are high, see Figure 32) and thus, if DMs believe the future to hold high prices of CO_2-allowances, then the OBF CCS case is clearly better. In comparison, what the DMs would be giving up if they, as a precaution for not being as sure about the high CO_2-allowance prices were to choose BF+ CCS, is the possibility to achieve larger emissions reductions; only if emission allowance prices turn out to be high do they also give up the option of making more money. If emission allowance prices are low, then it is highly probable that the risks of OBF CCS are realised, meaning the DMs would not be giving up the chance of making more money as this possibility is not connected to those particular futures.

A risk-free option such as the bio coke investment option in this business case is obviously very robust, even though other options might be making larger profits. The success of the PC CCS option is due to the fact that PC CCS makes very large profits in many futures, while bio coke always makes either net zero or a small profit. A robust decision is one that fares well in as many different futures as possible, but is not neccessarily the best one in any of them. In the end, the RDM analysis only offers up transparent information in the form of trade-offs to be made or risks to be acknowledgd. The method does not point to one winner case, but instead leaves it to the DMs to deliberate how valuable (in the terms of other performance criteria) they find high levels of robustness to be.

6.2.5 Results of the RDM analysis

The previous techno-economical analysises done for the same investment options by VTT researchers Onarheim, Tsupari, Kärki and Arasto[72] have described the success of the different investment options in relation to the price of electricity and the price of emission allowances. The statistical analysis performed in R as part of the RDM analysis showed that these two factors are indeed the two most significant variables in determining the failure or success of emissions mitigating investments like these made to a steel mill. This result lends more credibility to the previous analysises performed and it highlights the "reversed" approach to decision making taken in RDM; instead of defining a future and tailoring a solution to it, DMs are provided with information on which variables (and ranges) are critical when choosing wether to go with an available option or not.

A result from applying RDM to a previously defined set of decision options and building the model used for cost calculations on the previous model not designed for RDM is that the successful application of RDM requires an implicitly modelled BAU case. If decision options are modelled in relation to the current state, their characteristics being a function of the "choose-nothing-case", then comparing them to each other and then to the BAU case (i.e. checking if they are profitable at all, regardless of how they fare in relation to other decision options) becomes two different analysises. The information on whether a case is profitable in the first place in some certain type of future is naturally more important than whether it is one of the best options in that future, and thus the regret analysis –the core of RDM –is given less attention. When performed for a decision problem with several options and a BAU case, the RDM analysis offers all information on robustness in the form of the regret analysis; the option with the least regret is the most robust as it fares the least badly of all options, including the BAU case. If a BAU case is not modelled the analysis is possible to perform in two different parts as it is in this thesis, but the results are less clearly interpretable and the benefits repaed from applying RDM are thus diminished.

Applying RDM to a business case decision problem such as the one presented here, with both options readily selected today and options with larger technical consequence

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[72] Internal working document, part of the NCE research project. Some results are reported in (Onarheim, 2015; 2016)

and the next possible installation in 2030 (i.e. the options including changes to the furnace) highlighted the fact that options being compared with regret analysis in RDM must have the same technical, economical and temporal starting point. In the analysis performed for this thesis, the eight investment options were first all compared to each other in one group prior to splitting them up into the "furnace" and the "add on" group such as they are presented here. Since there is a 13-year gap between the posiible points of investment in the different options, the calculations on return on investment cannot be directly compared. A possible solution which allows for all options to be compared at once would be assuming that the investment decision takes place just prior to 2030. However, this would both answer a different question than the ones asked in the business case study in the first place ("Which option should the steel mill invest in [now]?" and "Is the integration of PtL technology in this steel mill a robust investment choice?") and it would make the analysis itself much less accurate, as DMs would most certainly hold more information and different beliefs about the future in 10 + years than they do today.

Splitting the investment options into two groups as done in the analysis performed here however essentially means that the investment decision is splitted into two separate decisions: i) will the investment made be one that requires changes to the furnace or not, ii) which one of the investments in the selected group of options is preferred? The two decisions can be made in whichever order but, essentially, a result of this analysis is that one choice is turned into two. In addition to altering the initial decision this also doubled the amount of analysises needed to present the results, and as alterations were made to the model, mistakes noticed and corrected and new decision options added (these were later discarded and are not part of the analysis presented in this thesis) -the number of calculations added up and were no longer easily handled in Excel. As an additional conclusion from this, other tools than Excel are recommended for creating the data needed in the statistical analysis.

Furthermore, the application of RDM requires much more engagement from the decision makers than a traditional techno-economical analysis does, and it is a learning process for both decision makers and analysts alike –most probably every time if consecutive use cases are not very similar. Executing new and challenging projects in a distributed team using conference calls to share information between the decision makers and the analysts as was done in the RDM analysis performed for this thesis, adds the the challenge of understanding the new analysis tool. The first workshop was held in Raahe with all participants present, and the difference between first workshop and the consecutive workshops and update conference calls was remarkable. A result of this the analysis is thus that when RDM is applied in teams that have not used the method before, workshops and update meetings should be held face-to-face.

The business case study performed with RDM in this thesis aims to answer the second research question:

> RQ2: Is the integration of PtL technology in Finnish steel production economically robust?

The question is examined by comparing a PtL investment option to other investment options that reduce emissions from blast furnace steel production, as reducing emissions from steel production is imperative meaning some technology for emission reduction most likely will be invested in before 2050.

The analysis shows that the PtL investment option for the Raahe steel mill in Finland is less robust than other options. The PtL option is in particular compared to the options of exchanging coke for bio coke and to the option of post combustion CCS, which are both solutions that do not involve changes to the furnace. The PtL option has higher costs and lower emission reduction potential than the bio coke option, and while the PC-CCS option requires a larger investment, this option too offers greater reduction in emissions than PtL as well as a better ratio of abatement- and investment cost. Due to the lack of a BAU case the options could not be compared both to each other and to a BAU case simultaneously, so instead the profitability of each case was examined separately. This analysis showed that the PtL option is a more costly choice than the BAU option in a majority of simulated futures. Due to its poor success the PtL option is not selected for vulnerability analysis: examining when an option fails is only interesting if the option looks good enough to be the selected solution in the first place.

The RDM analysis was not performed all the way through due to time limitations, meaning the final choice of a candidate strategy is not made –instead the analysis ends with a presentation of the trade-off analysis which would be presented to decision makers prior to their decision to either iterate further (i.e. test the success of a new strategy perhaps combined from the successful characteristics of other strategies) or to pick one investment option. The options recommended for comparison and trade-off analysis (in robustness, in the possibility of making large profits, in emissions abatement) are the Bio coke and PC CCS option if no changes to the furnace are made, and the OBF CCS and BF+ CCS options if changes are made to the furnace. Decision makers also have the chooice of combining cases to create new, more robust options and then iterate the analysis process.

Chapter 6.3 presents an extra analysis not part of the RDM analysis of the business case in order to examine the success factors of the PtL (PtMeOH) option and thus better understand why the option fails in relation to other investment options and the BAU case.

6.3 Sensitivity and “success analysis” of the PtMeOH strategy

In this chapter an extra analysis not part of the RDM analysis of the business case is presented: here the vulnerability analysis not performed for the PtL investment option is turned around to instead analyse the futures in which the PtL (PtMeOH) option was a success. The examination answers the question:

In what type of future would the PtMeOH investment be profitable?

First the price ranges for oxygen, methanol and electricity are changed manually to chart the price ranges within which the case breaks even. The oxygen and methanol price ranges are expanded while the electricity price range is reduced: the initial and adjusted price ranges are shown in Table 15 below.

Table 15. Altered price ranges in extra analysis of PtMeOH investment option

Variable	Old price range	New price range
Oxygen	20 – 70 €/t	20 – 90 €/t
Methanol	50 – 100 €/MWh	50 – 150 €/MWh
Electricity	10 – 130 €/MWh	10 – 100 €/MWh

The change in electricity price range does not affect the data mining results in R as much as the oxygen and methanol price range changes do, but a combination of the three new price ranges makes the case break even on average. Here it is important to remember what the price ranges mean; they are the definitions of *possible* futures and thus it is not said that the *average of all possible prices* is the most probable outcome. The profitability indicator (in the form of *Number of profitable outcomes / All possible outcomes*) is useful mainly as a way of checking if the option can be profitable at all, i.e. is worth investigating.

The same data mining procedure as in the data generation for the vulnerability analysis in the main RDM analysis is performed, but with the threshold defining "interesting futures" as those in which the case is profitable. The results are shown in Figure 33: the two most important factors in determining the success of the investment are the prices of electricity and methanol.

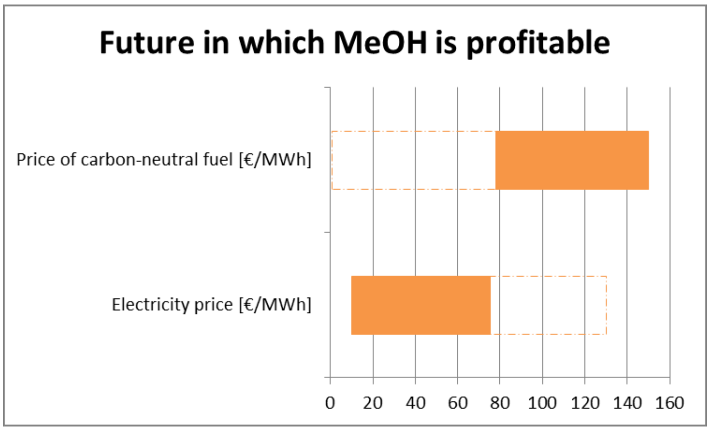

Figure 33. Definition of future type in which the MeOH case is profitable.

The results from the statistical analysis show that the PtMeOH case is very likey to be profitable in futures where the electricity price is below 75 €/MWh and the price of carbon-neutral methanol is higher than 80 €/MWh. Both of these price levels were part of the previously defined price ranges for the uncertain factors, and thus changing the price ranges has not changed this result, only the number of succeeding cases in proportion to the failing ones. This metric does, as previously discussed, not matter much in the RDM analysis: the important thing is that decision makers must believe it probable that these two price ranges will happen simultaneously.

What is particularly interesting is that the electricity and methanol prices are coupled – both in reality (it is probable that synthetic methanol which needs large amounts of electricity in production will be more expensive when electricity is expensive and the other way around) and in the model employed here- and this reflects the fact that both decision makers and analysts taking part in this study did not find it probable that the electricity price would be low and the methanol price high simultaneously. The analysis must next concern whether the new price ranges used in the sensitivity analysis combined with the obtained threshold values for the electricity and methanol price together represent "high" methanol prices and "low" electricity prices". This analysis is beyond the scope of this thesis but the result which can be obtained from the "success analysis" is that the PtMeOH case is, with high confidence, profitable when the electricity price is between 10 and 75 €/MWh and the price of carbon-neutral methanol is between 80 and 150 €/MWh.

7 Discussion

7.1 Research questions and thesis results

Research questions 1 and 2 have successfully been answered in chapter 5 and in chapter 6.2.5 respectively. Research question 3 is answered here following a summary of the key insights for questions 1 and 2.

7.1.1 RQ1: Comparison of 100% RES scenarios

The examination of four different 100% RES scenarios or scenario groups[73] in chapters 3 and 4 rendered that the energy system design in a 100% RES system depends greatly on the scope of the future scenario; if reducing emissions from society as a whole is the objective, as opposed to designing a 100% RES energy system, then the industry sector's need for non-fossil based raw material will alter the demand for carbon neutral carbohydrates. In the German THGND scenario, which aims to reduce emissions from society by 95% in comparison to 1990 levels, synthetic fuel and gas produced with a PtG/PtL process make up as much as 65% of final energy consumption –and in addition to this industry uses almost a 10% share of TPES (282 TWh out of approximately 3000TWh) as raw material. The Danish scenario does not allocate syngas for use as raw material in industry, and the share of methanol and DME out of TPES is 17%, comparable to the 10-15% share obtained in the TIMES-VTT modelling effort in the Finnish NCE scenario which also assumed syngas is consumed as fuel only.

The comparison found that the sectors transport, heat and electricity were coupled in all scenarios, but that the level of integration varied. All 100% renewable energy systems were higly electrified and in three out of four scenarios examined TPES declined by an order of magnitude of 20% between 2010 and 2050 or more[74]. Also final energy consumption declined in all scenarios, and the relation of final energy to TPES in 2050 compared to that of today depends on the amount of synthetic fuel produced as the conversion to PtG/PtL includes large energy losses. The factors driving introduction of PtG/PtL technology in the energy system were found to differ slightly between scenarios: in THGND the role of PtG includes the balancing of IRES, while modelling with TIMES-VTT showed that the demand for energy intensive fuel alone drives the ivestment if PtG. PtG or PtL technology is present in all scenarios except for that of Sweden, in which biofuels power the transport sector and biomass is used also for the production of heat and electricity, assumeably in CHP plants.

The assumptions on biomass availability were found to vary greatly; in the Finnish,

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[73] in NCE and in Fyra Framtider there are more than one 100% RES scenario withing the same research project and/or modelling effort. These are then discussed as a group, citing results from all scenarios and any major differences between them.

[74] The Swedish scenario does not report TPES figures.

Danish and Swedish scenarios biomass dependency is high[75] while the German scenario assumes virtually no use of biomass. Assumptions made on biomass availability were found to affect the role of PtG in the energy system: The Danish scenario Energy Vision is an iteration of previous 100% renewable energy system analysises, and the downward adjustment of assumed biomass availability increased the amount of synthetic gas (methane and DME) used by the transport sector[76]. The Finnsih NCE modelling done in TIMES-VTT showed that PtG has a strong foothold in circumstances with low biomass availability even with relatively high PtG technology prices, and comparison of the roles of PtG and biomass respectively in the four scenarios support this finding. The great variations in assessment of sustainably availabile biomass amounts were found to be a source of large uncertainty.

Finally, common for all the scenarios was that transport and industry are the hardest sectors to decarbonise; in the scenarios studied here transport was first electrified to varying extent after which biofuels or synthetic gaseous or liquid fuels were employed. In the German and Finnsih scenario syngas was also used as an energy source in the industry sector, and in the German scenario process related emissions were reduced from industry by utilising synthetic methane as raw material instead of fossil carbohydrates. Significant reductions in national GHG emissions are in all the studied scenarios achieved only by introducing measures in all GHG emitting sectors.

7.1.2 RQ2: Robustness of PtL investment in Finnish steel production

The second research question concernes whether the integration of PtL technology in Finnish steel production is economically robust, and was studied by comparing a PtL investment option to other investment options that reduce emissions from blast furnace steel production.

In the RDM analysis 5000 futures were simulated based on wide price ranges for all commodities that were assessed to affect the operations and performance of the steel mill. The business case study performed with RDM found that the PtL investment option is not economically robust; i.e. in most of the simulated futures the option fares badly either in relation to the BAU case or in relation to the other emission abatement technologies –or in relation to both. To further examine why this is, an extra analysis was performed separately from the RDM analysis of the business case itself. The “success analysis” presented in chapter 6.3 finds that the PtMeOH case is likey to be profitable in futures where the electricity price is below 75 €/MWh and the price of carbon-neutral methanol is higher than 80 €/MWh. With the price ranges given by decision makers in this thesis, this condition translates to “low electricity price and high methanol price” –which is considered a higly unlikely scenario du to the price dependency between the two commodities. The discussion of the adequacy of the price ranges and of a more exact relation between methanol and electricity prices is beyond the scope of this thesis.

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[75] Again, the Swedish scenario does not report TPES figures but by assessment biomass dependency in the Swedish scenarios is at least 30%.

[76] In terms of energy and in relation to the numbers presented in IDA Climate Plan (IDA, 2009a) –in which transport was powered by hydrogen.

7.1.3 RQ3: Insights from the application of RDM on a PtL business case in a high RES future

The third research question in this thesis concerns the adequacy of RDM as a tool for supporting a PtL investment decision under deep uncertainty. The question is answered here in the form of a discussion of findings from the application of RDM in this thesis.

> RQ3: What are the insights of applying RDM to an existing business case concerning PtL investment in steel industries in a high RES future?

The main insight from the business case study with RDM is that the application of RDM highlights new perspectives of an investment decision: a concrete example is the Bio coke investment option, which in a simulation of profitability in the "average future"[77] is far less profitable than the PC CCS option –but in the context of emphasizing robustness to future uncertainty it is in the end a very viable option. The analysis centers around the fact that the future is uncertain and unknown, acting as a constant reminder of this for decision makers who, when applying commonly utilised so-called Agree-on-assumptions approaches to decision support, might be inclined to only look for best performers in future simulations. Applying RDM to the business case concerning PtL investment in steel industries in a 100% RES future provides a deeper understanding of risks associated with options that perform well in future types we feel are probable.

The RDM method is data driven and the information attained from the analysis is based on statistical analysis of investment option performance in thousands of simulated futures; the variables which were found to be of highest statistical significance for the failure of plans matched those chosen in earlier analysises of the same (or part of the same) business case (see Onarheim et al., (2015; 2016) for earlier analysises). This result verifies the previously made assumptions as well as highlights the fact that with RDM, the variables chosen to depict the type of future in which a case fares badly are always data based, reducing the risk of human bias affecting the analysis.

The realisation that an implicitly modelled business as usual (BAU) case is essential for the clarity and brevity of the RDM analysis essentially indicates that the benefits reaped from an analysis with RDM should in general be greater than those achieved here. At it's best, the RDM analysis is clear, interactive and informative –but as this particular application shows, it can be contradictory and hard to follow if analysts and decision makers alike are new to the method or to the process of applying it. In relation to this, it must be stated that the application of RDM in this particular business case was challenging as a whole. In addition to the inexperience of the main analyst, the author, this was due to the low compatibility of the business case at hand with RDM. The eight investment options not being fully comparable to each other coupled with the absence of a BAU case in the model used as a source of technical data are what made the application of RDM challenging –a key insight is thus that case compatibility with RDM is recommended prior to beginning an analysis.

The value ranges selected for the variables defining the possible future space were found to paramountly affect the profitability indicator presented in Figure 24. This indi-

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[77] Here a future defined by the mean of each price range given is meant.

cator is a presentation of the percentage of futures in which options are profitable versus the percentage in which they are not. Such an indicator thus implicitly assumes that all of the simulated futures are equally profitable, which in itself is a contradiction of one of the core ideas in RDM: we do not know the profitability distribution of future scenarios. This finding suggests that the visualisation in itself is not a useful one. Furthermore, the addition of a run-only-in-profitable-years –option only to a part of the investment options feels problematic when evaluating the analysis results; this creates an uneven playing field and thus makes the here presented comparison of different options less true to reality.

The possibility of introducing such options as the run-only-in-profitable-years –option or the option of step-wise investment in different technologies however emphasises the benefits of performing a business case analysis with RDM. The method encourages portfolio-thinking by highlighting the vulnerabilities of different options: when DMs are familiar with the risks of an investment option it is possible to hedge against this by combinating different investment options to create new ones or, as in the case of step-wise investment, chosing an option that allows add-on investments later. An example of this in the context of the business case analysed here is forst investing in the Bio coke –option as this includes the option of later investing in either one of the PtMeOH or the PC CCS options.

An essential feature of an analysis performed with RDM was found to be that it requires far more time and engagement of the decision makers. This is itself is natural since the method differs from traditional techno-economical analysises in that it seeks to inform the deliberations of decion makers instead of providing a fixed answer: if discussion and deliberation is sought then the process will be more time consuming that one where an answer is simply calculated. However, the extra time consumed for understanding, following and participating in an analysis performed with RDM should be well worth it, given the deeper understanding of risks associated with the decision and the broadened possibilities when making a decision: the method inspires DMs to think of options like step-wise investment.

All in all, if the time is taken to understand and to apply RDM to a decision problem with decision options that are comparable between themselves (and a BAU case is described in the same way as other decision options, *if it is an option in the decision problem*) –then the RDM method offers a deeper understanding of the risks associated with different choices. The concept of deep uncertainty is highly relevant in a business case such as the one analysed here, since options include new technologies that have yet to be proven on a large scale as well as politically accepted (in particular CCS, but the sustainability of bio coke is also a central question). The statistical analysis provides unbiased information on which factors affect the decision most and in what price range of these decision options are vulnerable. This opens up the possibility for DMs to think more in a “this is a good option as long as the future does not look like X” way –and then contemplate the probability of X and their willingness to take that risk, than in a “this option fares best in the future, as simulated by someone else” type of way.

7.1.4 Implications of thesis results

The future renewable energy system scenario comparison in the first part of this thesis yields that the design of e 100% RES energy system is highly dependent on the intended scope of emissions reductions: the mitigation of GHG emissions from industry seems to increase the importance of PtG/PtL technology. Another factor greatly affecting the future energy system design is the assumptions made regarding availability of biomass for use in energy production. The two hardest sectors to decarbonise seem to be transport and industry, and no other solution for GHG neutral carbohydrates to be used as raw material in industry is suggested than PtG technology (in particular the production of methane). Emissions from certain industrial processes such a steel production can be reduced by developing completely new routes for production, thus not requiring CCS or CCU (carbon capture and utilisation; as in the PtMeOH option in the business case presented in this thesis).

The main conclusion to be drawn from comparing the renewable future energy system scenarios of four countries is that uncertainty regarding energy sources used and the shares of these –i.e. energy system design –is high. The redesign of energy systems to be 100% renewable and to possibly also accommodate for technical solutions that reduce emissions from non-energy sectors means handling a transformative change. Uncertainties abound and for this reason, a decision support tool such as Robust Decision Making that emphasises the role of the decision maker as the one assessing if a certain type of future seems likely enough to hedge against in a certain decision, can be useful when evaluating investments that facilitate 100% RES energy systems.

The results of the business case in Finnsh steel industries evaluated here with RDM implicate that investment in PtG technology is not a robust decision. As 5000 futures with “all imaginable” (as imagined by the decision makers in this case) commodity prices are simulated, the implication of this result really is that CCS technology is a cheaper route to reducing emissions from steel production than PtL technology is. The only thing that could change this (i.e. which was not simulated) is if investment costs for PtL came down by more than 33% (i.e. a larger reduction that that was not modelled: not saying that such a reduction would make the PtMeOH option more robust that CCS). Again, the uncertainty surrounding such decisions is brought into light by the technical detail that the electrolyser proposed for use in this analysis is larger than most today existing electrolysers in the world –and almost three times as large as the largest one using ater to produce hydrogen[78].

When contemplating the implications of the results from the two different parts of this thesis, the strongest conclusion to de drawn is still that uncertainty is enormous: in a business case where political uncertainty of CCS is taken into account still suggests that it is the most robust way to go, while only one out of four future scenarios allow the storage of carbon underground. Thus, a thesis result is that the application of RDM in decisions concerning future renewable energy systems is recommended to account for these large uncertainties. This recommendation stands even though another result of the thesis is that the RDM analysis can be complicated and results thereof unclear if performed for cases not quite compatible with the tool or by analysits and DMs not familiar with the process, such as was the case in this thesis.

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[78] The http://www.h2future-project.eu/ project electrolyser is 6 MW; hydrogen can later be synthesised to make e.g. methanol.

7.2 Threats to validity

No formal selection criteria were used in the performing of the literature review presented in the first part of this thesis; instead, scenarios were selected based on the author's assessment of comparability and of the inclusion of the description of a design for a 100% RES energy system. The underlying modelling efforts and previous research is not documented in all scenarios, meaning the unveiling of these included both further litterature review, corespondence with report authors and own conclusions based on the information at hand. This poses a threat to the validity of the here provided description of the research providing the base for the four scenarios.

A threat to the validity of the results obtained in the business case study is the inexperience of the head analysit, the author, with RDM. Also, the poor compatibility of the business case with RDM poses a threat to results obtained wiht RDM, as well as the use of technical data researched and calculated by other researchers than those acting as analysts in the RDM test performed here. By poor compatibility the lack of a BAU case modelled in a similar way as the other decision options is meant; if one of the options, in this case the ”invest in none of the options available” is not modelled (or as in this case the other options are modelled in relation to it) –then this option cannot easily be compared to the others. A similar compatibility issue arises from the fact that the examined busines case includes both investment decisons that can be made today and investment decisions that include changes to the furnace and can be made at the earliest in 2030.

A technical problem realised by the analysist too late was that keeping the zero investment assumption for the bio coke option made in previous research efforts actually renders this option incomparable with the others, as it is strictly speaking then not an investment. Combined with the added feature of designing some of the options so that they can be run in years when it is profitable to do so without having to run in years when it is not, the bio coke investment option becomes even less comparable to other options since it essentially cannot incur losses; the investment is zero and in years when it would not be profitable to buy bio coke to reduce emissions this is not done. The result is a super-option which can only bring profits and thus a) sqewes the comparison of investment options and b) is not a realistic rendering of the actual case, as some transaction costs must incur from switching between coal and bio coke.

In general, the added option to run only in profitable years is problematic, since it was added only to some cases, again sqewing the comparison. The comparison was also challenged by the split of options into two groups based on their type: options that include and options that do not include changes to the furnace. This step was felt neccessary by analysts due to the different time window of investment, but it does make the analysis far more complicated than it would need to be had the options been readily comparable between themselves. This choice essentially transforms one desicion into two, increasing the risks of the process being hard to follow and understand.

On the technical side, a threat to validity is the novelty of large-scale electrolyser technology; assessing the investment cost[79] of an electrolyser larger than the largest existing one is highly challenging. Similarly, in the model constructed for the RDM analysis the electricity and methanol prices are linked by using the same stochasitc variable to gen-

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[79] Done in previous research by VTT researchers Onarheim, Tsupari, Kärki and Arasto but used here

erate the prices in each simulated year –but the price ranges were not compared meaning a ”high” electricity price was not cross-checked to be in the same order of magnitude as a ”high” methanol price. As described in chapter 6.3, this fact could affect the performance of the PtMeOH case.

7.3 Future research

Recommendations for future research first and foremost include the application of RDM to a similar business case, but one that is compatible with RDM on the points described here in chapters 6.2.5, 7.1.3 and 7.1.4. The most important compatibility factor is that options are modelled in the same way and trule comparable; can they all be choden at the same time, with the same technical starting point and in the same order? If a similar case including a PtL option is analysed, then the further examination of the investment costs of the electrolyser could be of benefit. Furthermore, it is recommended that the electricity and methanol prices are linked in a relation that mirros that of electricity consumption in methanol production, as opposed to the high level “high electricity price means high methanol price” utilised here.

The perceived link between biomass availability and the role of PtG/PtL technology needs further examination; are there other energy intensive fuels that could replace biofuels or are there perhaps novel technologies that will render such liquid or gaseous fuels unnecessary? Further research is also needed regarding the indicative finding that PtG/PtL technology is more prominent in scenarios that aim to abate emissions from non-energy sectors in addition to designing a 100% RES energy system. An interesting topic for research would be to compare scenarios that only focus on 100% RES energy system design between each other and similarly do so for senarios that abate all GHG emissions from society –and compare the average shares of PtG/PtL in total primary energy supply.

8 Conclusion

In this thesis three future renewable energy system scenarios were compared to the Finnsih NCE future scenarios to compare the designs of future 100% renewable energy systems. In addition, a business case study was performed for the integration of PtL technology in a Finnsih steel production facility using the Robust Decision Making tool. The three research questions concern the differences in 100% RES energy system design, the success of the PtL investment option in the business case as well as the insights gained from applying RDM to a business case concerning the investment in GHG abatement technology, which is presumably highly dependent on the energy system design.

The future renewable energy system scenario comparison yields that all four scenarios include a higher electrification of the energy system as well as coupling of the sectors electricity, heating and transport. Only the Swedish scenario does not have a highly electrified transport sector and instead uses biofuels to power mobility. Other scenarios use either only synthetic fuel in addition to electricity in the transport sector, or a combination of synthetic fuel and biofuel; in the NCE scenario biofuel and synthetic fuel shares are approximately half and half of the energy needs of transport not suitable for electrification, while the Danish scenario uses half synthetic fuel and half biofuel upgraded with synthesised hydrogen. The most important energy sources for the production of electricity include solar PV, wind power and hydropower in all scenarios, with shares varying depending mainly on hydropower resources.

The largest difference between scenarios is the varying objectives; the Finnish and Swedish scenarios examined in this thesis are centered on designing a 100% renewable energy system, while the Dansih and German scenarios are demonstrations of the design of a GHG neutral society. This difference in starting point affects the level of integration of non-energy sectors with the energy system and thus the energy system design: a GHG emission free industry sector requires GHG neutral carbohydrates to be used as raw material, and in the German THGND scenario the production of these is an important part of the energy system. In addition to this structural difference, the most important differences in energy system design include the assumptions regarding biomass availability, the inclusion of CCS and the role of PtG/PtL: in THGND PtG/PtL is the key to sector coupling and a stabiliser if IRES while the main drivers for investment in PtG in NCE is the transport- and industry sectors’ need for energy intensive fuel.

Upon inspection, it is noted that the role of PtG/PtL technology in the future energy systems seems to depend on whether or not emission abatement from other sectors – most importantly industry – is an objective in the scenario or not. Biomass availability assumptions furthermore seem to affect the role of PtG/PtL technology prominence in the energy system, but this finding needs to be researched further. A result is also that the assumptions for biomass availability vary greatly; the German scenario assumes no use at all while the Finnish and Swedish scenarios have energy systems that are highly dependent on biomass. All in all, future energy system scenarios and in particular future 100% RES scenarios that are by definition of transformative nature are subject to large uncertainties and should be treated as such.

With a new energy system design come new technologies, services and products and thus numerous investment decisions to be made under deep uncertainty. Therefore, the Robust Decision Making method is utilised when avaluating a PtL business case for the Finnsih steel industry; RDM is an agree-upon-decisions approach to decision making that is designed to evaluate the success of decision options in thousands of possible futures instead of choosing between options that are successful in one or a few modelled futures. The business case study seeks to answer the two last research questions: whether investment in PtL in this case is a robust decision and what the insigths and benefits are from utilising RDM in the analysis as opposed to traditional agree-upon-assumptions approaches to decision support.

The business case in Finnsh steel industries evaluated with RDM shows that a robust decision for the Raahe steel plant would be either investing in post combustion CCS or in the use of bio coke instead of fossil coke –if changes are made now and do not include changes to the furnace. If changes to the furnace are preferred, then the OBF and BF+ route both have benefits –and it is more robust to invest in either one of them with CCS included that without it. The result clearly shows that investment in PtG technology is not a robust decision. RDM focuses the decision makers′ attention on the relevant question: Which of the available plans of action is most robust to surprises? A robust decision is one that fares well in as many different futures as possible, but is not neccessarily the best one in any of them.

The application of RDM in this thesis seeks to engage the decision makers to deliberate over the trade-offs (in robustness, in the possibility of making large profits, in emissions abatement) instead of focusing on the simulated future performance of investment options. This in itself is in fact a new way of thinking about decisions; in choosing between options we are often prone to look only for the best performers, forgetting that any simulated future performance is dependent on the assumptions made about that future. The use of RDM thus brings added value in terms of a deeper understanding of risks connected to investment options. The statistical analysis that is part of RDM offers answers to which factors are cruical for the failure or success of a strategy, highlighting what type of future conditions might realise the risks related to an investment option.

In light of the deep uncertainties related to future energy system design revealed in the scenario comparison in this thesis, the use of RDM to evaluate such business cases as the one presented here is justified. The method was found to emphasise the role of the decision maker as the one who understands the vastly different possible future outcomes and based on this decides which futures to hedge against in making an investment decision. RDM encourages to portfolio thinking by highlighting the risks of different options: options can be combined to create more robust options –and this type of thinking should benefit decisions made under deep uncertainty. Applying RDM however requires far more time and commitment than a normal cost-benefit analysis and if performed by inexperienced analysits or applied to a case that is not fully compatible with the method, results can be unclear and complicated to follow.

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List of appendixes

Appendix I

Business cases studied in NCE

The cases which have been explored and analysed within Neo-Carbon form the basis for the test done with the RDM tool in this thesis. The cases which had been explored and reported on during the 1st phase of the Neo-carbon project (June 2014 – June 2016) are described shortly here.

Table 16. Business Cases for the energy sector

Energy sector				
Business Case	**Application**	**Content**	**Profitability**	**Notable**
Integration of PtX with biomass fired CHP plant (gasoline production by P2MtG route)	Electricity and heat production Transport fuel produced	Steam and process heat from PtX are utilised as district heating, O_2 used to increase production in peak hours. Electrolysis when electricity prices low.	Payback time around 4 – 10 years	Integrates transportation fuel production into CHP plant, making use of three byproducts as well as both low and high electricity prices.
CHP PtG and PtH options	Electricity and heat production	Replacing of NG as fuel in the plant. IPSEPro model.	n/a	CHP plant uses synthetic gas insp
PtH_2 concepts	Electricity, heat and transport C-neutral alternative to NG H_2 produced in a less carbon-intensive way.	H_2 can be fed to the NG network (up to 5% saturation, potential of 8000 TWh globally) or PtH_2 could replace H_2 production with SMR[80] (and save energy).	Payback time around 3 – 4 years	n/a
PtG integration with NG production sites	Electricity, heat and transport	Utilisation of the CO_2 that is removed from raw NG to produce SNG with H_2 produced on-site with solar or wind power.	n/a Still in progress	n/a
Production of FT[81]-liquid fuels using solid oxide electrolyser cells (SOEC)	Transport fuel production	Combination of SOEC and FT plant to produce naphtha and diesel. Recycling of	Unfeasible with current prices.	

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[80] Steam Methane Reforming, a form of producing hydrogen often used in oil refining.

[81] FT = Fisher Tropsch

		heat.		
PtX applied to Brazilian sugarcane biorefineries	Transport fuel production, Produces SNG as well as heat as a by product.	CO_2 is captured and synthesized with H_2 produced with electrolysis. Increses biomass availability by making better use of sugarcane carbon content.	Levelised cost of fuel varies between 49 and 156 €/MWh depending amongst other things on electricity price.	Utilises PtX to increase use of biomass carbon content.
Hydrogen enhanced synthetic biofuels	Transport fuel production Biofuel and heat are produced.	Hydrogen is produced with RES-e and combined with the proportion of carbon normally left unused in biomass, thus boosting biofuel production.	Production costs range from 0.6 to 1.5 €/L_{geq} depending on the end product (SNG, methanol or gasoline). (geq = gasoline equivalent)	Makes use of residue biomass not otherwise used in biofuel production, thus increasing biomass availability.
PtG business opportunities in households	Households SNG and heat.	Small-scale PtSNG. Would produce SNG and heat, using RES-e.	Not yet economically feasible.	Produces SNG, utilises excess heat.

Table 17. Business cases for the industry sector, the business case presented in this thesis highlighted in green.

Industry sector				
Business Case	**Sector**	**Content**	**Profitability**	**Notable**
Integration options of PtX on existing steel mill based on BF (Methanol and gasoline production)	Iron & steel industry	Side product oxygen is used in steel production and the process gas CO can be used for synthetisation of fuels (replacing CO_2).	Payback time for the Swedish market 4 – 10 years, for the Finnish market 12 – 26 years	n/a
Use of H_2 in iron pellet production	Iron & steel industry	Replacement of natural gas by hydrogen produced from water electrolysis. *Emission reduction 30%.*	n/a Still in progress	n/a
PtG in the cement industry	Cement industry	Hydrogen is used to substitute part of the coal as energy source.	“Hardly profitable at the moment”	n/a
Light olefins from electricity and CO_2 via synthetic methanol	Chemical industry, plastics	The combination of synthyetic methanol manufacture with MTO technology would produce ethylene	Not profitable with today’s electricity market price scenarios. Levelised production	Focuses on end product, replaces coal in plastics. Not energy storage.

		and propylene.	cost 2000 €/t.	
PtX integrated with pulp mills (Methanol and MtG)	Forest industry	CO2 is captured by lime pre-calcination and oxygen is utilised on site.	Payback time 5 – 6 years for MeOH and 10 – 16 for MtG	n/a
Integration of electrolysis in a pulp mill process	Forest industry	Excess electricity from the mill is used for electrolysis and the produced hydrogen replaced fossil fuels in the lime kiln.[82]	Depends on the prices of the substituted fossil fuels, and on the electricity price since electricity is no longer sold.	n/a

Table 18. Business cases for the waste management sector

Waste management sector				
Business Case	**Sector**	**Content**	**Profitability**	**Notable**
PtG integrated to wastewater treatment (SNG produced)	Waste management	Oxygen, ozone, heat and methanol produced in PtG can all be utilised on site. Electricity production with wind or solar.	Payback time 10 – 15 years.	n/a

Table 19. Business cases for the agriculture sector

LULUCF sector				
Business Case	**Sector**	**Content**	**Profitability**	**Notable**
Fertilisers from air and water with low-carbon electricity	Agriculture Less carbon instensive fertilisers.	Hydrogen for ammonia production from electrolysis instead of from NG. Nitrogen from air or water	Becomes economically viable when long-term RES-e prices are below 30 $/MWh.	Utilises electrolysis to produce less carbon instensive fertilisers.

Source for all above tables: unpublished VTT internal working paper by Kärki & Vakkilainen, 2016

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[82] oxygen used for mill operations, such as generation of bleaching chemicals and effluent treatment.

Appendix II

Basic steel production process and base case scenario

This process description is taken as such straight from (Onarheim & Garðarsdòttir, 2015) where several of the investment options analysed in this thesis are presented.

Authors: Kristin Onarheim and Antti Arasto (VTT Technical Research Centre of Finland, Ltd.)

Process overview

Steel is mainly produced in a primary steelmaking process where iron is extracted from raw iron ore. The principle of extraction is to combust the combustible fractions of the ore and simultaneously smelt the metallic fractions in a blast furnace (BF). The extracted pig iron is further refined in a basic oxygen furnace (BOF) and blended to different steel grades.

The BF + BOF route uses carbon as a reducing agent in the blast furnace for transforming raw iron ore into pig iron alloy (iron making) and further into low-carbon steel. A simplified schematic illustration of the typical integrated iron and steel production process is shown in Figure A.

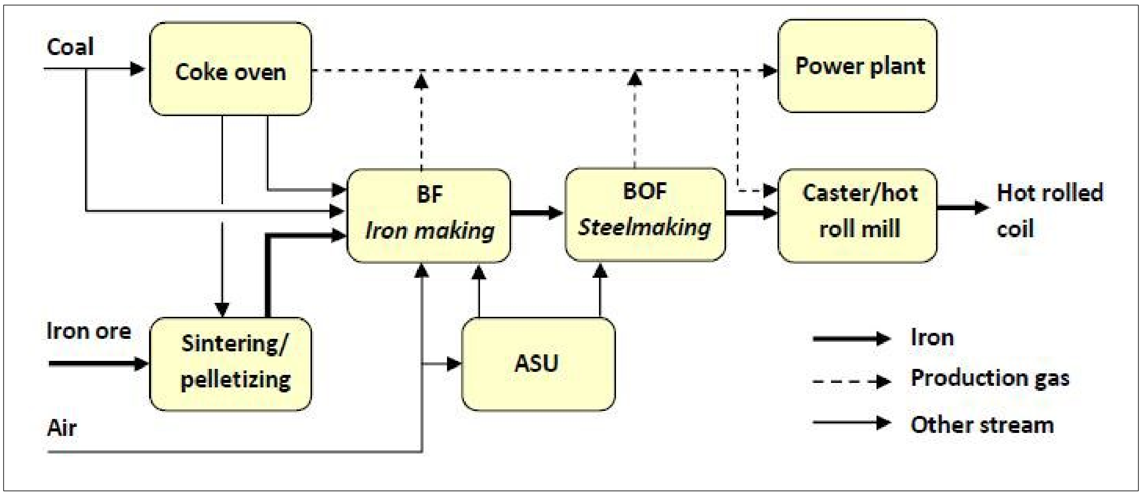

Figure A. Simplified block flow diagram of an integrated iron and steel production process based on blast furnace and basic oxygen furnace route via pig iron. Reproduced from [1].

Coal or lignite is pyrolyzed into coke in a coke oven consisting of tall, narrow oven chambers at about 1 000°C. The pyrolysis process, also known as dry distillation, drives off the volatile matters from the coal in an oxygen-free environment to result in pure carbon. The conversion rate is typically 75% coke and 25% gas. The heat required for the coking process is usually provided by the coke gases themselves after they have been cleaned, and in some cases partly also by blast furnace gases. Coke oven gas can also be used in the blast furnace [2,3].

The produced coke is used in the sintering or pelletizing process to agglomerate iron ore (Fe_2O_3 or Fe_33O_4) into small clusters. Iron ore typically consists of 60–65 wt-% iron (Fe). Coke is also used as a reducing agent and fuel in the blast furnace [2,3].

Iron agglomerates, or sinters, are charged at the top of the blast furnace together with coke, flux (e.g. limestone) and sometimes also lump ore at alternating frequencies. Sinters typically contain 55 – 60 wt-% pure iron. Also pulverized coal can be added to the blast furnace instead of coke [2]. In addition, hot air, or sometimes recycled flue gas, is added to the blast furnace. At the top of the blast furnace the feed is dried by the hot gases blowing through the furnace. As the feed travels downwards, the temperature increases. As a consequence, the carbon is burnt in a reducing reaction and the increasing heat causes the iron ore to melt. The combustion process takes place in the freeboard above the furnace bottom and the molten iron (also called pig iron) drips to the bottom of the vessel. The average temperature of the blast furnace is 1 500°C [2].

Besides melting the metal fractions in the iron ore, another important task for the blast furnace is to get rid of the oxygen in the iron ore. The additional coke fed directly to the blast furnace ensures an efficient reduction reaction producing mainly carbon monoxide, which again reduces the iron oxides to iron. In order to produce one ton of pig iron approximately 1.5 ton of iron ore and 450 kg of coke is needed [2].

The pig iron (hot metal, HM) produced in the blast furnace still contains some carbon after the reduction process, typically 4–4.5 wt-% [2]. This residual carbon makes the metal fragile and breakable and needs to be removed.

The top gas from the blast furnace exits at about 2–3 bar and contains +/- 20 vol-% CO_2. Gas from the blast furnace is typically used as fuel for the power plant and the hot stoves. As part of the fuel preparation of the gas, dust, and possibly also sulfur components, are removed in a wet scrubber and the gas is expanded in a turbine train [1,4].

The carbon enriched pig iron from the blast furnace is processed further in the basic oxygen furnace (BOF), also called converter. In addition to the pig iron usually also metal scrap is added to the BOF. The ratio is about 4:1 [2]. In the BOF a jet of almost pure oxygen is blown through the charge, removing most of the residual carbon and impurities in a range of reducing reactions. After the BOF the molten steel tapped and in some cases other alloys are added before it is casted and usually rolled [2].

The combustion of coke oven gases and blast furnace gases together with hot stove flue gases in the power plant result in relatively high CO_2 emissions. The layout of an integrated steel mill today also shows that the CO_2 emissions are distributed over several emission points on site, and this has to be taken into consideration when developing carbon capture solutions for the steel industry.

Figure B shows a schematic description of a conventional blast furnace with gas boilder plant such as in the base case in the business case in this thesis. The annual production rate is 2.6 Mt of hot metal. The blast furnace is supplied with coal, pulverized coal injection (PCI) and enriched oxygen blast. The blast furnace top gas is utilised on site for firing the hot stoves in order to heat up the hot blast for the blast furnace and in the power plant in order to produce power and heat. The power plant consists of a gas boiler and a steam cycle with steam extraction from the steam turbine to supply the mill with electricity and process steam. The mixture of fuel gases utilised in the gas boiler consists of blast furnace top gas, coke oven off-gas and converter off-gas. The steam cycle power production process typically has an efficiency of maximum 29% [14]. In addition to electricity, district heat for the surrounding premises is also produced in the power plant. The oxygen content in the blast furnace feed is 21-29 mol-%. The calorific value of the conventional blast furnace top gas is rather low, typically between 3-4 MJ/Nm_3 while the coke rate is 300-360 kg/Mt HM [14]. The heating value of the base case blast furnace top gas was 2.7 MJ/kg. The low heating value is mainly a consequence of the high concentration of nitrogen (45.1 vol-%) and CO_2 (22.1 vol-%). The base case serves as a comparison to the cases investigated in this work. A simplified flow sheet of the base case is illustrated in Figure B.

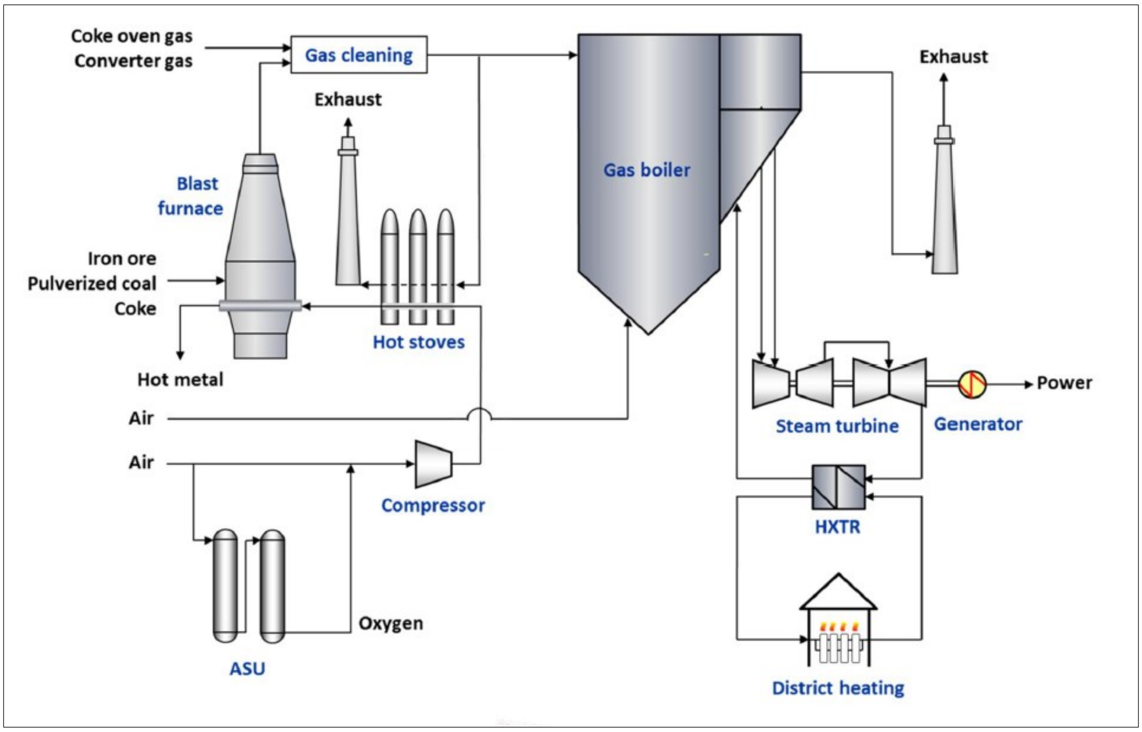

Figure B. conventional blast furnace with gas boilder plant.

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[1] Kuramochi, T.; Ramírez, A.; Turkenburg, T.; Faaji, A. 2012. *Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes*. Progress in Energy and Combustion Science **38**, pp. 87-112. doi:10.1016/j.pecs.2011.05.001
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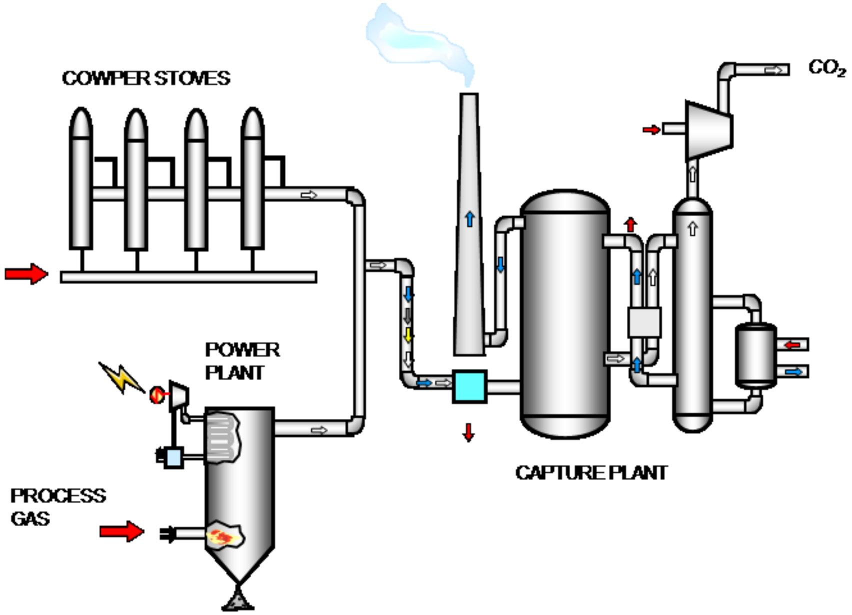
Appendix III

Proposed emission reducing measures

a) Post-Combustion CCS



The Post-combustion carbon capture and storage investment mitigates emissions from the largest CO_2 sources; the power plant and hot stoves flue gases. Achieved emission reductions are as high as 50 – 75% (in this case 2.9 Mt/a) and the case studied here is conventional amine-based post combustion capture with an advanced solvent. Different solvents were evaluated in the research by Arasto et al. and the data and assumptions regarding this investment option were obtained from (Arasto, 2015) (article I). Because the CCS unit captures flue gases which would otherwise be let into the atmosphere it is added on top of the existing steel mill processes and thus does not require changes to the furnace or any other major part of the mill. The unit requires space at the mill site though, and it consumes large quantities of electricity.

O&M costs for PC-CCS are here assessed (in accoprdance with Arasto 2015) to be higher than those of other CCS-options studied in this thesis due to the advanced solvent which is circulated but needs to be refilled regularly. See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.

b) Oxygen Blast Furnace

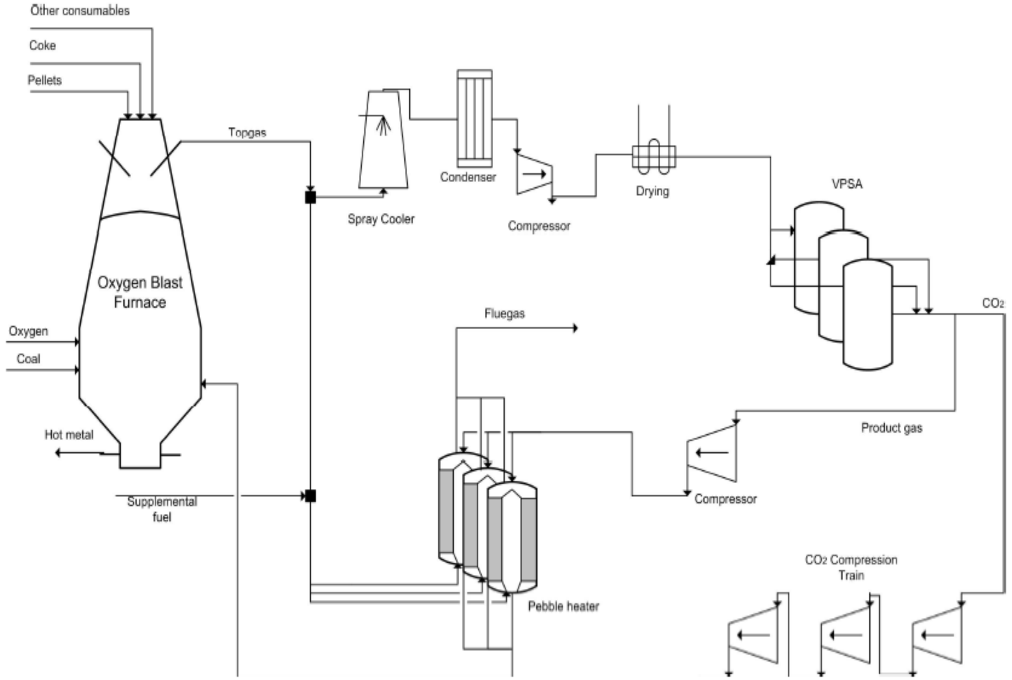


Figure from (Arasto, 2015) page 26

The Oxygen Blast Furnace concept entails replacing the furnaces with oxygen blast furnaces and the use of pure oxygen for hot blast instead of purified air. The OBF concept recycles the top gas from the oxygen blast furnace and this enables less energy-intensive CO_2 separation. The process uses LNG and more electricity than the base case while reducing coke consumption and CO_2 emissions are reduced by around 35% (1.2 Mt/a in this case). The OBF concept is documented in (Arasto, 2015).

c) Oxygen Blast Furnace with CCS

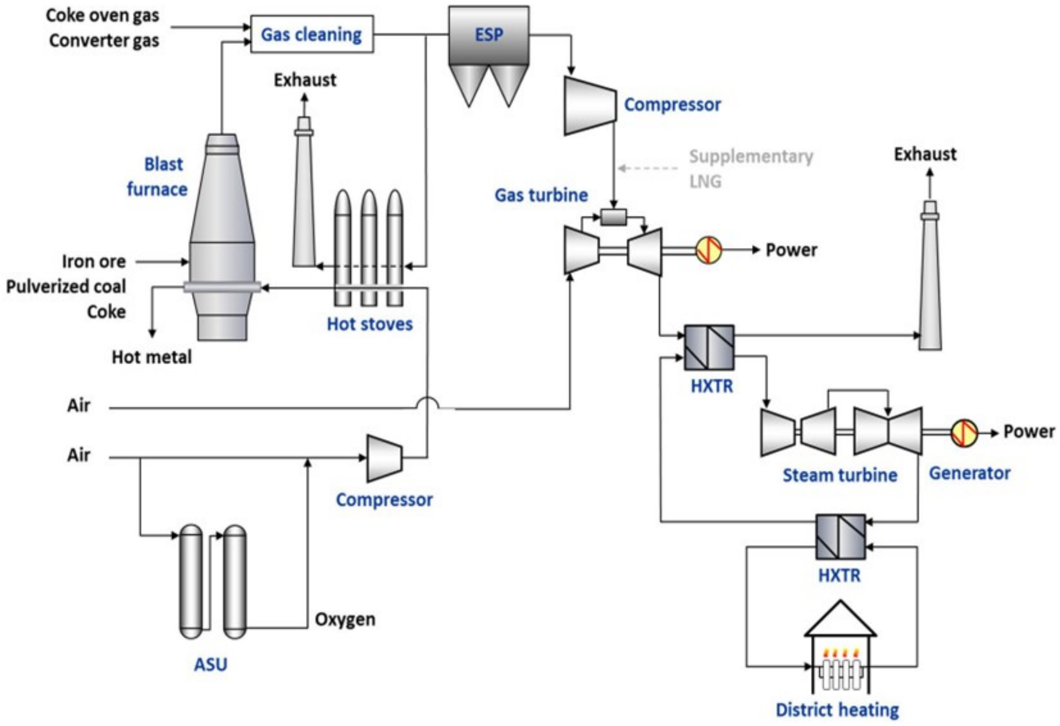
A carbon capture and storage option can be added to the OBF concept which further reduces the carbon dioxide emissions. Vacuum pressure swing adsorption (VPSA) was the chosen CO_2 separation technology in this study as per (Arasto, 2015) and emissions are reduced by as much as 70% in the OBF CCS investment case (2.6 Mt/a reduction in this case).

See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.

d) Increased PCI and GTCC (BF Plus)

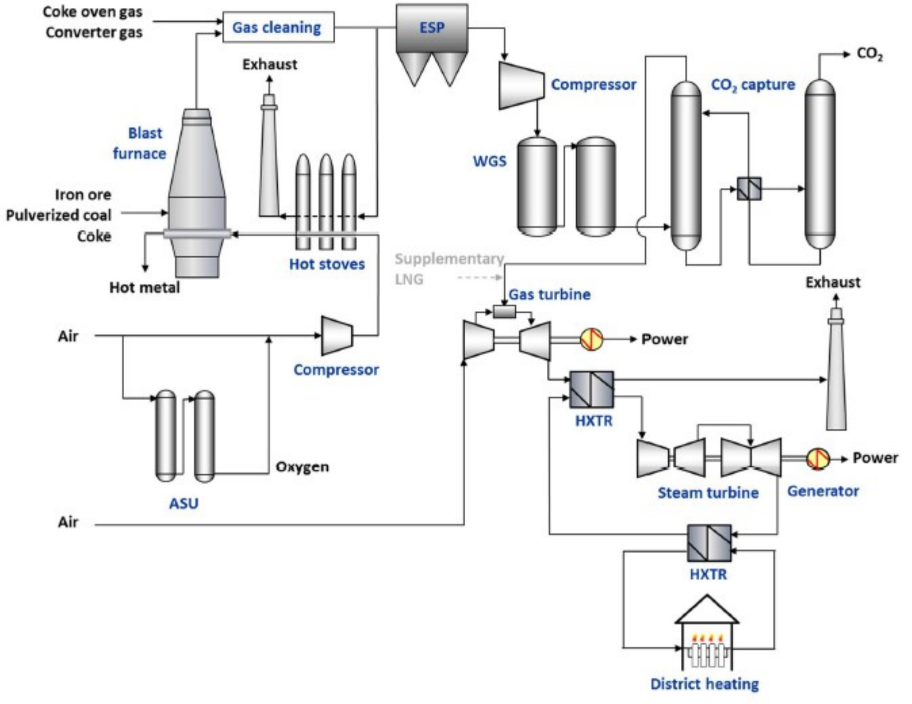
The Blast Furnace plus concept is a patented concept developed by Air Products and Daniel Corus. The calorific value of the top gas from the blast furnace is increased to allow the addition of a GTCC (gas turbine combined cycle) power plant which increses on-site power production. This is done by replacing part of the coke used in the blast furnace with pulverized coal injection (PCI) and adding enriched oxygen to the furnace.

The BF plus concept does thus not directly reduce CO_2 emissions but it these are allocated to both the produced steel and the produced electricity, thus lowering emissions per produced unit steel. The concept is described in more detail in (Onarheim & Garðarsdòttir, 2015). See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.



Conventional blast furnace with gas boiler power plant. Figure from (Onarheim et al., 2015)

e) BF Plus with CCS (Selexol) and
f) BF Plus with CCS (MEA)

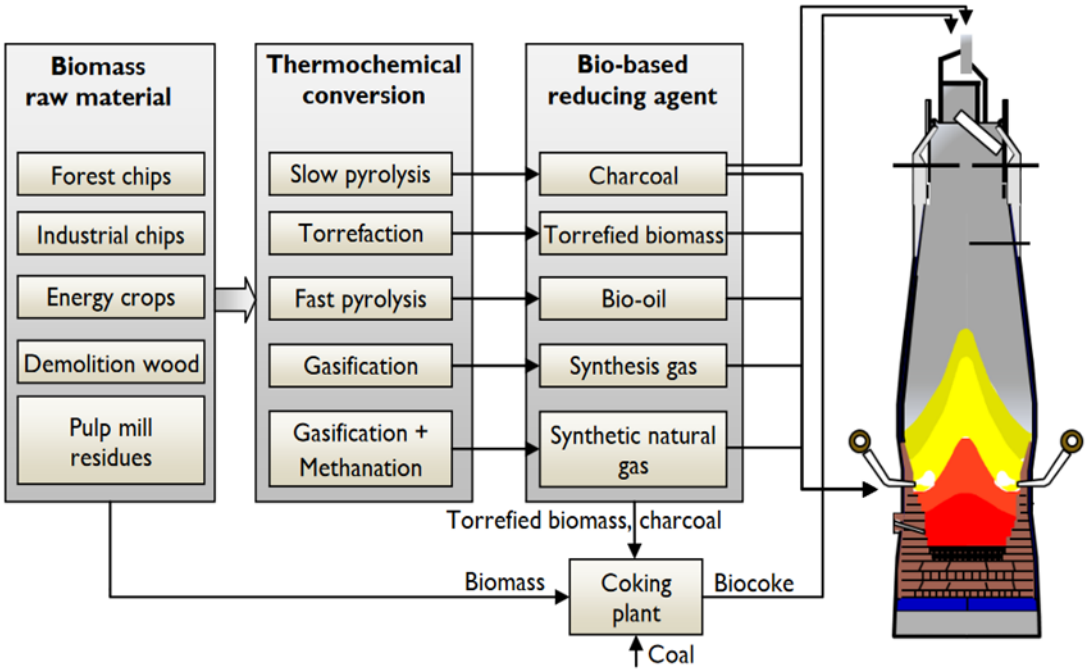


BF Plus concept with carbon capture and storage. Figure from (Onarheim et al. 2015)

The BF Plus concept can be modified to include CCS and two different solvents were analysed in this thesis based on the case specification in Orarheim et al. 2015. MEA is a well documented and researched solvent and is thus a good reference point when evaluating alternative CCS options. The MEA case uses more LNG than the Selexol case and it thus reduces emissions a little less; 1.4 Mt/a out of the steel mill's 4 Mt/a emissions compared to 1.8 Mt/a emission reductions achieved with Selexol.

See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.

g) Replacing PCI with torrefied biomass



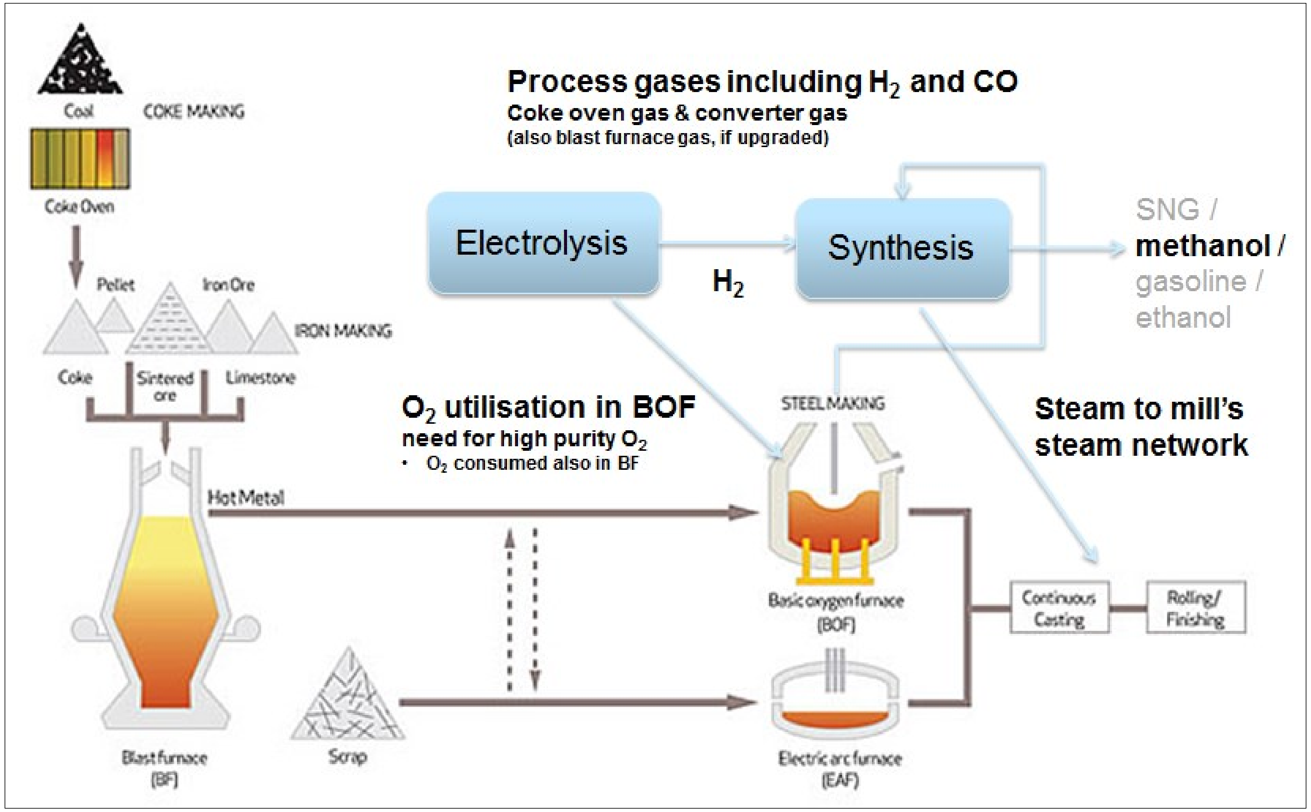
Biocoke production process. Figure from internal VTT working papers (Tsupari, Kärki, Onarheim and Arasto have conducted the research)

The so-called Bio Coke case (in figures and tables in this thesis) is built around simply substituting PCI (pulverized coal injection) with torrefied biomass (i.e. bio coke). In practise this would mean deploying a bio coke production line at the steel mill site, but in this case the bio coke is assumed to be purchased as such for simplicity. 30% of PCI is replaced in this case which was part of the cost-benefit analysis done previously at VTT (results not published yet). The substitution of PCI does not require any technical changes to the steel mill and it reduces emissions as fossil coke is replaced with bio –based bio coke.

The bio coke case is an “add-on” case since it does not require changes to the mill.

See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.

h) Power to fuels integration: Power to methanol



Original figure: http://www.worldcoal.org/coal/uses-of-coal/coal-steel

The power to methanol case can be added onto the steel production process without large modifications; it entails producing hydrogen through electrolysis and synthesising the hydrogen with the converter gases (carbon dioxide and carbon monoxide) to produce methane. More electricity is needed for this process than for the base case and the surplus oxygen can be sold.

Producing synthetic fuel from flue gases does not reduce the emissions of the mill on paper although it does prevent them from being let out into the air on-site; since the methane is sold as carbon-neutral the CO_2 emissions must be accounted for at the production site.

See the table in the end of this appendix for detailed figures on input- and output changes in relation to the base case and for sources for these.

The assumptions on which the eight investment plans were modelled are listed in the tables below. Sources are marked with numbers to save space in the table, they are as follows:

[1] Tsupari et al, 2012. Post-combustion capture of CO2 at an integrated steel mill – Part II: Economic feasibility (part of Arasto, 2015)
[2] Tsupari et al. 2015. Oxygen blast furnace with CO2 capture and storage at an integrated steel mill – Part II: Economic feasibility in comparison with conventional blast furnace highlighting sensitivities (part of Arasto, 2015)
[3] Onarheim et al. 2015. Industrial implementation of Carbon Capture in Nordic industry sectors
[4] EU ETS Directive (THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, 2003)
[5] Kärki et al. Summary of WP3 work -Phase I: 1.7.2014 - 30.6.2016 (Unpublished manuscript)
[6] Polttoaineluokitus 2015. (Tilastokeskus, 2015b)

Lower Heating Value (LHV) for PCI coal from [6] = 25.0 GJ/t
Lower Heating Value (LHV) for coke from [6] = 29.3 GJ/t

Plan	**Investment, M€**		**Yearly capital expenditure**		**Yearly O&M costs**		**Change in GHG emissions**		**Change in net electricity consumption**	
	Value	Explanation and source	Value	Explanation and source	Value	Explanation and source	Value	Explanation and source	Value	Explanation and source
Post combustion CCS	197.5 M€	From [1]. This technical solution is the same as in case 3 in the article.	20.1 M€/a	WACC = 8%, economic lifetime of investment 20 years	7.5 M€/a	Value from [1] (table 3, p. 284)	- 2590 kt/a	Value from [1] (page 282)	+ 746 GWh/a	Calculation based on values in [1] (p.282)
OBF	222 M€	Assessed as 60% of the investment of OBF with CCS. Investment cost for OBF CCS from [2].	22.6 M€/a	WACC = 8%, economic lifetime of investment 20 years	0.9 M€/a	4% of CAPEX	- 1300 kt/a	Value from [2]	+ 1410 GWh/a	Value from [2]
OBF with CCS	370 M€	From [2]	37.7 M€/a	WACC = 8%, economic lifetime of investment 20 years	1.5 M€/a	4% of CAPEX	- 2700 kt/a	Value from [2]	+ 1598 GWh/a	Value from [2]
BF plus	226.5 M€	GTCC BF Plus component (216.5 M€) + BF modifications (10 M€, expert estimate). [3]	23.1 M€/a	WACC = 8%, economic lifetime of investment 20 years	0.9 M€/a	4% of CAPEX	0 kt/a	Value from [3] (page 28)	- 411.1 GWh/a	Calculation based on values in [3] (page 28)
BF plus with CCS (Selexol)	350 M€	Extrapolation based on figures in [2], [3] and expert estimates. Differs from later obtained, possibly more accurate, figures.	35.65 M€/a	WACC = 8%, economic lifetime of investment 20 years	1.4 M€/a	4% of CAPEX	- 1730 kt/a	Calculation based on values in [3] (page 28)	- 32.68 GWh/a	Calculation based on values in [3] (page 28)
BF Plus with CCS (MEA)	359 M€	Extrapolation based on figures in [2], [3] and expert estimates. Differs from later obtained, possibly more accurate, figures.	36.56 M€/a	WACC = 8%, economic lifetime of investment 20 years	1.5 M€/a	4% of CAPEX	- 1460 kt/a	Calculation based on values in [3] (page 28)	- 365 GWh/a	Calculation based on values in [3] (page 28)
Biocoke purchase (PCI replacement)	0 €	Assumption based on the biocoke not being produced in site and on a substitution small enough (30% of PCI) to not require technical changes.	0 M€/a	WACC = 8%, economic lifetime of investment 20 years	0.0 M€/a	4% of CAPEX -This is a large simplification.	- 323.7 kt/a	Calculation based on the amount of substituted PCI coal	0 GWh/a	This case involves no other changes than PCI coal substitution with bio coke
Power to methanol integration	37.91 M€	Expert estimate	3.9 M€/a	WACC = 8%, economic lifetime of investment 20 years	0.2 M€/a	4% of CAPEX	0 kt/a	The produced synthetic fuel is carbon-neutral, meaning emissions must be accounted for at the production site. [4]	+ 151.4 GWh/a	Calculation based on value in [5]

Plan	**Change in biomass consumption**		**Change in coke consumption**		**Change in PCI coal consumption**		**Change in liquid or gaseous fuel consumption**	
	Value	Explanation and source	Value	Explanation and source	Value	Explanation and source	Value	Explanation and source
Post combustion CCS	No change	n/a	No change	n/a	No change	n/a	No change	n/a
OBF	No change	n/a	- 247 kt/a	Calculation based on values in [2] (page 141 table 1)	No change	n/a	+ 314 GWh/a	LNG use, value from [2]
OBF with CCS	No change	n/a	- 247 kt/a	Calculation based on values in [2] (page 141 table 1)	No change	n/a	+ 314 GWh/a	LNG use, value from [2]
BF plus	No change	n/a	- 113.6 kt/a	Calculated as difference between case and base case need for coke per unit of hot metal production, values from [3]	+ 1071 GWh/a	between case and base case need for PCI per unit of hot metal production, values from [3], LHV for PCI from [6]	No change	n/a
BF plus with CCS (Selexol)	No change	n/a	- 113.6 kt/a	Calculated as difference between case and base case need for coke per unit of hot metal production, values from [3]	+ 1071 GWh/a	between case and base case need for PCI per unit of hot metal production, values from [3], LHV for PCI from [6]	No change	n/a
BF Plus with CCS (MEA)	No change	n/a	- 113.6 kt/a	Calculated as difference between case and base case need for coke per unit of hot metal production, values from [3]	+ 1071 GWh/a	between case and base case need for PCI per unit of hot metal production, values from [3], LHV for PCI from [6]	+ 1734.6 GWh/a	LNG use, value from table 3.1 on page 28 in [3]
Biocoke purchase (PCI replacement)	+ 963.6 GWh/a	Calculated as 30% of PCI need, substitution of PCI as 1 GWh/a PCI : 1 GWh/a bio coke.	No change	n/a	- 963.6 GWh/a	Negative of change in biomass need: substitution of PCI as 1 GWh/a PCI : 1 GWh/a bio coke.	No change	n/a
Power to methanol integration	No change	n/a	No change	n/a	No change	n/a	- 116.1 GWh/a	Methanol, negative value because fuel is produced. Calculated from value in [5]

On the Power-to-methanol and all CCS investments: These figures do not include the investment in the component capturing of converter gases. In the case of the CCS cases this is because there are steel factories around the globe that already have this component installed, and in the case of the poer-to-methanol case it is because comparison to the CCS cases would have been meaningless if different basic assumptions were made for different technologies. The emission reduction investments presented in this thesis were researched and documented prior to this particular business case study and it is beyond the scope of this thesis to assess the validity of this data. The zero investment cost of the bio coke case is another case for discussion, but this too is beyond the scope of this thesis.

Appendix IV

Method for data mining and statistical analysis: description of the PRIM algorithm

The PRIM algorithm operates by first creating a binary matrix expressing whether data points are “interesting” or not; the definition of interestingness being the given numerical threshold. The data is divided into “boxes”, which are in essence groups of futures, and a trajectory of boxes on a coverage-density axis such as in Figure 34 is generated. The trajectory is a tradeoff frontier for the number of restricted dimensions (factors (U), shown in Figure 34 by the changing colour of the boxes), coverage and density.

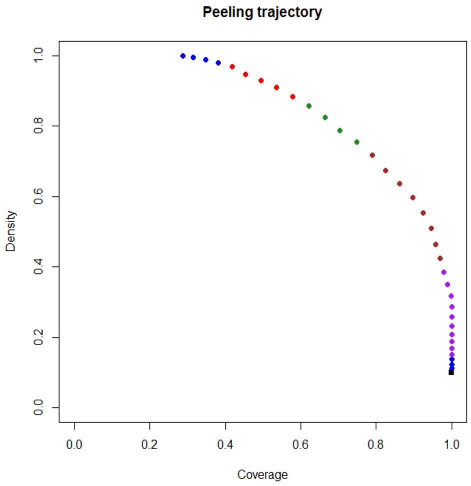


Figure 34. Example of a trajectory of boxes drawn with the sdprim function in R

The analyst selects a range of boxes to inspect further and after analysing their statistics he or she finally selects one of the boxes, possibly restricting the number of dimensions (factors (U)) kept. The selected box contains value ranges of one to four dimensions (uncertain factors) which combined cause the strategy in question to fail with the certainty of the density score of the box (density meaning the number of futures in which the strategy fails in relation to the number of futures in which it does not fail). The coverage value of the box describes how many of the futures in which the strategy in question fails are captured by the definition given by this box. Figure 35 shows the 5000 simulated futures mapped in a two-dimensional space defined by the prices of commodities A and B, with futures in which the strategy being analysed fails marked by filled-in dots and futures in which it does not fail marked as dots with no fill. Commodities A and B are the two dimensions (U) for the box described here.

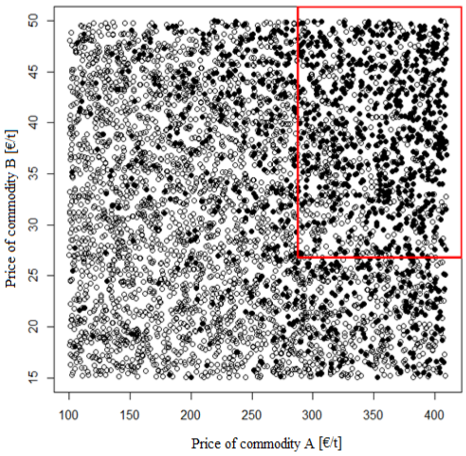


Figure 35. Output of analysis done in R software: The 5000 futures mapped in a two-dimensional space defined by example factors A and B, interesting futures are marked as black dots.

The red frame in Figure 35 shows the futures covered by the chosen box. Coverage is thus calculated as the number of filled-in dots within the red frame divided by all the filled-in dots (both inside and outside the frame; all futures in which the strategy in question fails), and density, mening how many of the dots within the box are "failure-futures", is calculated as the number of filled-in dots within the red frame divided by all fots, filled-in and with no fill, within the frame. A chosen box can be defined by the ranges of two uncertain factors such as in Figure 35 (Price of commodity A > 280 €/t and Price of commodity B > 26 €/t), by the range of just one uncertain factor –or by the ranges of three or up to four uncertain factors. If more than four factors are needed to define a box the future definition gets too complex for humans to intuitively imagine, and thus such a result is not helpful in decision support. Figure 36 is an example of a visualisation of the value ranges for four uncertain factors (U).

By *coverage* (which is displayed on the x-axis in the trajectory of boxes) the share of interesting futures covered by the box description in question is meant. *Density* means how many of the dots within the red square in Figure 35 are filled in relation to how many dots there are in total within the box; i.e. how many of the futures covered by this description are interesting futures (interesting futures = futures in which the case in question fails). Thus coverage tells us how well the future description describes the failure of a case, and density tells us how certain it is that a case fails if the future described comes to pass. Sdtoolkit is developed by the RAND corporation to support Robust Decision Making and it is documented in (Bryant, 2015).

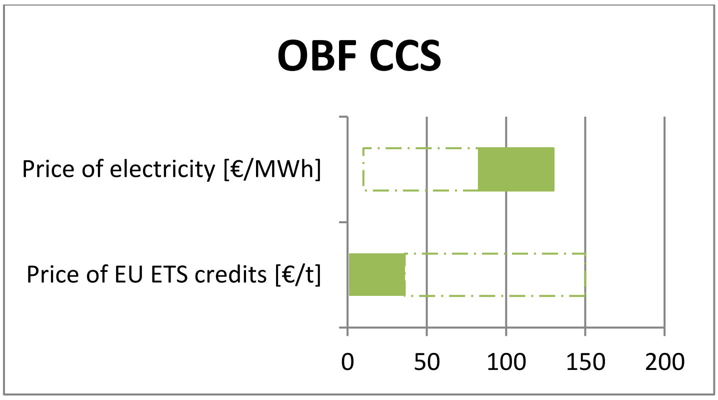
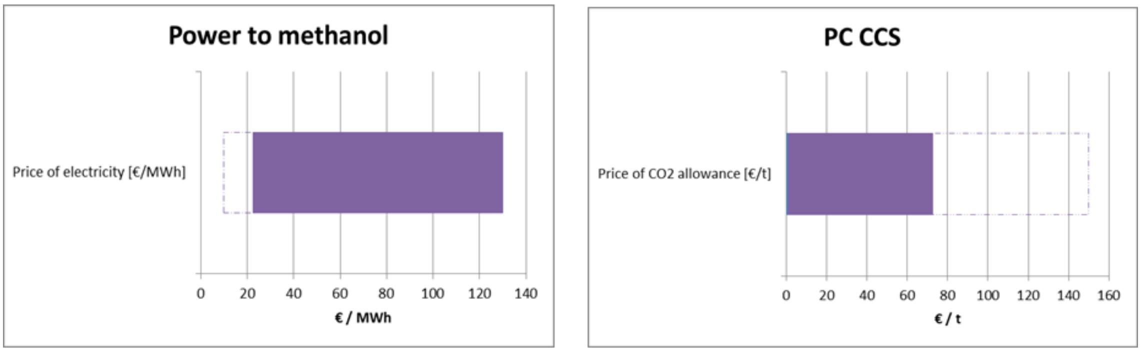


Figure 36. An example of the visualisation of future conditions that make an analysed strategy fare badly. The filled-in area of the bar represents price the ranges to which the strategy in question is vulnerable. Example data, visualisation adapted from (Kasprzyk et al. 2013)

In the case of the Add-On processes, it is noted that the statistical analysis with R is not meaningful for the Bio coke –investment plan, as this plan has no investment costs and can be run only when it is profitable to do so; thus this plan will never (when adhering to the assumption of zero investment as modelled here; this naturally is not quite accurate) adhere losses and thus it never "fails" as per this first simple definition.



Plan	Density	Coverage
Pt MeOH	**0.9996**	**0.904**
PC CCS	**0.8757**	**0.9479**

Figure 37. Results of the absolute vulnerability analysis for the add-on cases, excluding the bio coke case which never produced losses. The filled-in area of the bar represents the price ranges to which the strategy in question is vulnerable.

The *density* and *coverage* scores noted for each obtained relult are measures of the statistical significance of the result. The investment in question fails with the certainty of the density score of the box in case a future matching the box definition comes to pass (density meaning the proportion of futures described by the box description which is interesting, i.e. how many of the futures covered by the definition do actually fail). The coverage value of the box is the share of interesting futures covered by the box description in question (i.e. how well does the future description predict the failure of the case).