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Climate and Energy Security Policies in the EU: Conflict or Cohesion?

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Abstract in Norwegian:

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Klima- og energisikkerhetspolitikk i EU: konflikt eller samspill?

Ragnhild Sjoner Syrstad thesis for the Masterdegree

I januar 2009 oppstod det uenigheter om fornying av kontrakter for gassforsyning mellom Russland og Ukraina. Konflikten forårsaket en betydelig mangel på gass i Europa og en humanitær krise på Balkan. Som en respons på denne tilbudsforstyrrelsen har EU vedtatt en energisikkerhetsstrategi hvor unionen søker å redusere sin avhengighet av gass ved å øke bruken av fornybare energikilder internt i EU. I tillegg har EU vedtatt klimapolitikk for måloppnåelse innen 2030, som blant annet sier at fornybarandelen skal øke til 27 prosent innen 2030. Denne masteroppgaven analyserer hvorvidt det er samspill eller konflikt mellom EUs energisikkerhetsstrategi og klimapolitikk for 2030 ved hjelp av den numeriske likevektsmodellen LIBEMOD.

Oppgaven finner et sterkt samspill mellom EUs klimapolitikk og energisikkerhetsstrategi innen 2030, siden klimapolitikken fører til en større spredning i bruken av energikilder i den europeiske energimiksen. Måloppnåelse i klimapolitikken innebærer høyere subsidiering av fornybar energi og høyere pris på CO2.

Videre finner oppgaven at forbedringer i teknologiene for produksjon av sol- og vindkraft fører til lavere kraftpriser, lavere CO2-pris og lavere subsidier til fornybar kraft. Forbedringer i solkraftteknologien reduserer bruken av naturgass noe, men fortrenger i større grad andre fornybare energikilder i kraftmarkedet på grunn av et lavere behov for subsidiering av fornybar energi. Noe av den overflødige gassen i kraftmarkedet ender dermed opp med å bli konsumert av industrien i stedet til lavere priser. Totalt sett er EUs gassavhengighet marginalt påvirket av forbedret teknologi i fornybar kraftproduksjon.

Graden av samspill mellom klimapolitikk og energisikkerhetsstrategien er størst dersom man implementerer tiltak for økt energieffektivisering.

Climate and Energy Security Policies in the EU: Conflict or Cohesion?

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Master of Philosophy in Economics

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Abstract

The natural gas dispute between Russia and Ukraine in January 2009 caused severe shortages of natural gas in Europe. As a response to the supply disruption, is the EU envisaging a potential for renewable energy sources to reduce its dependency on natural gas. The EU has adopted a binding target in the 2030 Climate and Energy Framework of increasing the share of renewables to 27 percent. This thesis analyzes the degree of coherence between the climate policies for 2030 and the EU's energy security strategy, using the multimarket equilibrium model LIBEMOD.

The study finds a strong degree of coherence between the climate and the energy security policies by 2030, as the climate policy leads to a greater dispersion of energy sources. Accomplishing the climate targets implies raising both the common EU subsidies to renewables and the taxation of CO_2 emissions. Improvements in the solar and wind power producing technologies lead to lower electricity prices, a lower CO_2 price and lower subsidies for renewables. Some of the gas in the power market is replaced by more solar and wind power, but solar power suppresses other renewable energy sources to a greater extent than gas power due to the reduction in subsidies to renewables. Some of the excessive gas is consumed by the other end user sectors at lower prices, such that the EU's gas dependency is marginally affected by more renewables. In addition, the study finds that the degree of cohesion in climate and energy security policies appears to be stronger when implementing measures for increased nergy efficiencies.

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Ragnhild Sjoner Syrstad
January 2016

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Abbreviations

GHG – Green House Gasses

LNG – Liquefied Natural Gas

Mtoe – Million tons of oil equivalents

TWh Terra watt hours (a million Megawatt hours)

Abbreviation	Country
at	Austria
be	Belgium
bg	Bulgaria
ch	Switzerland
cy	Cyprus
cz	Czech Republic
de	Germany
dk	Denmark
ee	Estonia
es	Spain
fi	Finland
fr	France
gb	United Kingdom
gr	Greece
hu	Hungary
ie	Ireland
is	Iceland
it	Italy
lt	Lithuania
lu	Luxembourg
lv	Latvia
mt	Malta
nl	Netherlands
no	Norway
pl	Poland
pt	Portugal
ro	Romania
se	Sweden
si	Slovenia
sk	Slovak Republic

Introduction

The natural gas dispute between Russia and Ukraine in January 2009 that led to a humanitarian emergency in the Balkans and severe shortages in the European Union (EU), proved natural gas to be an important tool in the power battle of international geopolitics. It further proved the energy situation in the EU vulnerable.

The EU is the largest energy importer in the world. The EU imports 53% of the energy it consumes and some member states depend on a single external supplier for their gas imports (COM, 2014). Dependency on natural gas in particular contributes to the vulnerabilities in European energy supply. The fear of new disruptions after the Russo-Ukrainian conflict in 2014 has yet again raised the attention of preserving secure energy supplies to the EU. As a response, has the EU launched an energy security strategy, planning to reduce its dependency on natural gas.

According to the EU's Energy security strategy there is a "potential for renewable electricity to further reduce natural gas use in a number of sectors by the end of this decade. Notably, a fuel-switch to indigenous renewable heating sources can displace significant amounts of imported fuels" (COM, 2014, p. 12). This is my motivation for assessing to what extent renewables can replace natural gas in the European energy mix. If renewable energy sources are to be successful at suppressing gas, they must replace gas both in the power producing sector and by the end users of gas such as households, services and the industry sector.

I create a measure of energy security stating that a country is more vulnerable the more gas it consumes relative to total energy consumption. Moreover, due to the historic events of gas supply disruptions by Russia, a country is more vulnerable with a high share of net gas imports from Russia relative to total gas consumption.

Deployment of more renewable energy sources can occur through the market development with technological progress or governmental policies designed to push the market and technological progress in a desired direction. I use LIBEMOD, a multimarket equilibrium model presented in Aune et al. (2008), to assess how the EU's dependence on natural gas and Russian gas develops by 2030. The model is based on a set of competitive markets for eight energy goods. LIBEMOD simultaneously determines all energy prices and quantities produced, traded and consumed in five end user sectors in 30 European countries. These are the EU27 plus Norway, Iceland and

Switzerland (EU30). I apply the most recent version of the model, an extension where Russia enters as an endogenous model country. The geographical potential for renewable power generation determines which country that can benefit from the shocks to renewable power production. Out of the countries that still used gas in power generation by 2030, Latvia experienced a worsening of the energy security due to the shocks in solar power, but an improvement when the source of increased power production was wind power.

LIBEMOD models the interlinkages in the European Energy markets through substitution in demand, the transformation process of fuels to electricity and trade between countries in a detailed manner. I use the long run version of the model to allow for investments in the energy industry. This facilitates an assessment of how an increased capacity of renewable energy production in the low carbon economy in 2030 affects the energy security. The model also determines the emissions of CO_2 by country and sector, a prerequisite for assessing attainment of the EU's climate policies. The equilibriums are calculated with the programming software GAMS.

I approach the analysis in three steps. The first step investigates how the energy security in the EU is affected by a situation where the EU has accomplished the 2030 Climate and Energy Framework; a 40 percent reduction in the greenhouse gas emissions and increased the renewable share to 27 percent of the energy mix. This is the reference scenario of the study. The second type of scenarios assess effects on the gas dependency of increased annual cost reduction rates for both solar and wind power and higher efficiencies in the transformation of solar radiance to electricity. In the third and final step I consider how energy efficiency measures and alternative climate polices affect the energy security. Based on the findings in the European Commission's in-depth energy security study (2012) I focus my thesis on how Finland, Estonia, Latvia, Lithuania, Poland and Hungary score on energy security in the different scenarios.

The study finds a strong degree of coherence between the climate and the energy security policies by 2030, as the climate policy leads to a greater dispersion of energy sources. Accomplishing the climate targets implies raising both the common EU subsidies to renewables and the taxation of CO_2 emissions. The reduced gas dependency in the reference scenario is due to the stand still of gas consumption but an increase in the total energy consumption, caused by economic growth. With renewables constituting 27 percent of the energy mix, a lower demand for gas in the electricity producing sector leads to higher consumption of gas by the industry at lower prices. The redistribution of the gas consumption implies that some of the vulnerable countries (Finland, Hungary and Lithuania) no longer use gas in the power generation.

Improvements in the solar and wind power producing technologies lead to lower electricity prices, a lower CO_2 price and lower subsidies for renewables. Some of the gas in the power market is replaced by more solar and wind power, but solar power suppresses other renewable energy sources to a greater extent than gas power due to the reduction in subsidies for renewable power production. Some of the excessive gas is consumed by the other end user sectors at lower places, such that the EU's gas dependency is marginally affected compared to the reference scenario.

The degree of cohesion in climate and energy security policies is strong when implementing measures for energy efficiency. The energy efficiency objective eased the dependency on gas significantly in EU30. However, the increased energy efficiencies might in fact increase the gas dependency in some of the vulnerable countries if only the Western European countries experience increased energy efficiency. Lower demand for gas by Western European countries enables vulnerable countries in Eastern Europe to consume more gas at lower prices.

Having lower ambitions in the climate policy improves the energy security situation for countries with a greater potential for renewable power production. This is due to the increase in subsidies for renewables. On the other hand, when the climate ambitions are higher the CO_2 price increases considerably and the subsidy to renewables is zero. The high CO_2 price reduces the dependency on Russian gas in all countries. Some countries increased the gas consumption slightly, indicating that the renewable energy sources are important in the power markets in these countries. Having a higher target for renewables in the energy mix causes a considerable increase in the subsidies to maximize the potential for renewables. The gas dependency improves, mostly due to an increase in total energy consumption.

Chapter 1 describes main elements of LIBEMOD, with supplementary information provided in the Appendix. Chapter 2 presents different perceptions of the term energy security before defining a tailored application of the energy security term for this thesis. The chapter also presents an overview of the different scenarios in the study. Chapter 3 presents the new equilibrium for 2030 and its consequences for the energy security. Chapter 4 is devoted to shocks in the market for renewable power production and chapter 5 assesses how different climate policies affect the energy security. The thesis is wrapped up with some conclusive remarks.

1 Method

This section presents a brief overview of some distinctions on the modelling of energy markets and the main features of the multimarket equilibrium model used in this thesis; LIBEMOD.

1.1 Modelling Energy Markets

There two main distinctions the energy market models are between top-down or bottom-up models and general equilibrium or multimarket models.

The main difference between top-down and bottom-up models is how they emphasize the endogenous market adjustment and technological details (Böhringer & Rutherford, 2008). Top-down models describe the energy markets from an aggregated perspective, incorporating price-induced feed-back effects between markets. In these models data of importance on the demand side is consumption, prices, income and factor costs. The supply side is often modelled from specific sectors such as the industry or households. Bottom-up models emphasize the technological features of the entire energy system, with a range of supply and demand technologies for different fuels and sectors (Aune, Golombek, Kittelsen, & Rosendahl, 2008). The bottom-up models ignore price-induced behavior and feedback effects in the economy, a shortcoming that is important for the analysis of large-scale changes in the energy markets.

Computable General Equilibrium models (CGE) simulate equilibria in all markets of an economy, based on optimizing behavior of households and firms. Included in these models are markets for factors of production like labor and capital, income generation and trade relationships in open economies. In addition feedback effects between markets are incorporated and these models search for simultaneous equilibriums in *all* markets. CGE-models are typical examples of top-down models. Multimarket equilibrium models describes the energy markets in detail while the rest of the economy is seen as exogenous, for instance with a fixed GDP level or GDP growth rate. Multimarket models incorporate price-responsive behavior and price-induced feedback effects between several energy markets, which are typical features of the top-down up models.

1.2 LIBEralizing European Energy Markets MODel (LIBEMOD)

The European energy markets are closely interlinked. These interlinkages work through the mechanisms of substitution in demand, the transformation of fuels to electricity, the trade of energy goods and the common European energy policies in force in the single market in the

European Economic Area (EEA). These mechanisms are the building blocks of the energy multimarket equilibrium model LIBEralizing European Energy Markets MODel (LIBEMOD) used in this thesis.

LIBEMOD is in many ways an appropriate tool to assess how the policies in the 2030 Climate and Energy Framework comply with the policies in the EU's energy security strategy. LIBEMOD models the supply side of the energy markets in a detailed fashion, including fuels extraction and supply of eight possible electricity generating technologies and trade between the European countries. In addition, the model determines all prices and quantities traded in the world markets. The demand side is modelled with complex demand functions for five different end users to allow for substitution between energy commodities. More importantly are the possibilities of investment in new power production capacity. Allowing for investments for a future year facilitates an assessment of how an increased deployment of renewables towards in the low carbon economy in 2030 affects the energy security. The model also determines the emissions of CO_2 by country and sector, an essential element in order to assess the climate policies of the EU.

One important limitation of using LIBEMOD is that it lacks electrification. If certain sectors are switching from fossil fuels to electricity by 2030, the model will not encompass such effects. Such a development could for instance apply to the transport sector. If the future is to bring more vehicles with engines running on electricity, the demand for electricity may increase and demand for fossil fuels decrease. Possible side effects of electrification can thus be lower prices for fossil fuels (due to the lower demand) which again affects the competitiveness of renewables. The net effect of electrification depends on what price effect is larger and how the policy measures are adjusted along the road to meet governmental targets. In LIBEMOD, the transport sector is using oil and biofuels only. A greater use of electricity is a result of optimized behavior of the sectors that are modelled to use electricity. The change in the composition of the energy consumption from 2009 to 2030 that the model stipulates is thus not giving the entire picture. Some of the assumptions in the model may be wrong. Assessing how the different shocks affect electricity consumption and production within the same period, i.e. in 2030, however, is still comprehensive because I compare the results with an outlined reference scenario.

As LIBEMOD is a multimarket equilibrium model, and not a general equilibrium model, the effects of energy supply disruptions to the entire economy cannot be analyzed. Energy supply disruptions can have severe negative impact on a nations' economic welfare. The model calculates social surpluses from the equilibrium values of the objective functions of the agents in the energy markets, but is not a result of possible effects also occurring in the rest of the economy. This limitation comes into play when analyzing energy security. The affordability element of energy security discussed in chapter 2 calls for an assessment of energy prices and consumption relative to the aggregate price and consumption level. This thesis is thus focusing on how different shocks affect energy security through the market dynamics.

The following presentation of LIBEMOD is retrived from Aune et al. (2008) and the documentation of the extended version of the model used in this thesis, presented in Aune et al. (2009).

1.2.1 The Model

LIBEMOD is a top-down multimarket energy equilibrium model based on a set of competitive markets for eight energy goods; electricity, natural gas, oil, coking coal, lignite, steam coal, biofuels and biomass. The model simultaneously determines all energy prices and quantities produced of eight energy goods, traded and consumed in five end user sectors in all of the countries in the 30 model countries. These are the EU27 plus Norway, Iceland and Switzerland (EU30). This thesis makes use of a recent extended version of the model where Russia enters as a model country. The geographical scope of the model is further presented in the Appendix.

Natural gas and electricity is traded competitively in integrated European markets using gas pipelines and electricity transmission lines that connect the model countries. Biomass is also traded between pairs of model countries, whereas there are competitive world markets for coking coal, steam coal, oil and biofuels. There are only domestic markets for lignite. Fuels are traded in annual markets, and there are seasonal and time-of-day markets for electricity.

1.2.2 Demand

Consumption of the different energy commodities takes place in each endogenous country in the five sectors households, service, industry, transport and demand from electricity producers. The electricity producers' demand for fuels follows from their profit optimization problems. The first four sectors represent final demand, which is broken down into a detailed list of end users where each is modelled as a single consumer with a nested constant elasticity of substitution (CES) utility tree. Income is exogenous. The exogenous countries and regions are modelled with a linear demand function.

Extending the (CES) utility function utility function to a *nested* CES-structure allows the elasticity of substitution to vary between pairs of commodities and it accommodates both substitutes and complements in demand. A nest is a CES function of one, two or several primary market commodities. The level of each nest is a CES function of the constituent goods. The consumers maximize total utility subject to the nest utility, the price index of the cost of one unit of the nest level and the budget constraint.

LIBEMOD models end-user demand with a five-level CES function. The structure is in principle the same for all end users, but the transport sector is modelled using oil and biofuels only. At the top level in LIBEMOD, total utility is a function of two elements: energy related consumption (energy nest) and a “money” good, which is an aggregate of all other commodities consumed. The price of this commodity is fixed at one and thus acts as the numeraire in the model. At the second level, the energy nest is an aggregate of consumption related to the four main energy types; coal, natural gas, oil and electricity. Each of these is again a nest where an energy commodity enters complementarily to other goods that use the energy commodity. This is a way of modelling that natural gas can be used complimentarily to household gas appliances, such as cookers and heaters. These commodities are not modelled as markets, as their prices are fixed to unity.

1.2.3 Supply

Fuel supply

The modelling of fuel extraction vary somewhat between fuels. Extraction behavior is simply modelled by stating that producer price equals marginal costs. This applies to oil, steam coal, coking coal, bio fuel and biomass. For natural gas, the model distinguish between three types of goods, which are perfect substitutes for gas users; **(i)** Natural gas extracted from existing fields supplied by the five large producers Norway, the Netherlands, the UK, Russia and Algeria. **(ii)** Natural gas extracted from new fields (supplied by all countries) and **(iii)** Liquefied Natural Gas (LNG, supplied only by row2)

Total extraction is the sum of existing and new fields. The relation price equals marginal cost applies to the old and new natural gas fields, i.e. for (i) and (ii), except for gas extraction in the Rest of the World (row).

Electricity supply

Each power generator maximizes profits with respect to the following; how much electricity to produce in each time period, how much of the installed capacity to maintain and how much to invest in new production capacity. The latter part of the optimization problem is subject to a number of technology restrictions, either common to all technologies or for some technologies.

The sector with the greatest possibility of fuel substitution is the intermediate demand from the electricity production. With excess capacity in power plants, power production can easily switch from e.g. gas power plants to coal power plants, if relative prices make one choice more profitable. The possibility of investment in new capacity makes fuel switching feasible in the long run.

Instead of modelling the power sector as a single agent, there are several technologies, with each of these using a separate fuel. The optimization behavior of the power generators vary according to their technology, according to its cost structure. The annualized cost of production differs between technologies, countries and within each country.

Combustion fuels

There are five power technologies for old and four technologies for new power plants in each model country; gas power, steam coal power, bio power and oil power (lignite power can only old). The supply of power form each category of electricity production is modelled as if there is one single plant with decreasing efficiencies, implying increasing marginal costs.

There are six types of costs involved in electricity production by combustion fuels: operating costs, input fuel costs, maintenance costs, ramping up costs, capital costs for investment in new power capacity and finally costs of connecting the new power plant to the grid. For further details, see the Appendix.

The revenue for power producers can come from two sources; regular sales to the power market at price P_t^{YE} (which varies over time) or the producer can sell reserve power capacity K_t^{PR} receiving price P_t^{KPR} from the transmitting system operator (TSO). The profit of each power producer is thus the two revenue sources less the short run variable costs and any costs of new investment. The power producer maximizes profit given some constraints. First, maintained power capacity should be less than or equal to total installed power capacity. The second constraint limits the power production to the net power capacity after the allocation of some of the maintained capacity to reserve power. Third, production is constrained by the hours available for power production as some down time is required for maintenance.

A more detailed presentation of the electricity production of combustion fuels in LIBEMOD is provided in the appendix.

Efficiencies

The existing power plants modelled in the base year of 2009 have pre-determined capacities that cannot be expanded. These efficiencies vary between the plants according to the technology, i.e. between gas power plants and coal power plants. The new fuel-based power plants are ready for production in 2030 with determined efficiencies calculated according to a linear function of used capacity. The efficiencies are independent of the size of the plant and they are higher than the best efficiency in 2009. The production of fuel based electricity in 2030 is thus the total of production for new and old power plants, accounted for the depreciation of the existing plants by 2030.

Wind and solar power

In the long run version of LIBEMOD, investment in wind power and solar power is endogenous. As the power producers based on fossil fuels the wind power producers face an optimization problem. In each period they choose how much to produce, how much capacity to maintain and how much to invest for the next period.

The variable costs of wind power are low and production is thus run at full capacity. The model assume that maintenance of the wind power plant occurs when the wind is not blowing. This number of hours is much lower than total hours available of the year, such that this constraint is never binding. New investments are made at the best sites for wind power (in terms of annual wind hours) before the second best is developed and so on. This scarcity is reflected by the fact that the average number of wind hours is decreasing in the aggregate capacity for wind power plants. Maximum production of wind power in any period is thus the product of the expected share of annual number of wind hours in that period, the maintained capacity and marginal efficiency (which depends on the level of installed capacity).

LIBEMOD models Photovoltaics (PV), which is a way of generating electricity by converting solar radiance into electricity by using solar panels containing photovoltaic material. The annual energy capacity of solar power in LIBEMOD depends on the annual solar radiance per m^2 per country, the land made available for solar power production and the efficiency of the transformation process of solar radiance to electricity. Sites differ with respect to solar irradiance and LIBEMOD assumes that more and more land is available for solar power as the time evolves. Investment in new solar power occurs at the best sites first, which implies that the more solar power that is developed, the lower is the average amount of energy received by the solar panels. Production takes place in the maintained panels only. As with wind power, this constraint does not bind because the sun is not shining at all hours even at the best sites. Finally, LIBEMOD assume that solar power is not used as reserve power capacity due to its intermittency. The variable costs of solar power are close to zero.

Total wind and solar power production is the aggregate from both old and new plants.

1.2.4 Trade and Emissions

There are European markets for natural gas, biomass and electricity in LIBEMOD. These commodities are thus traded between pairs of countries restricted by the transmission capacity. Coal, oil and biofuel are traded in global markets. Each country is represented by a trade node, where all types of energy is transported to all types of users of energy, i.e. households, services, industry, transportation and electricity generation. This is modelled by a constant unit cost that differs between energy users and energy goods. The restrictions to international transmission capacities for both electricity and gas pipelines can be expanded if the investment is profitable. The only exception is however investment in transmission capacity between Russia and other countries. It is assumed that these investment are not conducted with economic motives, and will thus not be modelled either.

The emissions of CO_2 from activities modelled in LIBEMOD are the sum of emissions from consumption and from own use in the extraction of fossil fuels in each country. In most model scenarios, the CO_2 emissions are calculated sequentially after the simultaneous model solution. The model does not quantify the welfare effect of decreasing the negative external effects of climate and environmental effects, which partially is the rationale of the tax in the first place.

2 Energy Security

"Energy security is the uninterrupted availability of energy sources at an affordable price" (OECD/IEA, 2015). The definition from the international energy agency makes the concept of energy security appear straightforward. The term is however quite subtle. The literature has provided more than 30 definitions of energy security (Winzer, 2012). Accepting the IEAs definition without further discussion may cause overlooking important features and crucial interdependencies within energy systems. This chapter presents an overview of how the concept of energy security may be conceived before determining a measure of energy security.

2.1 Energy Security in the Literature

The main concerns about energy security is related to the interruptions, disruptions and manipulations of supply shocks that can lead to sudden, sharp increases in prices and can impose heavy economic and political cost (Yergin, 1988). Classic energy security studies are mainly concerned with political costs and nations' sovereignty related to the dependency on a single commodity, often equalizing the energy security term to a secure supply of oil. Yergins (1988) study concludes that ensuring the availability of oil at reasonable prices remains the primary concern, which suggests it is the role of the government to smooth variations in energy prices, if one cannot control the market price directly. Deese (1979) defines energy security as a condition where a nation perceives a high probability that it will have adequate energy supplies at affordable prices. Affordable prices are defined as a price development that does not disrupt normal social and economic activity (Deese, 1979).

The four As of energy security presented by Kruyt et al. (2009) are commonly repeated definitions in the literature. The first A comprises the physical existence of the energy source; the *Availability* of energy to an economy. The second A covers the difference between possible discrepancies between consumption and production of resources; the *Accessibility* of energy. Accessibility may as well hinge on geopolitical factors as energy commodities often are traded across national borders. The third A covers a cost and economical perspective: *Affordability*. Lastly, the theory of the four As comprises a sustainability dimension with environmental and societal elements: *Acceptability*.

Cherp and Jewell contribute more substance to the theory of the four As by asking a set a questions which they claim should be applied to any security issue: i) Security for whom? ii)

Security for which values? iii) Security from what threats? (Cherp & Jewell, 2014). They claim that the well-established theory of the four As fail to deal with these questions. They argue that it does not give an explicit answer to "security for whom?" as *Affordability* may apply to households, the profitability of commercial parties and the government in terms of subsidy levels and trade balance. Identifying a referent object is important for clarifying *Acceptability*, a term that has frequently been used to address the environmental impacts of energy systems. However, what is deemed "environmentally acceptable" varies between entities like the local population, environmental NGOs, industries and nation states (Cherp & Jewell, The concept of energy security: Beyond the four As, 2014).

Cherp and Jewell (2014) further claim that the four As are characteristics of energy systems, not human values. The characteristics of energy security are linked to political, economic and social priorities among others. The theory of the four As does not explicitly state what values that need to be protected, an insufficiency when dealing with policy questions in relation to energy security. Energy security concerns are shaped by experiences of disruptions and perceptions of risk, because energy security policies are concerned with already attained standards (Cherp & Jewell, 2014).

2.1.1 Origin of Risk to Energy Security

It is challenging to identify all possible risks or vulnerabilities within the concept of a secure energy system. Sources of risks could be technical risk factors such as infrastructure interdependency, mechanical failure, thermal failure and emissions**.** Human risk factors include demand risk, strategic withdrawing, capital underinvestment, sabotage and terrorism and political instability. Natural risk factors are resource intermittency, resource depletion and natural disasters (Winzer, 2012).

Cherp and Jewell (2011) present three perspectives to the origin of risk to energy security. The *robustness perspective* present threats to energy security as quantifiable factors such as growth in demand, scarcity of resources, aging of infrastructure, technical failures or extreme natural events. The *sovereignty perspective* introduces threats to energy security posed by external actors. This could be hostile states, terrorists, unreliable exporters or powerful foreign energy companies. These threats originate from intentional actions and may display themselves as embargoes, malevolent use of market power or acts of sabotage and terrorism. The *resilience perspective* identifies threats related to practical challenges of establishing functioning energy markets and ensuring effective long-term investment in energy systems and technologies.

Threats can stem from regulatory changes, unforeseeable economic crisis or booms, change of political regimes, disruptive technologies and climate fluctuations. This approach aims at ensuring the protection against any threat by spreading risk and preparing for surprises by increasing the flexibility, adaptability and diversity of energy systems (Cherp & Jewel, 2011).

Classic energy studies developed based on the existing energy systems of that time, the supply of oil. Threats are no longer limited to political costs or nations' sovereignty, but possibly to the source of energy itself. Aging infrastructure, terrorist attacks, natural events or intermittency of solar and wind power are more resent supplements to potential threats to energy security. The contribution by Cherp and Jewell (2014) stating that energy security is "a low vulnerability of vital energy systems" links the classic theory with the 21st century.

2.1.2 Costs of Energy Security

A prevalent feature of measuring energy security is the variability and availability of supplies relative to demand. The continuity of the balance between demand and supply can be measured at different stages in the transformation process from primary energy to end-user utility (Winzer, 2012). Defining what measures to apply when assessing energy security depends on what values to protect. The short-term dimension of energy security concerns supply disruptions while long-term energy security concern structural aspects of the system as a whole. There is a link between the two however, as underinvestment in long-term energy supply may cause short-term disruptions at some point in the future (Kruyt, van Vuuren, & de Vries, 2009).

Price shocks are direct effects of supply disruptions to a traded energy commodity. Richter and Holz (2014) find that gas disruptions can cause a price increase of 23 percent on average in the first year of a disruption in the EU, when using a partial general equilibrium model. Applying the holistic approach to energy security, long-term price shocks can affect the terms of trade, which in turn affects the involved countries' current accounts. In a country where energy constitutes a significant share of the trade balance, sudden price changes to the energy commodity may cause movements in the national currency market as well, which has welfare effects for the entire economy (Bohi & Toman, 1993).

Bohi and Toman (1993) further raises the point that high energy prices can cause energy intensive industries to cut down on energy as input in production leading to a lower marginal productivity of labor (given they are complementary inputs in production). This argument links the costs of energy disruptions to the aggregate unemployment level. Lower productivity implies increased costs for the industry, which again may lead to reducing the number of employees. As a consequence, aggregate unemployment rises (Bohi & Toman, 1993)

2.2 Energy Policies of the European Union

There is a widespread perception that Russia can use gas as a political lever in its relations with European countries (OIES, et al., 2014, s. 74). This perception is stronger in previous Soviet countries, where political and economic ties remain strong. This is partly due to Kremlin's interest in the energy policies of successor states that became transit corridors for its oil exports to Europe after 1991 (OIES & Grigas, 2012). This study is thus paying more attention to Eastern European countries that either border to Russia or import Russian gas via Belarus and Ukraine.

In 2013, Russian gas imports comprised some 30 percent of Europe's gas needs (Simon Pirani, 2014). The Nord Stream (from Russia to Germany via the Baltic Sea) and Yamal-Europe pipelines (from Russia via Belarus to Poland and Germany) supply the North-Western and Central Europe respectively. Much of the transit through Ukraine is destined for Italy, transiting through Austria, Hungary, Bulgaria, Greece, former Yugoslavia and Turkey. The construction of the Nord Stream pipeline has lowered the transit volume of Russian gas passing through Ukraine to Europe from 80 to 50 percent (Simon Pirani, 2014). The Russian company Gazprom operates the pipelines transporting gas to Europe and has supplied Europe with gas since 1973 (Gazprom, u.d.). The dependency on pipeline capacity when trading with gas adds a risk element, in that the monopoly operator can halt the gas flow, for whatever reason.

The serious gas dispute between Russia and Ukraine in January 2009 showed the suffering and costs a gas supply disruption could cause. There was no agreement on a price for Russian gas supply and a tariff for transit of Russian gas to Europe before contract expiration by the end of 2008. Subsequently, gas supplies were cut off on January 1st 2009 (OIES, Pirani, Stern, & Yamifava, 2009). The EU member states experienced severe shortages while the Balkans suffered a humanitarian emergency because of the restricted possibilities of heating.

I subsequently consider gas dependency as a threat to the energy systems, while oil dependency does not. Oil is traded on the world market and European countries are thus not dependent on Russian oil imports. The Baltic States for instance can simply change the supplier at their oil terminals on the seacoast. Russia is not dependent on the Baltics for transit of their oil either (Grigas, 2012).

2.2.1 The EU's Energy Security Strategy

The European Commission launched an energy security strategy in May 2014 as a response to the EU's concerns on Russian gas dependency.

> "A strategy for energy supply security must be geared to ensuring, for the well-being of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development." (European Commission, 2000)

The European Commission's definition of energy security covers most of the outlined perspectives above. The European Commission has paid more attention to energy security during the last couple of years and presented aims at promoting the energy security of the European Union in its communication dated 28th of May 2014 to the Parliament (Commission, European Energy Security Strategy, 2014).

The short-term measures includes actions to map the need for back up mechanisms, such as emergency infrastructures, reverse flows, reducing energy demand or switching to alternative fuels. The Commission reviewed existing mechanisms to safeguard security of energy supply, like build - up of oil stocks, preventing and mitigating gas supply disruption risks and protection of critical energy infrastructures. The immediate focus in 2014 was on the member states on the eastern boarder of the EU.

In the long run, moderating energy demand is set out as one of the more effective tools to reduce the EU's external energy dependency and exposure to price hikes. The commission aims at building a well-functioning and fully integrated internal market by creating a single energy market. The strategy further states that increasing energy production in the European Union can reduce its dependence on particular supplies and fuels by maximizing the use of indigenous sources of energy. Continuing the deployment of renewable energy sources is linked to achieving the targets outlined in the 2020 Climate and Energy strategy. In addition to taking actions for internal development, the EU seeks to diversify external supplies and related infrastructure by pursuing an active trade agenda. This is supposed to ensure access to natural gas and LNG exports.

2.2.2 The 2030 Climate and Energy Framework

The European council reached a conclusion on the EU's climate and energy policy framework by 2030 in October 2014. This policy framework is a complement to the 2020 and 2050 framework. There are mainly three elements of the energy and climate framework:

Target 1) Reduce the greenhouse gas (GHG) emissions with 40 percent by 2030 compared to the levels in 1990

Target 2) at least 27 percent share of renewable energy consumed in the EU in 2030.

Target 3) 27 percent energy savings compared to the business-as-usual scenario[1]

These binding targets apply to the union as a whole. The reductions in the ETS and non-ETS sector amount to 43 and 30 percent respectively by 2030 compared to 2005 (Council, 2014). The EU Emissions Trading System (ETS) puts a limit on emissions from high emitting industry sectors, within which companies can buy and sell emission allowances (Commission, The EU Emissions Trading System Factsheet, 2013). The methodology to set the national reduction targets for the non-ETS sectors will be continued until 2030, with efforts distributed on the basis of relative GDP per capita. All Member States will contribute to overall EU reduction in 2030 with the targets spanning from 0 to 40 percent compared to 2005.

The share of renewables of EU energy consumption is the sum of renewables in the electricity production (minus bio power) and total use of bio energy divided by total final energy consumption.

2.3 Assessing Energy Security with LIBEMOD

A crucial requirement when analyzing energy security is that LIBEMOD can provide the indicators. I have outlined that I consider gas dependency as a threat to the energy system. The costs of disruptions are larger the higher dependency on the commodity. This is in line with the long-term aims in the EU energy security strategy to reduce its dependence on particular supplies and fuels by maximizing the use of indigenous sources of energy (Commission, 2014).

[1] This is an indicative target based on the Energy Efficiency Directive implemented into national law of EU member states in June 2014. The target values for 2020 are fixed in Article 3 of Directive 2012/27/EU: the Union's 2020 energy consumption has to be no more than 1 474 Mtoe of primary energy by 2020. The target will be reviewed in 2020 aiming for 30 percent reduction by 2030. (Parliament & Council, 2012).

Less Russian gas can be a result of a more diversified portfolio of external supplies. Less gas relative to total energy consumption can be a result of increased domestic energy production. LIBEMOD has functioning energy markets that have effective long-term investment in energy systems and technologies. I will thus ignore the short-term robustness of the energy systems under scrutiny since the results are set for 2030.

The volume of net import of Russian natural gas is determined according:

(1) $Domestic\ production + Imports^{2} = Consumption + Exports + Transport\ losses$

such that total supply equals total demand. Many European countries are fully dependent on importing all the gas they consume, as they have no indigenous gas production. The last term on the demand side makes it possible to have more than 100 percent Russian gas in the gas consumption. Some of the traded gas is lost during transport[3]. The reported volume in LIBEMOD is the exported gas and will thus be somewhat higher than the volume inmported and finally consumed. The volumes of the losses are not reported and will be disregarded in the following implying that a net gas import from Russia constituting a greater share than 100 percent is the same as full dependency on Russian gas. The energy security measure is defined as:

a *= net gas import from Russia,* ***b*** *= total gas consumption,* ***c*** *= total energy consumption*

a/b *= dependency Russian gas* *&* ***b/c*** *= gas dependency*

Figure 1 displays the energy security situation in the calibrated equilibrium in LIBEMOD in 2009. Scoring in the northeastern part of the diagram indicates a poor energy security situation. For instance, Lithuania and Hungary have a relatively high dependence on natural gas (35 and 37 percent) and almost all of this gas is Russian. Malta, Cyprus and Iceland do not import any

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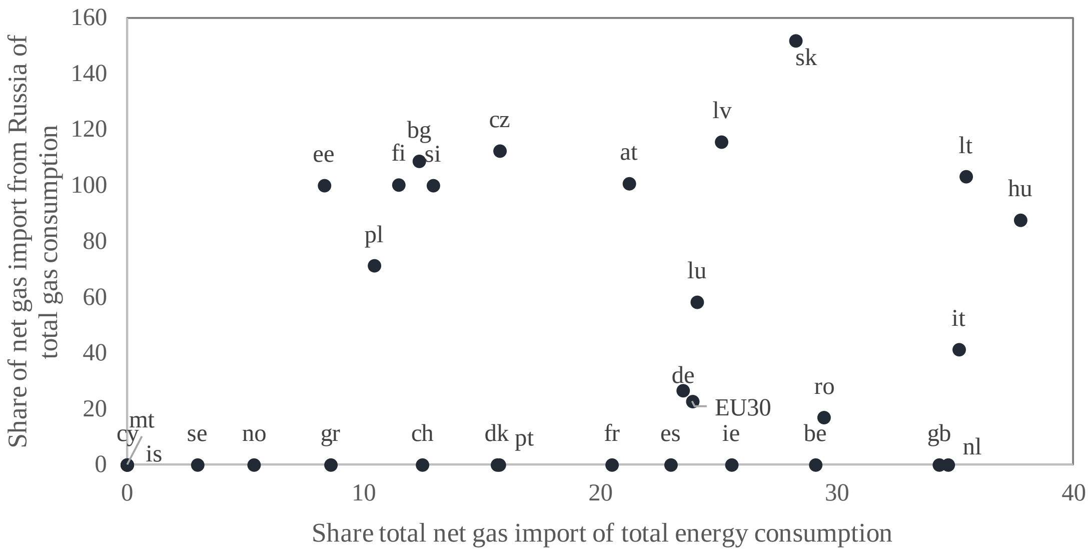
[2] I classify a country's import of natural gas into two; Russian gas or other sources of gas. In LIBEMOD, other sources of gas can come from the Rest of the World, LNG or other EU30 countries' production (mainly the UK, the Netherlands and Norway).

[3] This contributes to Slovakia being an outlier. Slovakia is a transit country, meaning that the loss in transport would be higher. With Slovakia consuming relatively small amounts of gas, the dependency becomes very high. Alternatively, the outlier can be a result of a poor calibration for Slovakia in LIBEMOD.

as and have a good energy situation accordingly.

Figure 1 Gas dependency EU30 countries in the calibrated 2009 equilibrium. Percent.



Quite a few countries are completely dependent on Russian gas for their gas consumption; Estonia, Finland, Bulgaria, Slovenia, the Czech Republic, Austria, Latvia, Lithuania and Hungary. Only the latter two have a notable share of gas in total energy consumption. These shares are relatively high compared to the EU total of 24 percent gas in the total energy consumption mix and 24.8 percent Russian gas. The EU30 includes countries with significant domestic production (like Norway, the UK and the Netherlands), which lowers the average.

Being dependent on gas is not a problem in itself, given a predictable supply. The European Commission made an in-depth energy security analysis in 2012 showing that some countries and areas are highly dependent on one source of supply. Figure 2 shows a map of countries highly reliant on a single supplier of gas. The darkest red color indicate that more than 60 percent of total gas supply comes from one single source. The analysis is thus focusing on Finland, Estonia, Latvia, Lithuania, Poland and Hungary[45].

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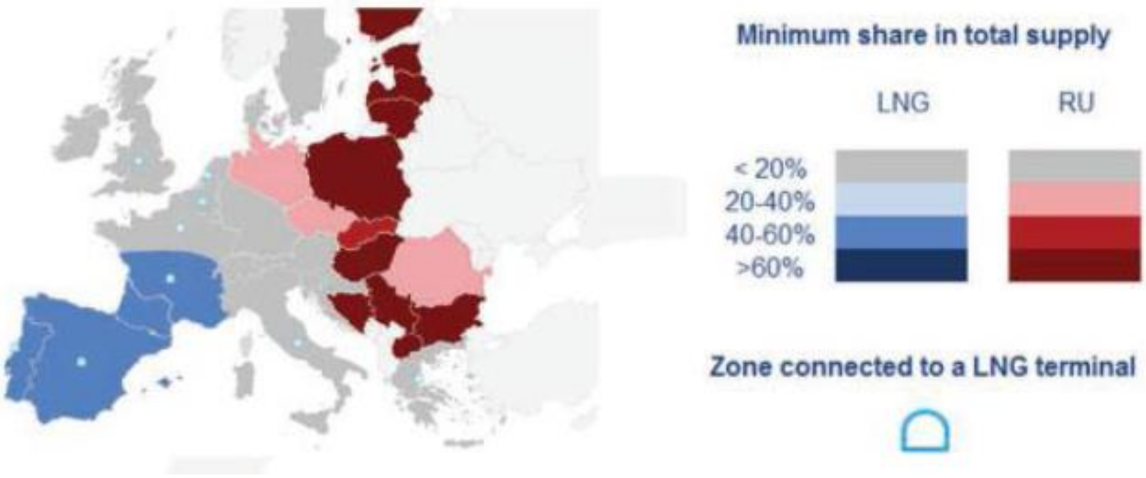
[4] Bosnia Herzegovina, Yugoslavia and the Republic of Macedonia are not model countries in LIBEMOD and are consequently not analyzed any further. It is worth noting that these countries where affected severely during the natural gas dispute in 2009 (OIES, Pirani, Stern, & Yamifava, 2009) and represents an interesting region when addressing energy security issues.

[5] I do not pay more attention to Bulgaria because gas imports from the Caspian region is projected to start flowing by 2020. In addition, according to the output in LIBMOD, Bulgaria imports only LNG in 2030.

Figure 2. Supply source dependence (natural gas) in 2013.



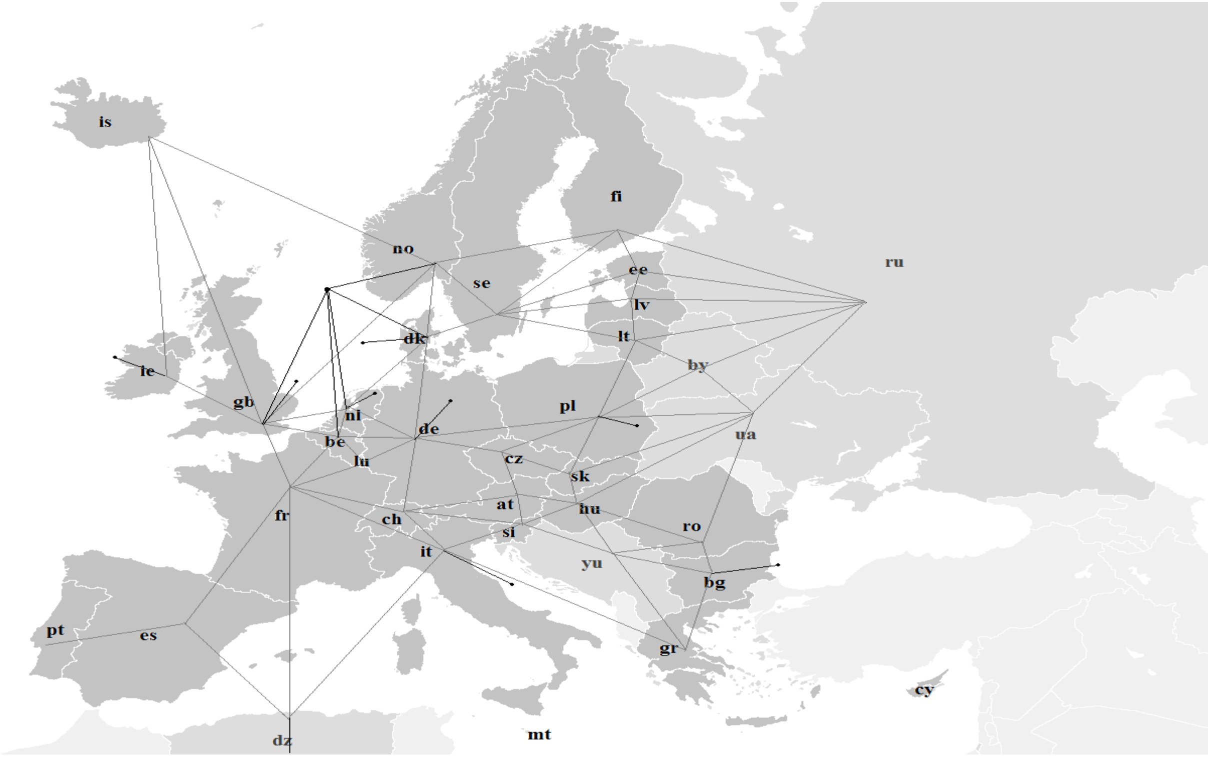
Source: (European Comission, 2012)

In the model, trade takes place only between pairs of countries. Following up on the Commission's approach, by counting the number of sources of supply, becomes trivial in LIBMOD. It is impossible to increase the *number* of suppliers of external natural gas supply for each country by 2030 in the model. The *volume* traded between the two nodes can change according to gas supply and demand, but the trade web remains unchanged.

A consequence of having trade between pairs of countries in the model is that gas is either directly imported from Russia, which is the case for Estonia, Latvia and Finland, or indirectly through transit countries. Many EU-countries import Russian gas indirectly. This complicates the calculation of the volume of Russian gas consumed.

The trade network in LIBEMOD is modelled to assimilate the real gas flows, which enables the assumption that all the gas passing through Ukraine is Russian. According to the trade matrix in LIBEMOD, Ukraine imports gas from Russia (western region "ru" on the map) and the rest of the world (row). The volume coming from the trade node row in LIBEMOD is a way of separating the traded volumes in the model according to real world pipelines. The gas Ukraine imports from the rest of the world (row) in the model is most likely gas originally extracted in Russia. The rest of the world (row) is exogenous which makes it impossible to clarify whether this gas for sure is Russian. Hence, I assume that the gas in LIBEMOD is either Russian or *other* gas, i.e. LNG or Norwegian, British or Dutch gas.

Figure 3. Map of potential trade nodes in LIBEMOD.



Source: LIBEMOD documentation 2009. Production nodes are black and consumption nodes are grey. The map is missing a trade connection between Ukraine and the rest of the world (row)

2.3.1 Gas Dependency as a Measure of Energy Security

There are many variables that may function as indicators of energy security: resource estimates, reserves to production, diversity indices, import dependence, political stability, the energy price, mean variance portfolio theory, share of zero-carbon fuels, market liquidity and demand-side indicators. In addition, there are some aggregated indices created in an attempt to define energy security uniformly (Kruyt, van Vuuren, & de Vries, 2009).

The energy security terms *Availability, Accessibility, Affordability* and *Acceptability* are in many ways incorporated into the dependency measures. Using LIBEMOD to assess energy security is convenient because the term *Availability* and subsequently *Accessability* is taken care of, by modelling that the more profitable reservoirs and energy resources will be extracted and developed first. In addition, running the scenarios contingent on the goal attainment of the EU 2030 Climate and Energy Framework attends a common perception of the level of *Acceptability*, namely the level agreed upon by the member states of the European Union. Addressing the term *Affordability* in an analysis of the coherence between climate and energy policies requires the use of a general equilibrium model in order to compare energy prices with the general price level in the economy.

The gas dependency measures indicate a degree of security for the households and industry sector, and consequently for the government as well. If the government runs the nation with the intention of maximizing the wellbeing of their citizens and ensuring a well-functioning economy, low dependency on imports from an unpredictable supplier reduces the potential negative consequences of a disruption. The values to protect by are the welfare and economic efficiency of the nation, of which adequate access to energy is crucial. The threat imposed to Europe, and the Eastern European Countries in particular, is a potential disruption by the Russian exporters and their inclination to use natural gas supply as a tool in conducting their political interests.

2.4 Overview of the Scenarios

In order to compare how more renewables affect the energy security in 2030 it is crucial to have a situation to compare with, a development without any shocks. This a situation with goal attainment in the EU's 2030 Climate and Energy Framework. The reference scenario is thus ensuring goal attainment of the climate policies such that the CO_2 emissions are 40 percent lower than the levels in 1990 and renewables constitute 27 percent of the energy mix. The renewable share was 14.1 percent in 2012 (Comission, u.d.).

The internal development in the Russian gas market is an important determinant for Russian exports to the EU. I construct a basis scenario by locking total Russian gas exports to the same level as in the base year 2009. The Russian gas prices to both households and the industry are regulated and have been significantly lower than the European gas prices. During the fall of 2013, the government decided to let real gas prices grow slowly from 2016, with the annual growth rate declining by 2030 (Aune, et al., 2015, s. 7). In LIBEMOD, these regulations appear as subsidies to end users such that the calibrated prices equals the observed market price in 2009. The adopted price reduction plans will thus correspond to lower subsidies in LIBEMOD, which is applied to all scenarios in this study.

Scenarios 2A – 2E assess how technological progress to renewables affect the energy security. LIBEMOD models technological learning by 2030. Technological learning takes the form of cost reductions followed by increased experience by the power producers (Lindman & Söderholm, 2011), The reference scenario incorporates an annual cost reduction rate of 3 percent for solar power. There are various estimates on how the investment costs for PV modules will develop by 2030 in the literature. Schröder et al. (2013) present a range of estimated investment costs between 600 - 1884 €/kW (Schröder, Kunz, Meiss, Mendelevitch, & Hirschhausen, 2013). Compared to the assumed investment cost in LIBEMOD in 2009 of 2545€/kW, accomplishing the range of estimated costs by 2030 corresponds to annual cost reduction rates between 1.5 – 6 percent. I assess the effects of increasing this rate from the initial 3 percent in LIBEMOD to 5 percent in scenario 2B, which implies a decrease from 2545 to 867 €/kWh from 2009 to 2030.

For wind power, the annual cost reduction in LIBEMOD is 1 percent such that the reference scenario has incorporates this development. Ek and Söderholm (2011) discuss the impacts on global and national effects on the learning curve for wind power and find a national learning rate of 2 percent in Europe (Ek, 2013). I am thus assessing an increase from the initial 1 percent to a 2 percent annual cost reduction rate for wind power, i.e. comparing the reference scenario with 2E.

The reference scenario comprises only two of the EU 2030 Climate and Energy Framework; emission reduction and an increased renewable share. In the long run, moderating energy demand is set out as one of the more effective tools to reduce the EU's external energy dependence and exposure to price hikes. LIBEMOD has already incorporated improvement in the energy efficiency by 2030, in line with estimates by the IEA. In scenario 3A and 3B I assume that the efficiency rates increase such that hypothetically, if the consumers are facing the same set of energy prices in 2030 they would consume the same amount of energy as in 2009, despite the growth income

The instruments the EU can use to realize these targets in LIBEMOD are a tax on CO_2 emissions (in both the ETS sector and non-ETS) and subsidies to promote renewables. The renewable subsidies from the EU come in addition to national subsidies, which are constant in the model. The common EU subsidies however are adjusted in order to reach the climate and energy targets. The model calculates the size of the subsidies and the CO_2 price, which are crucial figures in determining the new equilibriums. Scenario 4A and 4B assess the outcome of different targets in cutting the GHG emissions by 2030. These scenarios are included to evaluate how important the climate polices are for energy security.

Table 1 Overview of all the scenarios.

SCENARIO	CONTENT[6]
SC_2009	Calibrated equilibrium constituting the base equilibrium of the model
BASIS	• The ETS and Non-ETS sector in the EU comply the target of a 40 percent reduction in greenhouse gas emissions compared to the emission levels in 1990. • The share of renewables of total energy consumption is 27 percent. • Net gas export from Russia is locked to the same level as in 2009.
REFERENCE	• The ETS and the non-ETS sector in the EU comply the target of a 40 percent reduction in greenhouse gas emissions compared to the emission level in 1990. • The share of renewables of total energy consumption is 27 percent. • Trade with Russian gas is endogenously determined, constrained by the pipeline capacity. New investment in pipeline capacity between Russia and other countries is thus not occurring.
2A	As reference + an increase in the area available for sun power generation. The model assumes 0.5% of agricultural land will be available for solar power by 2050. Looking at an increase to 1%.
2B	As reference + an increase in the annual cost reduction rate for investment in solar power generation between 2009 and 2030. Changing from 3% to 5%.
2C	As reference + an increase in the efficiency of the transformation process of solar radiance to electricity. Changing from 18% to 21%.
2D	As reference + implementing the same changes as in 2A-2C. The “catch-all” scenario.
2E	As reference + an increase in the annual cost reduction rate for wind power from 1% to 2% between 2009 - 2030.
3A	As reference + increased energy efficiency rates in EU30 by 2030
3B	As reference + increased energy efficiency rates in Western Europe by 2030
4A	Almost as reference, but lower the emission target for 2030. Reducing from 40% to 20%.
4B	Almost as reference, but increasing the emission target for 2030. From 40% to 50%.
4C	Almost as reference, but increasing the renewable share to minimum 35 %.

[6] No subsidies to Russian gas consumers in all scenarios.

3 Energy Security in 2030

The path towards a low carbon economy by 2030 can be enforced through governmental policies or technological progress. The possible governmental policies that can be applied in LIBEMOD in order to enforce a low carbon economy are to change the targeted cut in CO_2 emissions, increasing the land available for solar power production or changing the targeted level of renewables in the energy mix. Technological progress on the supply side can occur by improved effectiveness in production and cost reductions. On the demand side, technological progress can result in energy savings.

This chapter presents the energy security development by 2030 in line with the climate policies of the EU. In the successive chapters, I describe in turn how technological progress and changing the climate policies affect the energy markets and the accompanied energy security situation. The successive analysis sections are compared to the reference equilibrium outlined in this chapter.

Table 2. Content of the main scenarios for 2030.

Both scenarios	• The ETS and non-ETS sector in the EU comply the target of a 40 percent reduction in greenhouse gas emissions compared to the emission levels in 1990. • The share of renewables of total energy consumption is 27 percent.
Basis	Net gas export from Russia is locked to the same level as in 2009.
Reference	Trade with Russian gas is endogenously determined, constrained by the pipeline capacity. New investment in pipeline capacity between Russia and other countries is thus not occurring[7].

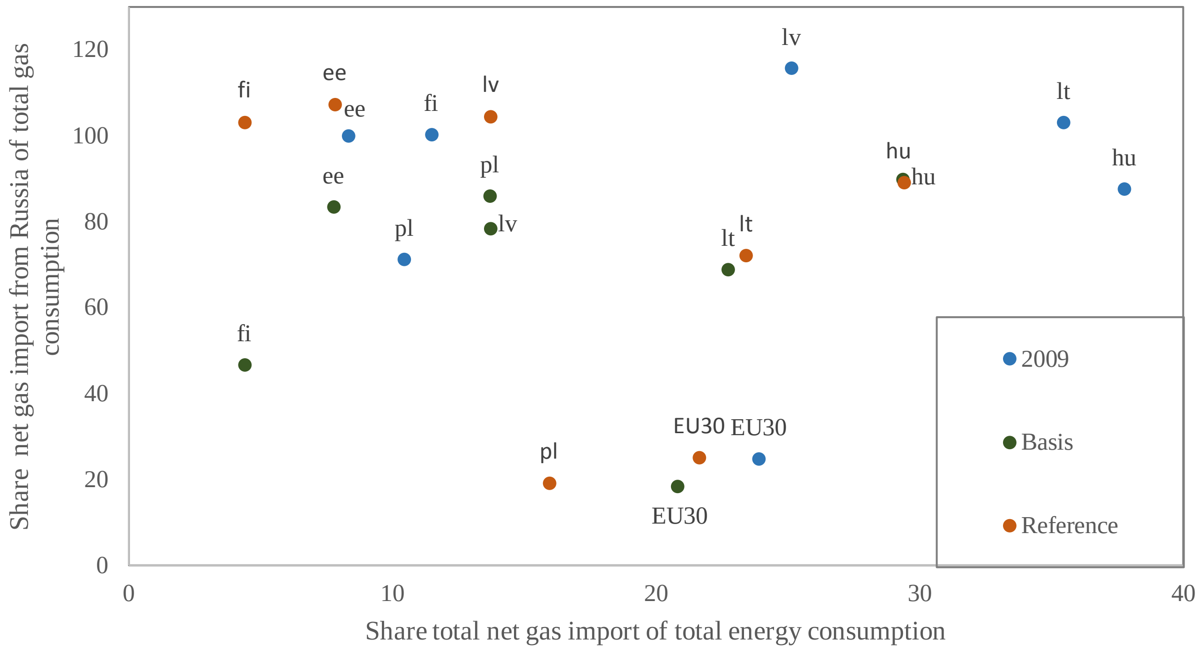
[7] Investments in transmission capacity are not modelled to be results of firm's optimizing behaviour. Russia is a post-communist country and politics plays and important part in the decision-making in energy business. This kind of decision making is overlooked in LIBEMOD by having no investment in transmission capacity between Russia and other countries.

3.1.1 Energy Security in the Reference Scenario

Energy consumption increases by 182 million tons of oil equivalents from the base year 2009 to the reference case scenario in 2030. Income and population growth drive the increase in energy consumption, based on World Bank projections. The economic growth rates vary between 0.6 to 4.2 percent among the model countries. There are higher growth rates in the Baltic States and Eastern European countries, averaging at 4 percent. Southern European Countries have lower growth rates, with 1 percent and below.

Figure 4 shows how dependent the Eastern European countries are on gas, and Russian gas in particular. The vertical axis shows the net import of Russian gas of total gas consumption while the horizontal axis shows the total gas consumption relative to total energy consumption in each country. All the vulnerable countries reduce their gas dependency by 2030 in the reference scenario, except Poland. Poland reduce their dependence on Russian gas and import more liquefied LNG in stead.

Figure 4. Gas dependency. Calibrated equilibrium 2009, Basis and Reference scenario 2030. Percent.

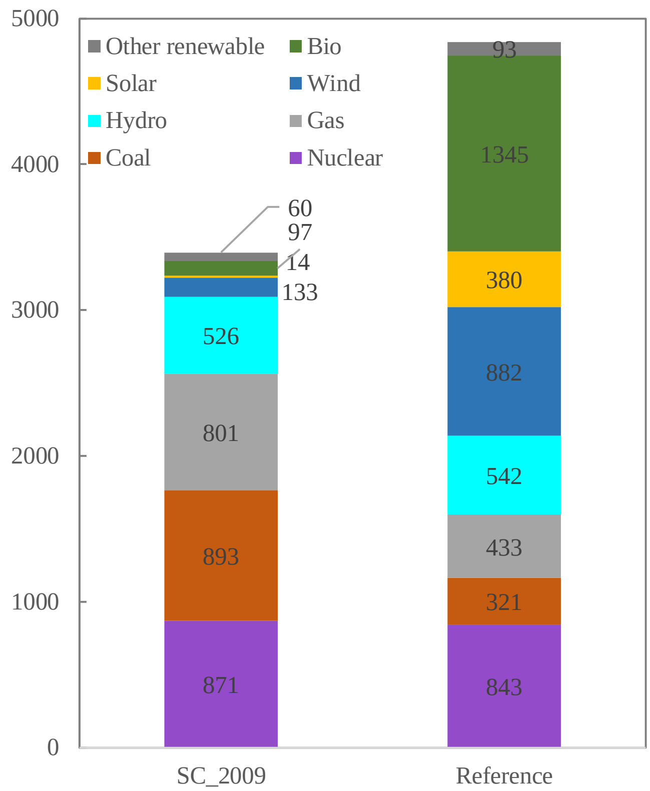


Gas constituted 24 percent of the total energy consumption for EU30 in 2009. This share decreases to 21.6 in the reference scenario. Gas has become less competitive due to the higher CO_2 price on emissions. In addition, more subsidies aid the competitiveness of renewable energy sources. Many of the renewable energy are favored in the aggregate power production because of the low marginal cost of production. All the vulnerable countries reduce their consumption of gas relative to total energy consumption. This is related to the new and higher share of renewables in the energy mix, imposed to be 27 percent.

Gas consumption relative to total energy consumption is decreasing by 2030, but the total import dependency of gas for the EU 30 has increases. Total EU gas imports relative to total gas consumption was calibrated to be 41 percent in the base year of LIBEMOD, and increases to 68 percent by 2030. Domestic gas reserves are extrapolated gradually as the demand for gas increases with income growth. The need for more imports over the time horizon is evident. More import is not worsening the energy security per se, the dispersion of gas suppliers are of greater importance. The dependency on Russian gas for EU30 increase slightly between 2009 and the reference scenario in 2030, from 24.8 percent to 25 percent.

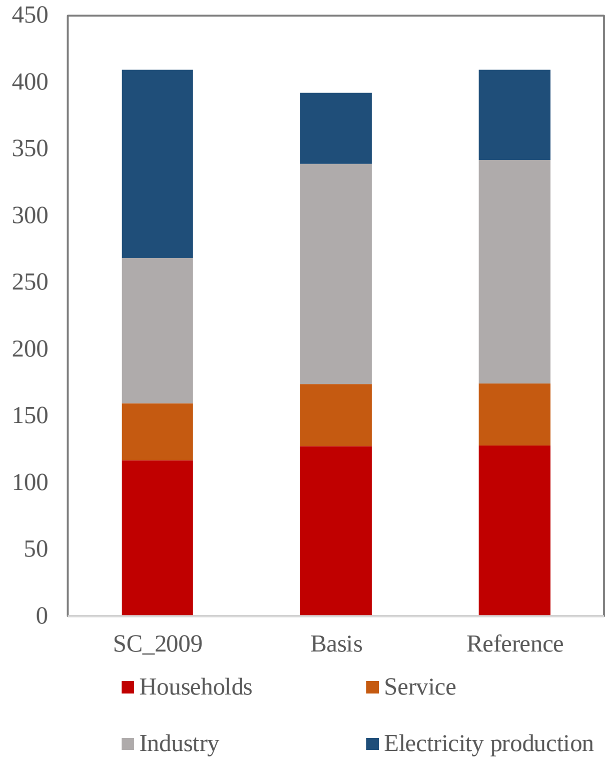
Power generation within the EU increases by 1445 TWh from 2009 to the reference case in 2030, an increase of 53.6 percent compared the 2009 level. Figure 5 displays the new distribution of the power generation. Coal and gas fired power generation decreases, respectively by 64 and 46 percent from the 2009 level. Renewables constitute a considerable higher share of total power production, increasing from 24 percent in 2009 to 67 percent in 2030. Bio power contribute the most, followed by wind and solar power. These technologies have increased 1290, 565 and 2596 percent respectively relative to the 2009 level. Hydro increases by 3 percent, while nuclear decrease with 3 percent. Other renewables is exogenous.

Figure 5. Power production in EU30 by source. TWh/year.



These changes are enforced by the EU policy changes. The pricing of CO_2 contributes to this new composition, with a cost of 11.4 Euro per ton CO_2 emission in the ETS sector. This is a rather modest increase compared to today's level: the CO_2 price was 8.51 EUR/ton CO_2 on the 1st of December 2015 (European Emissions Exchange, 2015). The price for the non- ETS sector is 242 EUR/ton CO_2. This considerable difference shows that relatively more effort is placed in the non-ETS sector in order to reach the targets.

Figure 6. Distribution end user gas consumption. Mtoe.



Producer prices for electricity and gas have decreased. All the fossil energy sources experience higher prices due to the taxing of emissions. Bio fuel and bio mass have become more expensive due to both the scarcity of the energy source in combination with the need to exploit it in order to reach the climate and energy goals for 2030. Gas is also subject to the CO_2 price but emits less GHG emissions than coal and oil fired power production. Total gas use in power production is almost half of the level in 2009 (see figure 5, where gas decreases by 368 TWh/year). This decrease is considerable, but seeing that gas still constitutes a notable share of total energy consumption (21 percent) gas is consumed by the other end users in stead.

Figure 6 shows the new composition of gas demand from 2009 to 2030. Total gas consumption in Mtoe has not changed much from 2009 to the reference scenario. With higher subsidies for renewables and the higher costs of producing with emitting technologies there are cheaper ways of producing electricity than with gas. The excess supply of gas is absorbed by the other gas consuming sectors at lower prices. As indicated by figure 6, this effect is stronger by the industry sector, but households increase the consumption of gas somewhat too. Table 3 displays the new set of energy prices fort both consumers and producers in 2030. The producer prices for electricity and gas decrease, while the other increase. The dynamics causing this is further assessed in the next chapter.

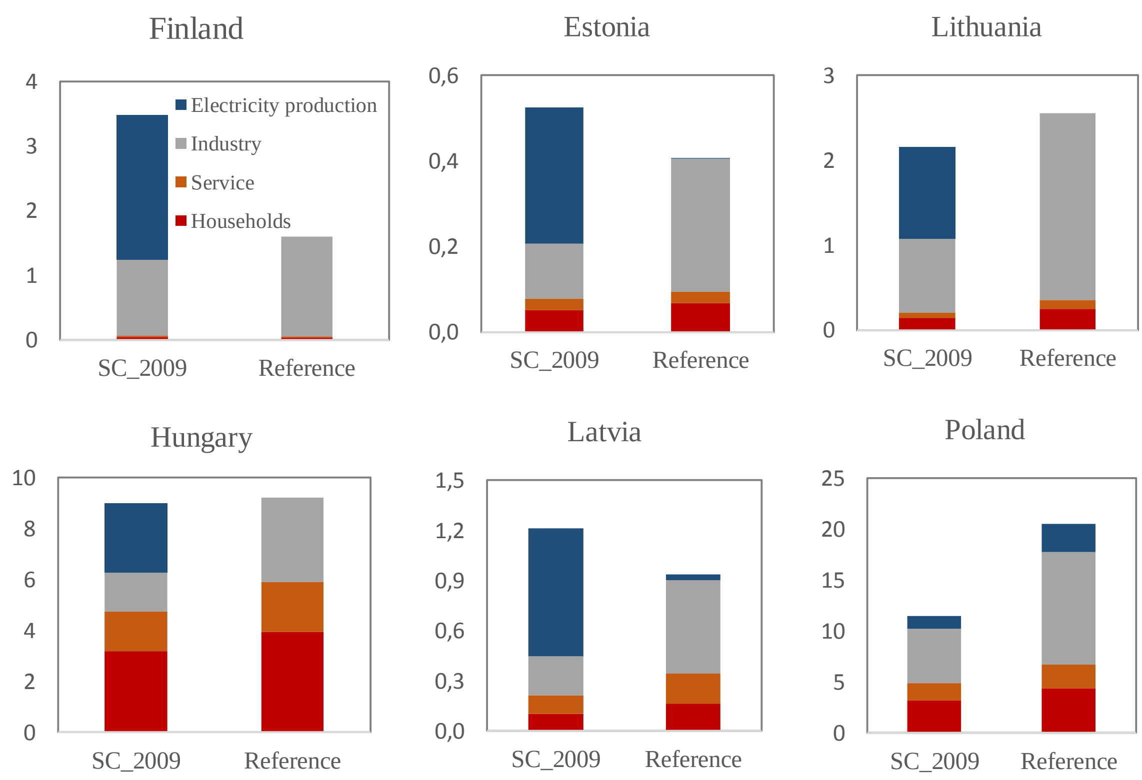
Table 3. Consumer and producer prices. EUR/Mtoe (EUR/TWh for electricity)

Consumer prices	SC_2009	Basis	Reference	Producer prices	SC_2009	Basis	Reference
Electricity	132	103	102	**Electricity**	51	41	40
Gas	504	607	583	**Gas**	199	148	138
Steam coal	137	325	350	**Steam coal**	102	116	116
Coking coal	215	280	279	**Coking coal**	188	208	208
Oil	862	1771	1776	**Oil**	326	555	556
Biofuel	1235	1531	1520	**Biofuel**	1008	1270	1270
Biomass	263	201	198	**Biomass**	43	102	102

.

The shift in the consumption distribution limits the share of gas in power production that the renewable energy sources can suppress beyond the level in the reference scenario. Figure 6 shows the new composition for the EU30 countries as a whole. The distribution of gas can vary between countries. Figure 7 displays the new composition within the vulnerable countries outlined in section 2.3.

Figure 7. Consumption distribution gas vulnerable countries. Mtoe.



According to the figures above, all countries but Poland, Estonia and Latvia stop generating power with gas in 2030. Gas consumption has increased in Lithuania, Hungary and Poland. In the former two, this comes from the household sector and industry sector respectively. In Poland, all sectors increase their use of gas, as it is a good substitute for coal. The fact that gas has ceased to work as input in the power generating sector in many countries limits the possibilities for renewables to improve the energy security beyond the situation in 2030.

3.1.2 Energy Security in the Basis scenario: Exogenous Russian Exports

The basis scenario is almost like the reference scenario, only that total net gas exports from Russia is locked to the level in 2009. This also causes less exports of Russian gas to the EU, causing a considerable improvement in the dependency on Russian gas, down from 25 percent in the reference scenario to 18.3 percent in the basis scenario. Finland, Latvia and Estonia benefit in terms of an improved energy security situation, with gas constituting only 18 percent of the gas consumption in the basis scenario. The difference in Russian gas exports between the basis and the reference scenario is 30 Mtoe. Germany has better possibilities of choosing its sources of energy supply than the Eastern European countries due to its geographical location. I do not consider this increase a threat to the energy security of Germany.

The European gas demand increases over time due to economic growth. Without limits on the total Russian gas export, all incremental gas demand would need to come from somewhere else. The countries resolve to other sources of gas imports such as LNG. Total LNG imports are approximately 10 Mtoe higher in the basis scenario than in the reference scenario and do not replace the cessation of the cheaper Russian gas. The limited inflow of gas reduces both total gas consumption and total power production in EU30 compared to the reference scenario. Naturally, this reduction goes for gas power production in particular. Coal power production is replacing some of the lost gas power, which requires a higher CO_2 price in order to reach the climate targets. The higher CO_2 improves the relative competitiveness of bio power, which is the renewable power source that increases with a noteworthy degree[8]. Limiting the total supply of gas pushes up the gas and electricity prices too (see table 3). If aiming for a certain degree of affordability in the definition of energy security, this element dampens the initial improvement in energy security.

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[8] The dynamics in the gas and electricity market causing these changes is examined more thoroughly in chapter 4.

The energy prices are lower in the reference scenario than in the basis scenario. Allowing for more gas imports than in the basis scenario increases total supply and contributes to the fall in the European gas producer prices, from 199 Eur/Mtoe in the basis scenario to 138 Euro/Mtoe in the reference scenario. With a higher consumption of Russian gas in the reference scenario, the EU needs to increase the subsidies to renewable energy sources in order to reach the renewable target. The common European subsidies increase from 8.1 in basis to 9 euro per MWh for renewable power production in the reference scenario.

3.2 Summary Energy Security 2030

Table 4. Net import of Russian gas (Mtoe), gas and energy consumption (Mtoe) and gas dependency (percent). From calibrated equilibrium in 2009 to Basis and Reference in 2030.

	SC_2009	Basis	Reference
Russian gas net import EU30 (Mtoe)	102	72	102
Total net gas consumption EU30 (Mtoe)	409	392	409
Total energy consumption EU30 (Mtoe)	1709	1884	1891
Dependency Russian gas (%)	24.8	18.3	25.0
Gas dependency (%)	24.0	20.8	21.6

** Net import Russian gas/total gas consumption*
***Total gas consumption/ Total energy consumption*

The output from LIBEMOD indicate that the climate policies for 2030 fulfill the same objectives as the long-term objectives in the EU's energy security strategy. Accomplishment of the climate policy targets implies a standstill in the total gas consumption, while the total energy consumption is increasing due to economic growth by 2030. The total gas dependency is thus decreasing, from 24 percent in 2009 to 21.6 percent in the reference scenario in 2030 (see table 4). The new set of energy prices cause a redistribution of the total gas consumption, from the gas power producers to the industry. The effort made in the 2030 Climate and Energy Framework increases the deployment of renewable energy sources which improves the energy security in regions that can deploy more of the renewables. All the vulnerable countries install more wind power and all but Latvia and Estonia install more bio power from 2009 to the reference scenario. Only Hungary install some more solar power by 2030. Finland, Hungary and Lithuania decrease the gas consumption considerably by 2030 and they stop using gas in power production entirely. The dependency on Russian gas improves considerably in the basis scenario. The imposed cap on Russian exports limits the EU's consumption of Russian gas, experiencing an increase in the import of alternative energy sources, such as LNG.

4 Renewable Power and Energy Security

We have seen that the policy measures in the 2030 Climate and Energy Framework are improving the energy situation by 2030 to some extent. This chapter analyzes effects on energy security of a more rapid technological progress for renewable energy sources than already accounted for in the reference scenario. I am presenting the market dynamics, price and quantity effects in 2030 due to shocks in the renewable power producing technologies solar and wind power. A main feature of the analysis is whether more solar or wind power can suppress gas in power generation and in the consumption by end users in order to reduce the gas dependency beyond the level in the reference scenario. Table 4 displays the scenarios under scrutiny in this chapter.

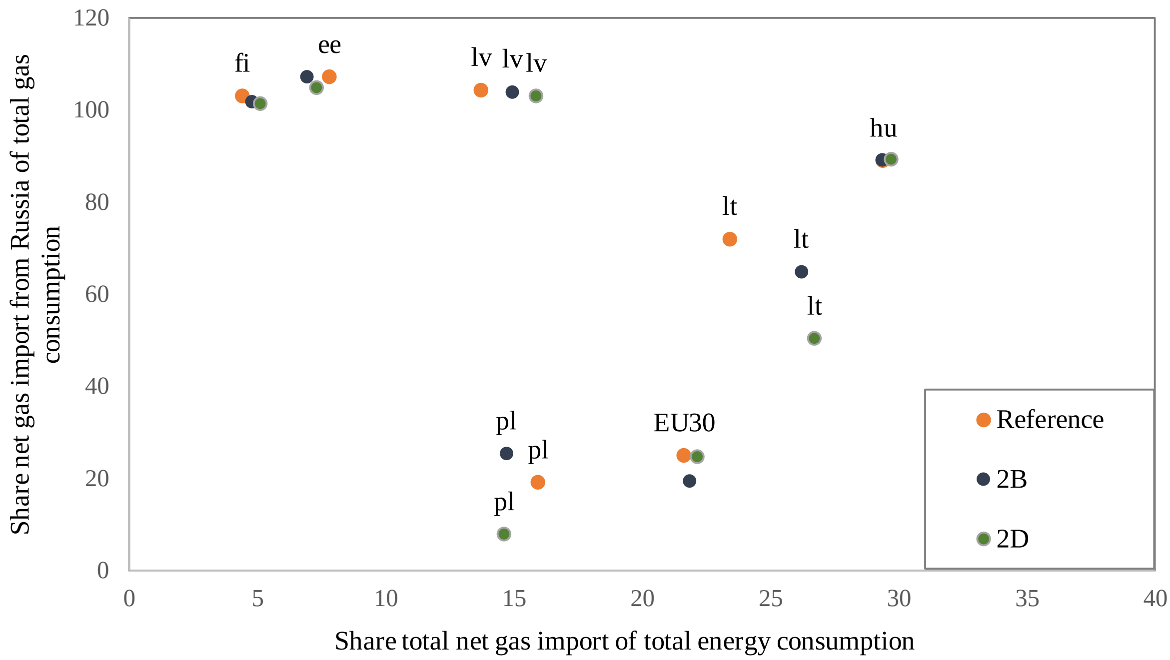
Table 5. Scenarios renewable energy

	DESCRIPTION
2A	As reference + increasing the share of agricultural land available for solar power. From 0,5 to 1%
2B	As reference + increasing the annual cost reduction rate for investment in solar power, from 3 to 5 %
2C	As reference + an improvement in the solar power technology. Increasing the efficiency rate of transforming solar radiance to electricity from 18 to 21 %
2D	“Catch-all” scenario. As reference + implementing the same changes as in 2A-2C
2E	As reference + increasing the annual cost reduction rate for investment in wind power. From 1 % to a 2 %annual cost reduction rate.

4.1 Solar Power

Two effects must occur if solar power is to suppress gas in the European energy mix. Firstly, it must replace some gas in the electricity production. Second, the end users must replace some of their gas consumption with electricity. Figure 8 indicates that improvements in solar power affects energy security differently according to the geographic spread. The EU in total is marginally affected by the improvement in solar power, there is a small increase in the gas dependency when comparing the reference and catch-all scenario. Lithuania, Latvia and Poland however, are affected more. The dependency on Russian gas decrease in Lithuania, but the general gas dependency increases. LNG constitutes a greater share of the total net gas imports. Latvia has also increased their dependency on gas, without any improvement in the dependency on Russian gas. Poland is the only country to reduce its gas dependency. The trend for all the countries is however that the greater the improvement in the solar power technology, represented as the change between 2B to 2D, the higher the gas dependency.

Figure 8. Gas dependency. Reference and Solar power scenarios 2B and 2D. Percent.



The remaining of the chapter is devoted to explaining why the energy security situation has changed. I explain the dynamics the shocks to solar power cause in the electricity and gas market theoretically and explain the partial effects affecting the new equilibriums. Finally, I assess the total effects in the new equilibriums from LIBEMOD.

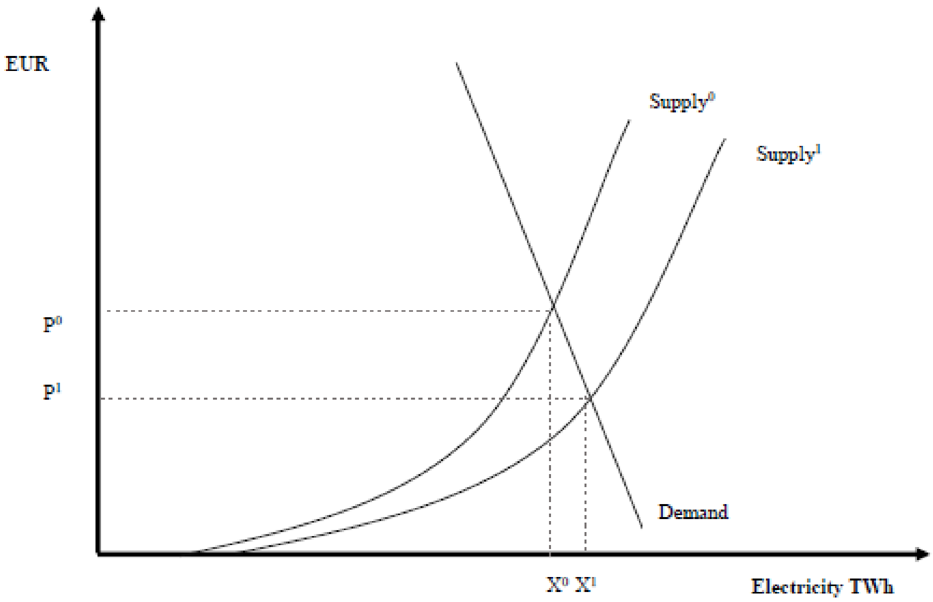
4.1.1 The Interplay Between Gas and Solar Power in the Electricity Generation

The different shocks in solar power cause increased investment in solar power. Once the solar power plants are built, and investment costs are sunk, the solar power plants will always produce at full capacity because the solar radiance comes for free. The cost of input in production is zero.

Figure 9 illustrates the shock in solar power to the electricity market. With subsidies for renewable power, power can be produced at negative producer prices. Shocks to solar power change the need for subsidies to renewable power, which in itself causes a new shape of the supply curve. The partial and total effects of changing the subsidies are discussed later. The curves in figure 9 are a theoretical illustration of the electricity market without governmental intervention. Alternatively, one can think of the analysis being conducted with constant policy variables.

The increase in solar power production affects the merit order of the marginal cost curve for electricity generation by skewing it to the right. The range of the supply curve between the origo and the point where the marginal cost curves have positive values represent the marginal costs of some of the renewable technologies being close to zero. The demand curve for electricity is falling in the price of electricity (denoted in euros). The costs of producing electricity is increasing in quantity, as more costly technologies must be applied the more is produced[9]. The initial price of electricity before the shock to solar power is where the demand curve intersect with the supply^0 curve. Once the shocks to solar power take effect in the form

Figure 9. Electricity market. Shock in solar power.

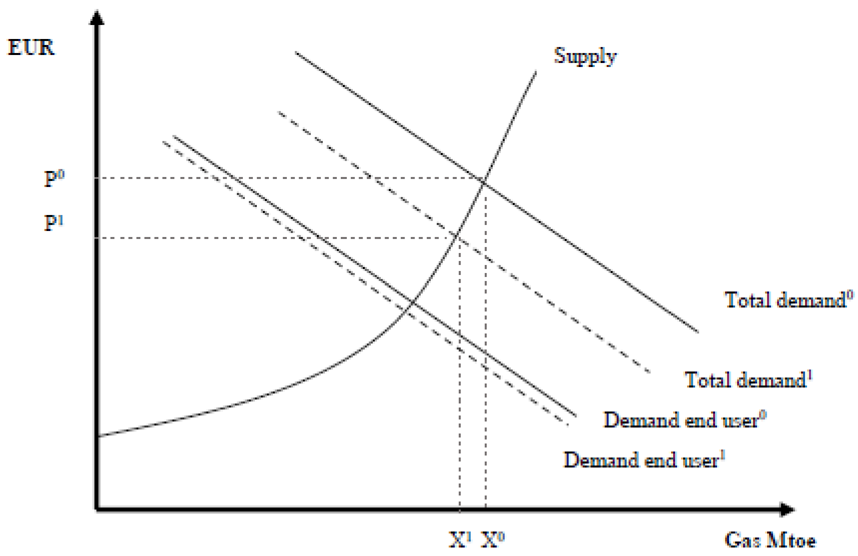


of an increase in the total power production, the aggregated marginal cost curve is skewed to the right. The consumers absorb the excess supply of electricity at lower prices, there is a movement along the demand schedule. The new equilibrium is found at the lower price P^1 and the higher quantity X^1. All the solar scenarios affect the market in the same direction but to a varying extent.

[9] This sketch applies for no changes in policy variables, but it is worth noting that the supply curve would become steeper (gentler) for large quantities if the CO_2 price is higher (lower) as the last power units are produced using emitting technologies such as coal and gas.

Figure 10 illustrates changes in the gas market due to the shocks in solar power (for constant policy variables). The total demand schedules represent the aggregate of all the sectors' demand. Total demand less end user demand equals the gas demand by the electricity producers. Shocks to solar power cause electricity prices to fall. As both the electricity producers and the end users adapt by using more of the cheaper electricity instead of gas, their demand schedules shift downwards in the diagram. They are thus demanding less gas for any price level. This is illustrated as a shift in both total demand^0 and end user demand^0 to total demand^1 and end user demand^1. The new equilibrium is the result of both the reduction in demand by electricity users and end users. The new equilibrium is found by moving along the supply schedule, where the supply and total demand^1 intersect. The new price P^1 clears the market, and the corresponding quantity is X^1.

Figure 10. Gas market. Shock in solar power.



These schedules are drawn arbitrarily and are displayed to illustrate the dynamics in the market. The supply schedule for gas in the real world would be based on figure looking more like a staircase, representing the marginal costs of the different gas extraction fields. A typical characteristic of gas extrapolation is a steep marginal cost curve. The quantum reduction of gas is thus dependent on the initial level of production. I will discuss the actual output from LIBEMOD shortly.

I have drawn a larger shift in the total demand curve than in the end user demand. There is a greater substitutability between electricity and gas in the intermediate demand from electricity producers than by the end users. Gas power production is modelled according to the technology with price being the main variable causing new adaptions. End users on the other hand, are modelled with a complex demand structure. The initial shock in power production spreads through the economy and reduces all energy prices. This causes a reduction of gas by end users too, but less than in the power producing sector. In addition, consumers optimizing according to the new set of relative prices can imply a potential tilt of the demand schedule. The cross price elasticities in LIBEMOD are however calibrated to be very small, these effects are thus subordinated and disregarded in the illustration.

4.1.2 Short and Long Run Dynamics in Power Production

Since the cost of solar radiance is zero, the solar power producers optimize their objective function by always producing at full capacity. They are simply producing electricity whenever the sun is shining. Gas power producers on the other hand, have more constraints limiting their (optimal) behavior. The fossil fuels power producers optimize with respect to how much electricity to produce, how much capacity to maintain and whether to ramp up production, incurs additional costs. The gas power producers optimize their level of production at the point where price equals marginal cost, if the shadow prices on a set of alternative actions are equal to zero. For further details, see the appendix, equation A.10. The fuel input requirement will dampen the competitiveness of gas power production over time, because the increasing costs of gas extrapolation in line with the scarcity of extracting additional units of gas.

All power producers need to have some down time to maintain their plant. LIBEMOD introduces this constraint by limiting annual production to a share of the maintained capacity (Equation A.13 in the appendix). The optimality condition for maintained capacity states that the cost of increasing the capacity marginally should be equal to the value of increased annual production following from maintaining that additional capacity unit. The costs of maintenance are the maintenance costs themselves plus the forgone profit which the unmaintained capacity unit could have produced alternatively during the down time.

The foregone profit on the margin by performing maintenance for new gas power plants is higher than for solar power, because the solar power plants can perform maintenance when the sun is not shining. This indicates that the *total* maintenance cost is lower for solar power, (given that the cost of doing the maintenance itself is equal across power plants). This cost element favors solar power in electricity production in the short run.

The power producers invest for the future, even though LIBEMOD is a static model. The model allows for investment in new capacity for the year we are assessing, 2030[10]. The optimality condition for new investment for gas power producers states that if new investment is to be positive, the total annualized investment cost is equal to the additional gain in revenue from the last unit of installed capacity (Equation A.15). This investment criterion changes according to the initial level of production of the different technologies, thus over scenarios and time. New investment in solar power plants takes place at the best site for solar power first, then the second best etc. The more solar power that is invested, the less will an additional capacity unit yield.

4.1.3 Dynamics in the Power Market

The difference in the technology and the cost structure of gas and solar power plants says something about the substitutability between those two energy sources in the electricity production. Price responsive behavior is important in determining the new power market equilibrium with shocks to solar power, but changes in the EU subsidies for renewables and adjustments of the CO_2 tax affect the outcome too. The partial effects are described in turn below.

Price responses: As solar becomes cheaper, other renewables and other fossil fuel based electricity production becomes relatively more expensive. The adaption in power generation with a higher share for solar power reduces the demand for the alternative input energy sources. Prices decrease for the alternative energy sources too. Isolated, this spill over effect dampens the initial improvement in the competitiveness of solar power somewhat as solar power becomes relatively more expensive again. These changes occur simultaneously in LIBEMOD.

Subsidies: With more solar power than in the reference scenario, there will be excessive investment in solar power and over fulfillment of the targets in the 2030 Climate and Energy Framework if the subsidy levels remains unadjusted from the reference scenario. The improvements in technology and reduction of costs in solar power reduce the need for subsidies in order to reach the minimum renewable energy share of 27 percent, and the subsidies are

[10] The investments in different technologies occur simultaneously and the final outcome for 2030 can be viewed as a jump in time to this new time period. The model does not say anything about the details on the path towards this new equilibrium.

subsequently reduced[11]. The reduction in subsidies reduces the profitability of other renewable energy sources. The EU subsidy is a common for all countries. This implies that renewable power production in areas where the new solar power capacity is not installed will receive less subsidies too. Table 6 shows that the common European renewable support decreases in all the scenarios, relative to the level in the reference scenario. The reduction is greater in the catch-all scenario, falling from 9 Euro/MWh in the reference scenario to 5 Euro/MWh in the catch-all scenario.

The CO2 price: With an improved competitiveness for solar power, the zero emissions PV technology will contribute a larger share of the aggregate power production. As a consequence, the total amount of GHG-emissions decrease. LIBEMOD captures the GHG-emissions reduction goals as a target level of CO_2 emissions. The target will be easier to achieve with more solar power, implying that the CO_2 price need not be as high as in the reference scenario. Table 6 shows the level of CO_2 tax in the different scenarios. The tax decreases more in the catch-all scenario, from 11.4 EUR/ton CO_2 in the reference scenario to 9.4 EUR/ton CO_2.

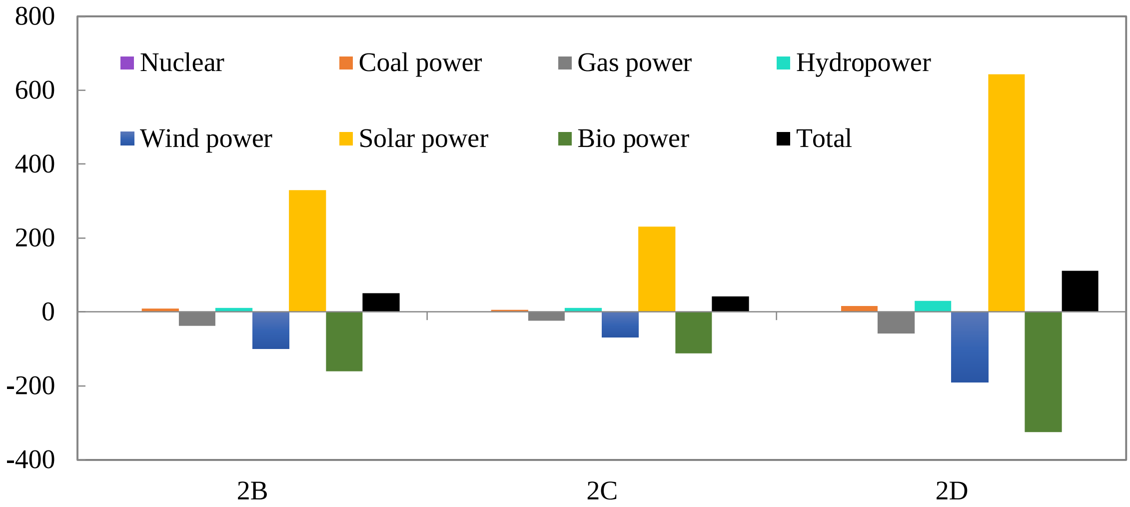
Table 6 CO_2 price (EUR/ton CO_2) and renewable support (EUR/MWh). Solar power scenarios

	Reference	2B	2C	2D
CO_2 price ETS (EUR/ton CO_2)	11.4	9.9	1.3	9.4
Renewable support (EUR/MWh).	9.0	7.0	7.6	5.0

Total effects: Figure 11 shows the total effects in the power market, i.e. changes in TWh electricity produced by different electricity technologies from the reference scenario according to the different shocks to solar power. The results from the scenario with increased availability of agricultural land (2A) for solar power are omitted because the results were marginal. The dynamics of the effects are the same in all scenarios and vary only in the impact degree. I am thus focusing on the results in the catch-all scenario 2D.

[11] In the real world, there is likely to be time lags between observing an increased cost reduction rate and responding to the shocks. LIBEMOD does not take the time lags into account. In addition, the long time horizon minimizes the risk of these rigidities occurring.

Figure 11 Changes from reference scenario in power production by source. Solar power scenarios 2B-2D. TWh.



Total power production increase in all the scenarios. Solar power increases by 642 TWh from the reference scenario. An increase of 169 percent. Solar power constituted 8 percent of total power production in the reference scenario. With the speed up of the technological development, this share increases to 21 percent in the catch-all scenario (2D). Table 7 shows the price changes from the reference scenario by energy source. The electricity price decreases approximately by 8 percent in the catch-all scenario. The producer prices electricity decrease more than for the other fuels, as the shock hit in the power generating sector in the first place.

Table 7. Total change in producer prices from the reference scenario by energy source. Percent.

	2B	2C	2D
Electricity	-4.06	-3.08	-7.91
Gas	-1.82	-1.32	-2.27
Steam coal	0.01	0.10	-0.18
Coking coal	-0.03	-0.02	-0.04
Oil	0.00	0.00	0.00
Biofuel	-0.05	-0.03	-0.09
Biomass	-13.62	-9.57	-25.03

The renewable power generation reduces because of receiving less revenue for each unit sold, and receiving less subsides per unit produced. The only renewable power generation to increase, despite the lower subsidy, is hydro power. Hydro is modelled with three technologies in LIBEMOD; reservoir, pumped storage and run-of-river power. The reservoir and run-of-river power technology produce at full capacity whenever the water is running in the rivers and there has been sufficient trickle of water. The pumped storage producer buys electricity in one period and uses that energy to pump water up to a reservoir in order to produce electricity in a different period, by letting the water flow down again. To profit from this, the electricity is bought when cheaper, i.e. during the night when demand is low, and sold again at higher prices during the day. Pumped storage increases by 36 TWh from reference to the catch-all scenario, while pumped and reservoir remain unchanged. Production with pumped storage can be realized in these scenarios because more solar power production causes a greater price difference between day and night. The input of more pumped storage is smoothing the price differences between day and night.

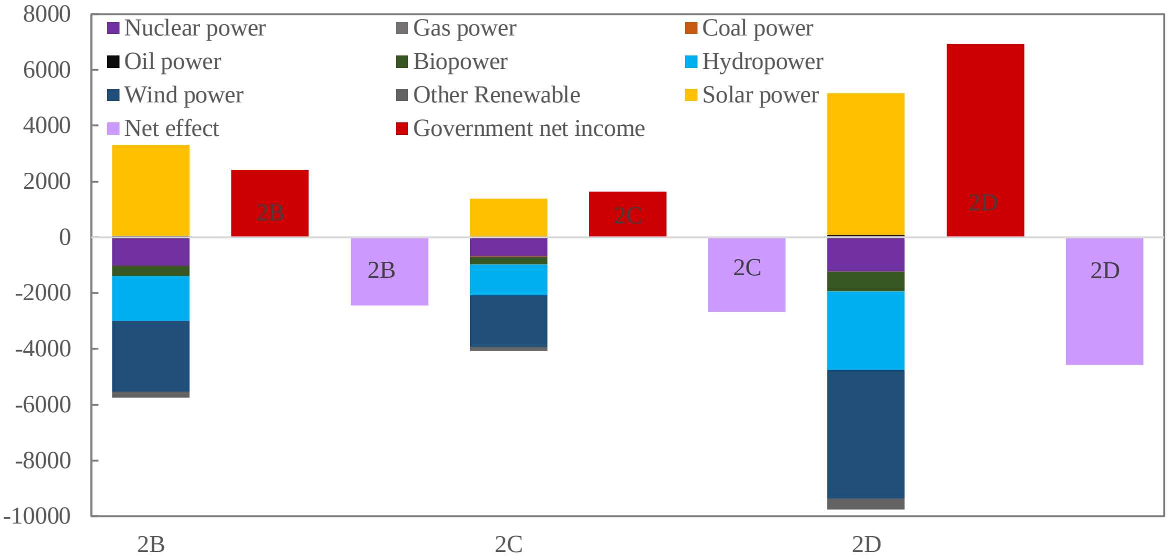
Nuclear power production is unaffected by the shock to solar power and the lower power prices. In nuclear power plants, the time and cost to start up and shut down make it infeasible to vary the used capacity between time periods and seasons. In addition, there are no ramping up costs and the price of the input uranium is exogenous in LIBEMOD. All the nuclear power is produced with old nuclear plants in the updated version of LIBEMOD used in this thesis. The model restricts investment in new nuclear power plants .

The lower CO_2 price improves the competitiveness of the emitting power plants, such as gas, coal and oil-fired plants, relative to the non-emitting electricity producing technologies. The gas and coal power production is reduced slightly in the solar power scenarios. Gas power production reduces with 60 TWh in the catch-all scenario, a decrease of 14 percent from the reference scenario. This means that the effect of the reduced electricity price due to more solar power dominates both the effect of the reduced CO_2 price and the benefit of reduced input costs as gas prices fall as well (2 percent in the catch-all scenario).

4.1.4 Profit Distribution and Welfare

The price and quantity changes cause new allocations of profits, displayed in Figure 12. With lower electricity prices the power producers receive less earnings for each unit sold, causing a reduced surplus for all electricity producers, except solar power producers. With marginal costs close to zero, the solar power producers will benefit from a larger volume produced at any (positive) price level. Wind power producers experience the highest reduction in profits, followed by hydro power, bio power, nuclear and other renewables. These producers experience both a price and volume decrease. The gain by the solar power producers does not outweigh the loss by the other power producers (the pink bars), i.e. the net effect for all power producers is negative.

Figure 12. Change in profits in power generation from reference scenario to solar power scenarios. Government net income. Million 2009-Euro.



The affordability perspective in energy security states that energy should be supplied to the consumers at affordable prices. Classic energy security studies dealt with the economic risk caused by variable oil prices. Ensuring low oil prices was desired by the politicians. Moving towards a low carbon economy by accomplishing the targets within the EU 2030 Climate and Energy Framework can turn the affordability element upside down. Some of the reluctance towards investing in renewable power generation in 2015 originates from the risk of negative prices that the power producers face. While energy security measures in the 1970's were implemented to protect consumers, one can imagine that the power producers becomes a vulnerable group in 2030.

If the affordability perspective is to be applied to of energy security, the energy prices needs to be compared to the other prices in the rest of the economy in order to provide any useful information. A more comprehensive measure of affordability could be welfare changes. LIBEMOD provides the changes in welfare components relative to the reference scenario. The results in the catchall scenario indicates a positive net welfare effect for the EU30 compared to the reference. However, the welfare changes does not consider that the shocks and policy changes may influence other sectors of the economy. To do that, a general equilibrium model is needed. In addition, changing the parameters in LIBEMOD comes at no additional cost. This does for instance imply that there are no costs associated with increasing the land available for solar power production[12]. Efforts made to improve the technology of solar power, say costs spent on research to achieve the new level of technology, are not modelled.

Moreover, LIBEMOD does not take into account that the budget of the government must balance or that there could be possible distortive costs of implementing taxes. Changing the subsidy level comes for free as well. LIBEMOD does however report the net effect of changing the subsidies and the CO_2-price. In the solar power scenarios, does the lower CO_2 price imply less revenue for the government for each TWh produced with emitting technologies. The volume of power generated with emissions reduces slightly compared to the reference scenario, further contributing to the lower revenue. The considerable adjustments in EU subsidies will affect the government surplus positively. The effect of the decreased subsidy is larger, implying a positive net effect on government income of the changes in these two variables (see Figure 12)

4.1.5 Substitutability of Gas by End Users

The second option for solar power to suppress gas for the entire energy economy is that the consumers can replace some of the final gas demand with electricity. The lower electricity prices causes additional effects in the economy. End users, i.e. households, industry, service and electricity producers consume more electricity when it becomes relatively cheaper because consumption between nests can be substituted. The degree of substitution however vary across sectors. The substitution effect of lower electricity prices implies a lower demand for all other commodities than electricity (such as gas, oil and coal), both as input in power generation and for end users. The income effect of lower prices reduces the total expenditure of end users for unchanged consumption quantities, which contributes to an increase in demand for all commodities. Commodities consumed within the same nest are complementary goods, implying that an increase in the use of electricity also implies an increase in the demand for the electricity using commodity.

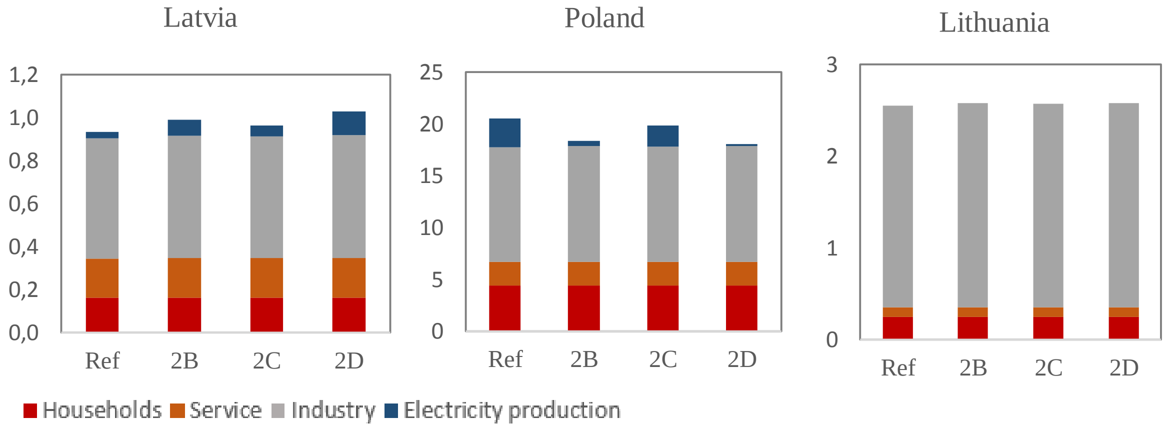
Total energy consumption in the EU30 decreases from the reference scenario to the catch-all scenario of solar power. It seems a bit surprising at first given that all energy prices fall compared the reference scenario. The reduction in total energy consumption comes primarily

[12] The opportunity cost of more land to solar power is the forsaken value creation from agricultural production on the fields allocated to solar power.

from a reduction in the consumption of biomass, and secondly gas consumption. The reduction in biomass is a result of less supply when the subsidies to renewables decrease. The demand for biomass decrease too, because the energy prices of the alternative goods fall and the consumers are replacing some of the biomass with the cheaper energy goods. Subsequently, both price and quantity for biomass is reduced. The reduction in total energy consumption explains the increased gas dependency for the EU30, despite the lower gas consumption (see figure 8).

Figure 8 of the new gas dependency situation indicates that all countries but Estonia and Poland increase the gas consumption when the solar power production increases. The countries affected the most is Latvia, Poland and Lithuania, countries that still use gas to generate power in 2030. Figure 13 shows the distribution of the gas consumption for these countries in the reference scenario and solar power scenarios.

Figure 13. Distribution end-user gas consumption for Latvia, Poland and Lithuania. Solar power scenarios. Mtoe.



More solar power causes gas power production to increase in Latvia, but to decrease in Poland. Latvia is still producing power with gas in 2030, and increasingly so in the solar power scenarios. The country does not install any solar power, so the lower CO_2 price and less subsidies to their wind power production implies an increased gas power production. Poland's gas dependency is unaffected between the 2B and 2D scenario, but becomes less dependent on Russian gas. Solar power in Poland increases to 24 TWh in the catch-all scenario, which enables an reduction of gas power production. Lithuania scored with a higher gas dependency (see figure 8) because the decrease in total energy consumption, and the gas consumption increasing marginally. The EU30 consumes less Russian gas, reduces the net gas consumption and consumes less total energy consumption in the solar power scenarios. The latter effect is greater, thus increasing the total gas dependency.

4.2 Wind Power

As presented in chapter 3, wind power production is likely to increase towards the low carbon economy in 2030. This section assesses a further increase in wind power assisted by a more rapid market development. Scenario **2E** is as reference plus increasing the annual cost reduction rate for investment in wind power. From 1 % to a 2 % annual cost reduction rate.

Following the approach outlined in the solar power scenario, I assess the potential of wind power to suppress gas, both in power generation and in the end user demand. The market dynamics in action when analyzing the wind scenario are similar to the analysis in solar power. The results in this scenario will thus be presented more briefly.

Figure 14. Gas dependency. Wind power scenario 2E. Percent.

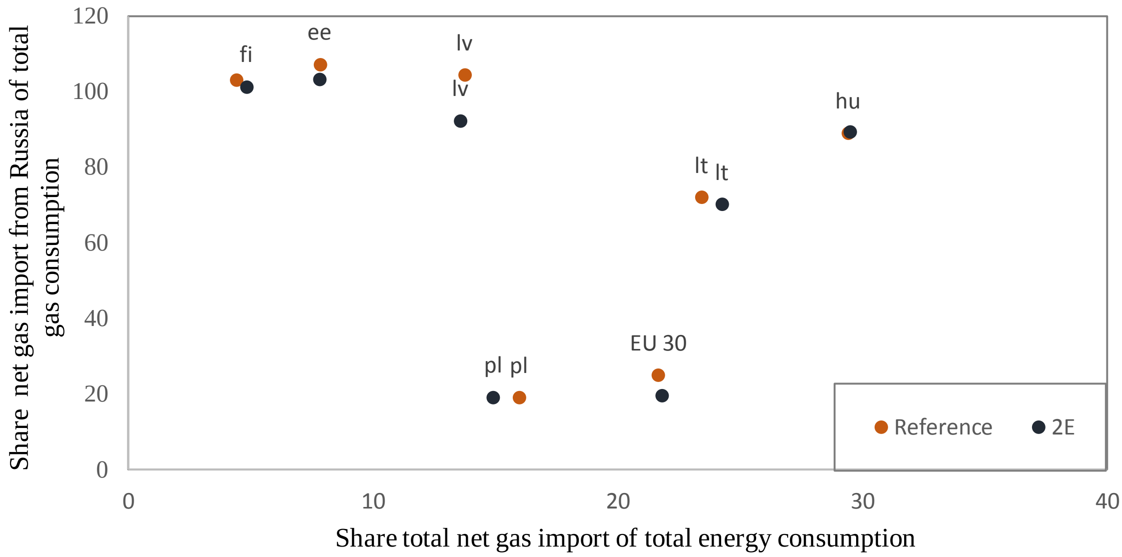


Figure 14 shows the new situation for gas dependency. All border countries to Russia experience a small reduction in the dependency on Russian gas, but the overall gas dependency is marginally affected. The case for Poland is however the opposite, with less dependency on gas and a slight increase in the dependency on Russian gas.

4.2.1 Interplay Wind and Gas in Power Generation

Wind power share many of the same production characteristics as solar power. Wind power producers do not choose how much power to produce; they simply generate power whenever the wind is blowing. The wind power producers will never shut down when it is blowing as the input in production comes for free. Maintenance of the power plants can be conducted when it is not blowing. Wind power is not sold as reserve power either in LIBEMOD, due to its intermittency. The higher annual cost reduction rate lowers the investment costs by 2030, which increases the total capacity of wind power compared to the reference scenario. This shock increase the electricity supply. Investment costs are sunk, and thus ignored in the optimization decision within each period. The low marginal costs enables wind power to suppress other energy sources in electricity generation, when the wind is blowing.

Figure 15. Power production wind scenario relative to reference. TWh.

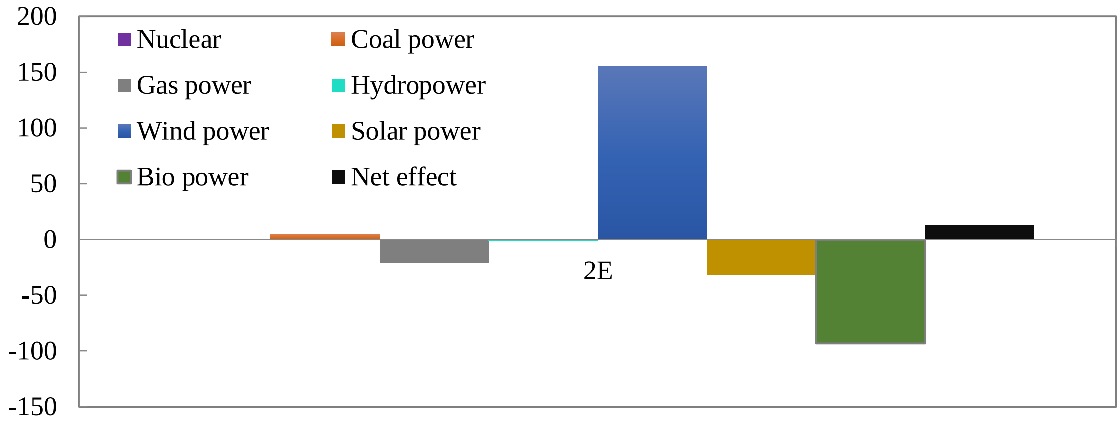


Figure 15 shows the changes in power production due to the shock in wind power. Wind power increases by 155 TWh. The excess supply of electricity is absorbed by the end users at lower prices. In the new equilibrium, all energy prices have decreased, see Table 9. Oil prices are unaffected of the shocks because the oil prices are determined on the world market. The increase in wind power leads to a lower CO_2 price than in the reference scenario, which improves the competitiveness of combustion fuels in electricity production. Gas power production reduces nevertheless, which indicates that the lower electricity prices causes some gas power plants to be unprofitable and consequently shutting down.

Table 8. CO_2 price (EUR/ton CO_2) and renewable support (EUR/MWh). Wind scenario.

Policy measures	Reference	2E
CO_2 price (EUR/ton CO_2)	11.4	10.5
Renewable support (EUR/MWh)	9.0	7.9

Table 9. Change in producer prices from reference scenario. Wind power scenario. Percent.

Electricity	Gas	Steam Coal	Coking Coal	Oil	Biofuel	Biomass
-1.5	-1.11	0.04	-0.01	0.00	-0.03	-6.83

The subsidies to renewables decreases from 9 to 7.9 EUR/MWh from the reference scenario when wind power becomes more profitable, which explains the reduction in solar and bio power. As opposed to the solar power scenario, hydropower decreases slightly in when the wind power increase. This indicates that the differences in prices between day and night not are large enough to make pumped storage profitable when wind power is the source of the increase in renewable power generation. Total power production increases by 13 TWh in the wind scenario, compared to the reference scenario.

Latvia ceases to use gas in power generation with the reduced costs of new investments in wind power plants, explaining the small reduction in the dependency on Russian gas. Latvia is apparently better suited for wind power than solar power production. In Lithuania, which does not use gas in the power generation sector by 2030, is the industry sector increasing their gas consumption as a response to the lower gas prices. Poland reduces the gas power production, installs some additional 4 TWh with new wind power capacity compared to the reference, and the total gas dependency decreases.

4.3 Summary Renewables and Energy Security

Table 10. Net import of Russian gas (Mtoe), gas and energy consumption (Mtoe) and gas dependency (percent). Renewable power scenarios.

	Reference	2B	2D	2E
Russian gas net import EU30 (Mtoe)	102	101	99	102
Total net gas consumption EU30 (Mtoe)	409	405	402	407
Total energy consumption EU30 (Mtoe)	1891	1853	1817	1869
Dependency Russian gas (%)	25.0	24.9	24.7	25.1
Dependency gas (%)	21.6	21.8	22.1	21.8

** Net import Russian gas/total gas consumption*
***Total gas consumption/ Total energy consumption*

The overall gas dependency for the EU30 is marginally affected in most of the scenarios with shocks to renewable power (bottom line table 10), compared to the reference scenario. The shock to the solar and wind power producing technologies lead to lower producer prices for power producers, a lower ETS CO_2 price and lower subsidies for renewables. Some of the gas in the power generation is replaced by more solar and wind power, but solar power suppresses other renewable energy sources more than gas power due to the reduction in subsidies for renewable power production.

The geographical potential for renewable power generation determines how the gas dependency develops. Countries that benefit from the shocks to renewable power production have sites suitable for solar and wind power production, which enables its consumers to relish cheaper electricity. The cheap electricity, and subsequently cheap gas because of the reduced demand in the power generating sector, makes gas a profitable input in power generation for countries who do not have suitable areas for solar power production. Out of the countries that still used gas in power generation by 2030, Latvia experienced a worsening of the energy security due to the shocks in solar power, but an improvement when the source of increased power production was wind power.

Direct comparison of the different scenarios in order to state what shock affects the energy security more is obscure because they are highly dependent on the size of the shock I have imposed. In addition, the choices of the inputs in the reference scenario is important, because a key feature of the analyses is the comparison with the reference scenario. Worth noting however, is that all the consumption variables for the EU have decreased from the reference scenario (see table 10). The gas dependencies of the EU30 in all the renewable scenarios increase because the energy consumption decrease relatively more than the gas consumption.

This section analyzed the market development of renewables, but did not say anything about how the shocks occurred. To conclude on a degree of compliance or conflict between climate and energy security policies calls for short discussion beyond the limitations in LIBEMOD. Imagine the changes in chapter 4.1 arise as results from governmental support to solar power, not already incorporated in the subsidies to renewable energy production or consumption, e.g. as funds to a research program or something of the similar. The government is thus actively promoting the existence of these shocks, and in effect favoring solar power. This in turn contributes in the ousting of other renewables, as the subsidies to all renewable energy sources are reduced. The partial effect of supporting research to a specific technology (solar power in this case) can ease the path towards the low carbon economy. Doing so is however in conflict with the energy security policies once the total effect takes place. The reduction in the subsidies to renewable power production caused the geographical areas that cannot benefit from more of the specific renewable technology to experience a poorer energy situation, as was the case with Latvia. A strong cohesion between climate and energy security policies is recognized by the climate policy supporting a wide range of energy sources.

5 Coherence in the Climate and Energy Security Policies

Chapter 4 showed that the subsidies and the CO_2 price play vital roles in determining the new equilibriums in the European energy market by 2030. I devote this chapter to assessing how the different policy measures in the 2030 Climate and Energy Framework affect the European Union's energy security. There are three main policy elements under scrutiny; energy efficiency, to what extent the GHG emissions should be reduced and changing the renewable share in the energy mix.

5.1 Energy Efficiency and Energy Security

Reducing energy demand enters the EU's 2030 Climate and Energy Framework and in the energy security strategy. The latter does not outline any specific objectives of how much demand should be reduced with. The 2030 Climate and Energy Framework aims at saving 27 percent of the energy it would have consumed in the business as usual scenario by 2030. This is only an indicative target and will be reviewed in 2020. The target outlined in Article 3 of Directive 2012/27/EU states that primary energy should not be higher than 1474 Mtoe by 2020 for EU28.

The target by 2030 of 27 percent reduction is indicative and the European re has not presented any further details on the exact measure by 2030. It is not straightforward to compare the maximum consumption level outlined by EU with the results from LIBEMOD. First of all, the figures are calculated with different methods. In addition, LIBEMOD provides result for EU27 when subtracting the consumption in Norway, Iceland and Switzerland) as the last EU member Croatia is not a model country in LIBEMOD. LIBEMOD has already incorporated assumptions on the development of energy efficiency by 2030, i.e. also contributing to the results in 2030. I am thus assessing energy efficiency by assuming that the annual rate for improvement in the energy efficiency in LIBEMOD increase. I impose an increase such that, hypothetically, if the end users optimize according to the same set of energy prices as observed in 2009, they will consume the same amount of energy goods, despite the increase in income caused by economic growth. To give an idea of how important income growth is for energy security, I also assess the effects of only the Western European countries experiencing energy efficiency[13]. This is

[13] West-Europe in this consists of Austria, Belgium, Luxembourg, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom.

based on the idea that the income elasticities decline as income rises (Karimu & Brännlund, 2013). The scenarios are thus:

3A: As reference + increased energy efficiency rates in EU30 by 2030

3B: As reference + increased energy efficiency rates in Western Europe by 2030

I separate these effects into two scenarios to incorporate that the European economies differ in their GDP levels. The East European countries are modelled with higher economic growth in LIBEMOD and I allow that the energy demand growth to follow GDP growth in this part of Europe. One can think of these scenarios as results of implementing some measure for energy efficiency in order to reach the energy efficiency target in the climate and energy strategy. Scenario 3B assesses the effects of the measures only implemented in the west or simply working better in Western Europe. Implementing shocks in LIBEMOD comes for free, so how they occur is not important in this particular analysis.

In LIBEMOD the income elasticities vary between sectors and fuels. For natural gas the income elasticity is 0.9 for both households and the industry sector. The income elasticity for electricity is 0.8 for households and 0.7 for the industry sector. This implies that the demand growth for

Figure 17. Gas dependency. Energy efficiency measures increase in EU30. Percent.

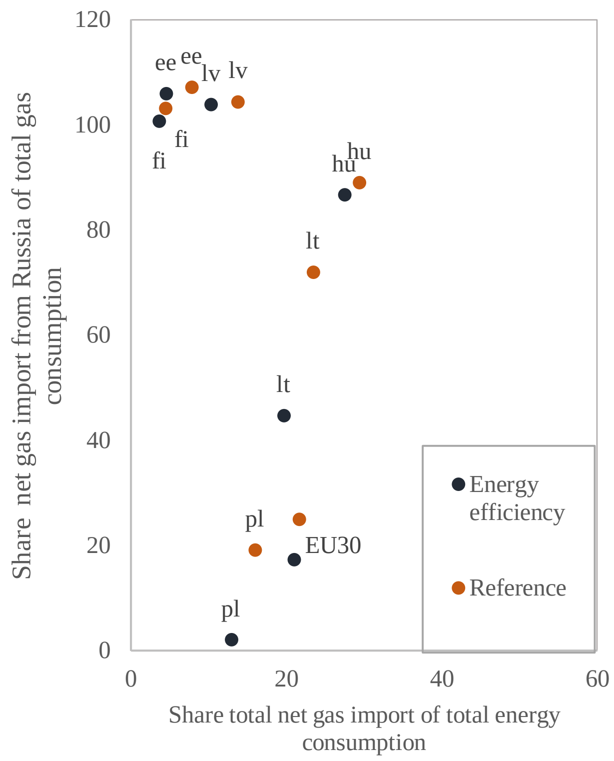
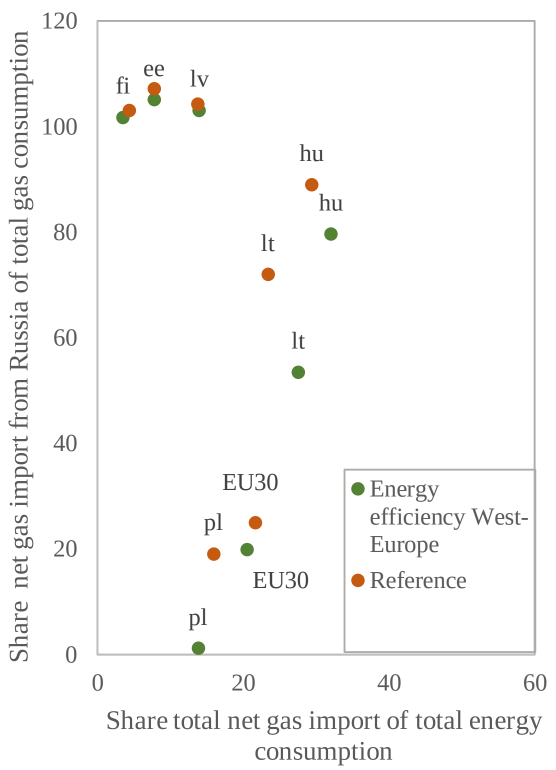


Figure 16. Gas dependency. Energy efficiency measures in Western Europe only. Percent.



natural gas, ceteris paribus, would be higher than the demand growth in electricity over time in line with economic growth. Other aspects such as relative prices, taxes and subsidies affect the final equilibrium too.

Figure 16 shows the effect on energy security by in the two scenarios. When running scenario 3A, total energy consumption in the EU30 is 1674 Mtoe, 12 percent lower than the consumption level in the reference scenario of 1891 Mtoe. This improves the energy security, with total gas dependency by the EU being 20.9 and the dependency on Russian gas the lowest of all the scenarios, at 17.3 percent. This is due to both a decrease of total consumption and gas. Hungary, Lithuania and Poland improve their energy security relatively more than the other vulnerable countries. These countries receive the gas they consume via transit countries.

The improvement in gas dependency is greater when all countries experience lower demand for energy. In the scenario where only the Western European countries reduce their demand for energy, the Eastern European countries increase their gas dependency, compared to the reference scenario. Most of the vulnerable countries[14] increase the gas dependency in 3B compared to the reference scenario, especially Hungary and Lithuania. When the Western European countries reduce their demand for gas, gas prices decrease. The Eastern European countries do not experience any improvements in the energy efficiency relative to the reference scenario, and consequently more of the Russian gas is consumed in Eastern Europe. This argues for the importance of ensuring that the energy efficiency measures can take effect equally within the EU. The difference between the scenarios 3A and 3B indicates that the vulnerable countries in the Eastern Europe can become even more dependent on gas if only the Western countries succeed in increasing the energy efficiency. Hungary and Lithuania increase the gas dependency, but the total gas consumption increase more than the incremental import of Russian gas demand (they import more LNG), such that the dependencies ratios on Russian gas decrease.

The ETS CO_2 price is zero in both of the energy efficiency scenarios, while the subsidies increase from the reference scenario. The higher CO_2 price in the reference scenario is no longer needed at the new, low levels of energy consumption in 3A and 3B. With a lower demand for energy, reaching the renewable share target becomes more challenging and the subsidies increase. This contributed in the improves the energy security because of less use of natural gas

[14] Finland has the same result in 3A and 3B: the increase in the energy efficiencies still intact in 3B because Finland is included in Western Europe.

by the power producers. Gas power production declines by 190 TWh when all the EU30 countries adopt energy efficiency measures, compared to the reference scenario. When the Eastern European countries *do not* improve the energy efficiency (3B), coal power production increases relative to the reference. The other power generating sources are declining less in both 3A and 3B, however less than a situation where the entire Europe becomes energy efficient. The non-ETS is also relatively low in this scenario, more than 70 percent lower than in the reference scenario.

5.2 <u>Changes in the EU's 2030 Climate and Energy Framework</u>

The EU's 2030 Climate and Energy Framework has been important for the effects on energy security by 2030. This section will therefore take a closer look at how energy security is affected by changes in these policies. The scenarios under scrutiny are:

4A: Almost as reference, but increasing the emission target for 2030. From 40% to 20%.

4B: Almost as reference, but increasing the emission target for 2030. From 40% to 50%.

4C: Almost as reference, but increasing the renewable share to minimum 35 %.

5.2.1 Less Ambitious Climate policy: Decrease to 20 Percent Cut in Emissions

Figure 18. Gas dependency. Emission target 20 % lower than 1990-level.

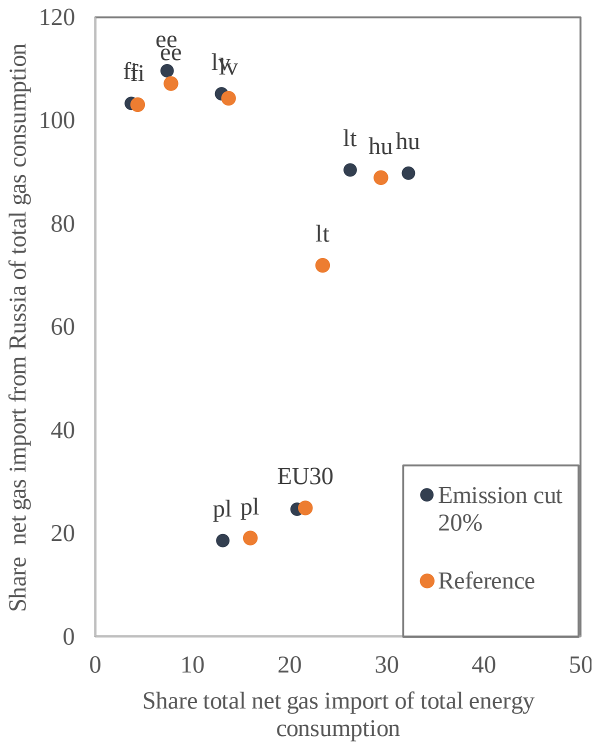
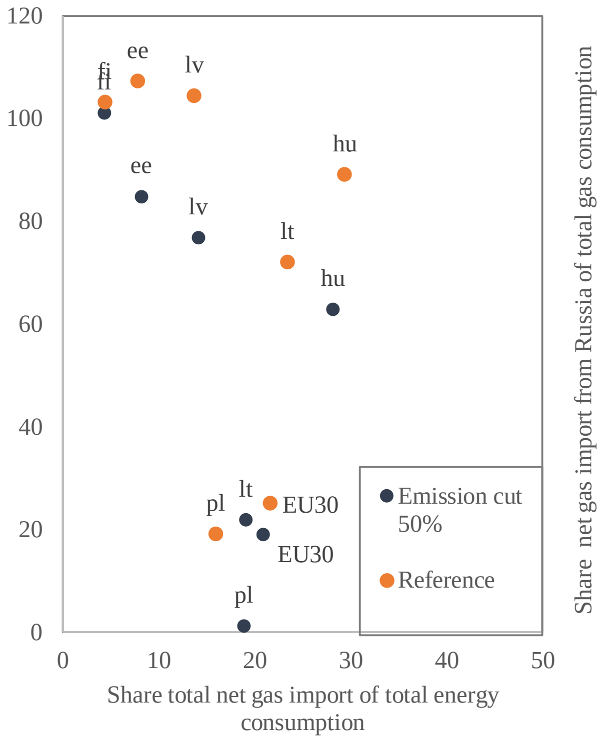


Figure 19. Gas dependency. Emission target 50 % lower than 1990-level.



Having a lower green house gas emissions target (see figure 18) causes all vulnerable countries to improve their energy security, reducing the gas decency slightly from the reference scenario. At first glance, this may appear as a surprising result as one commonly expects lower ambitions for the climate to cause a lower CO_2 price and thus improving the competitiveness of gas. The CO_2 price is reduced to zero in this scenario (see table 11), while the renewable support increases, from 9 to 13 EUR/MWh. The renewable target is still intact, and the subsidies must increase in order to reach the desired 27 percent of renewables in the energy mix to compensate for the relatively poorer competitiveness on renewables due to the lower CO_2 price.

Table 11. CO_2 price (EUR/ton CO_2) and renewable support (EUR/MWh). Climate policies scenarios.

	Reference	4A	4B	4C
CO_2 price (EUR/ton CO_2)	11	0	45	8
Renewable support (EUR/MWh)	9	13	0	17

Table 12. Producer price change in climate policy scenarios from reference scenario. Percent.

	4A	4B	4C
Electricity	-9.3	23.7	-5.5
Gas	9.7	-9.7	-2.6

With lower ambitions in the climate policies, total power production increase and the electricity price decrease by 9 percent compared to the reference scenario. In addition to the lower CO_2 price contributing to lower electricity prices, new allocations in the power market contribute to the price decrease. Coal power production has increased considerably compared to the reference scenario, by 377 TWh (4A, see figure 20). As coal becomes more competitive due to the lower CO_2 price and thus constitutes a larger share of total power production, the demand for other energy sources reduces. Gas power is reduced the most by 210 TWh followed by bio power, which reduces by 150 TWh. The other renewables increase slightly because of the increase in subsidies.

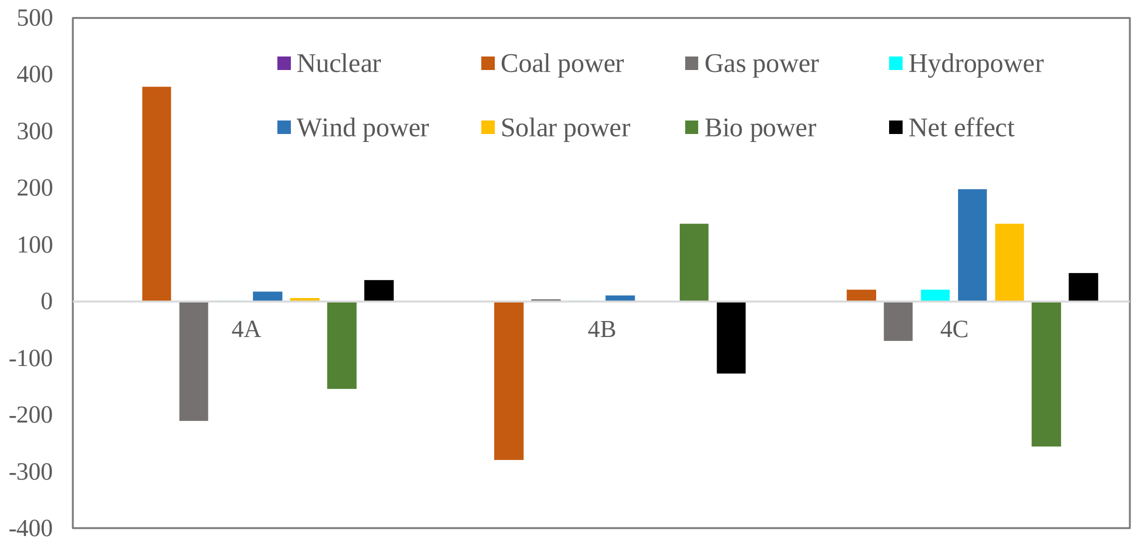
5.2.2 More Ambitious Climate Policy: Increase to 50 percent Cut in Emissions

Looking at the scenario with a more ambitious climate policy in figure 19, most of the vulnerable countries decrease their dependency on Russian gas, but the overall gas dependency is mostly unchanged. This is due to reductions in both total gas consumption, net import from Russia and total energy consumption. Poland increase their gas dependency somewhat, but import more LNG rather than Russian gas via Slovakia. The outcome of this scenario is in many ways a mirror of the previous scenario, in that the CO_2 price has increased significantly, to 44.7 EUR/ton CO_2, and the renewable subsidy is zero (see table 11).

These dramatic changes in the policy variables compared to the reference scenario cause an increase in the bio power generation, and a decrease in the use of coal fired power plants (see figure 20). The renewable subsidies are zero in this scenario because the renewable target is over accomplished, with renewables constituting 28.6 percent of the energy mix. This is also mirrored in the increase in bio power production (see figure 20, scenario 4B). Gas power increases slightly. The electricity price increases by 24 percent compared to the reference scenario, and the gas power producers benefit from the higher electricity price. The decrease in coal power outweighs the increase in bio power and the small adaptions in renewables such that total power production decreases.

The small increase in gas power despite the high CO_2 price is because combustion of coal emits more GHG than combustion of gas. The small increase in gas power production indicates that the improved energy security is due to lower gas consumption by the end users.

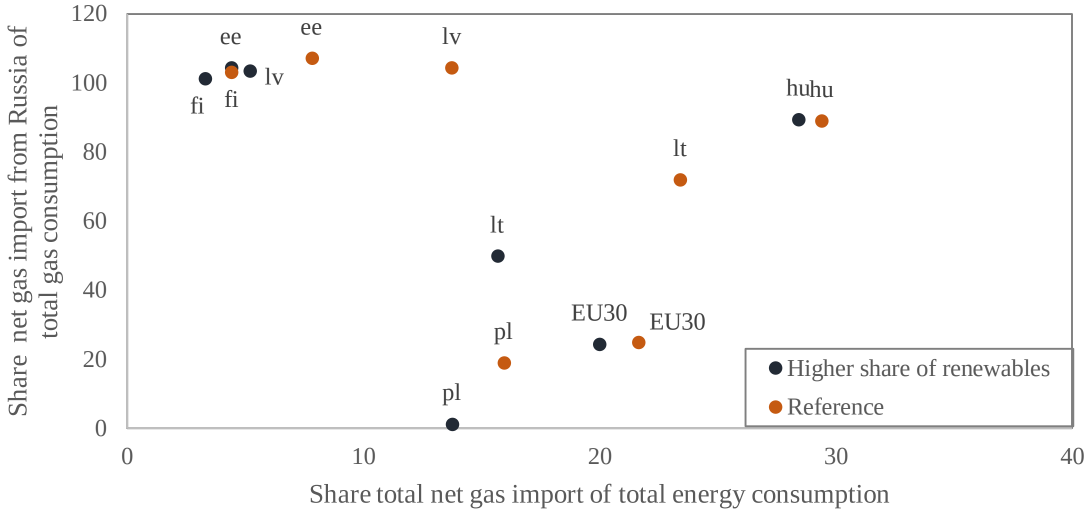
Figure 20. Changes in power production compared to the reference scenario with policy changes 4A-4C. TWh



5.2.3 Higher Share of Renewables in the Energy Mix

The energy security improves compared to the reference scenario when imposing the share of renewables in the energy mix to be 35 percent in stead of 27 percent. The increased deployment of renewable energy sources reduces the gas dependency in all countries. Worth noting is the improvement of Lithuania and Latvia. They reduce the gas consumption relative to total energy consumption from 23 and 13 percent to 15 and 5 percent respectively. For Lithuania, this also causes less dependency on Russian gas.

Figure 21. Gas dependency. Higher renewable share scenario. Percent.



Implementing the higher renewable share requires an increase of the subsidies to renewables to 17.4 EUR per MWh. The greater governmental support leads to an increase in the power production of 50 TWh compared to the reference scenario, naturally caused by increasing the power production with renewables, see figure 20. Consequently, the demand for gas in power production reduces and prices fall by almost 5 percent. With more use of renewables, the targeted cut in emissions is reached more easily and the ETS CO_2 price is reduced. This favors coal production which increases by 20 TWh Wind and solar increase more of the renewable energy power producers. The potential for power production on the margin is better from these less developed power plants than for hydro power plants. Investment in wind power increases more than solar power in the vulnerable countries. Bio power is reduced yet again, due to the lower producer price for electricity, decreasing by 5.5 percent. See table 10.

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5.3 Summary Climate Policy and Energy Security

Table 13 presents an overview of the energy security measures in all the scenarios with changes in the climate policies.

Table 13. Net import of Russian gas (Mtoe), gas and energy consumption (Mtoe) and gas dependency in percent. Climate policy scenarios.

	Reference	3A	3B	4A	4B	4C
Russian gas net import EU30 (Mtoe)	102	61	72	106	69	98
Total net gas consumption EU30 (Mtoe)	409	350	365	426	361	401
Total energy consumption EU30 (Mtoe)	1891	1672	1775	2054	1732	2003
Dependency Russian gas* (%)	25.0	17.3	19.9	24.8	19.1	24.4
Gas dependency** (%)	21.6	20.9	20.5	20.7	20.8	20.0

** Net import Russian gas/total gas consumption*
***Total gas consumption/ Total energy consumption*

Increasing the energy efficiency improves the energy security in all the countries, by decreasing both the gas and the total energy consumption, such that the dependency on Russian gas and gas dependency in general in EU30 decreases considerably (scenario 3A and 3B). The higher energy efficiency gives the lowest dependency on Russian gas of all the scenarios in this study, at 17.3 percent. Some of the eastern European countries experienced worsened energy security in the form of a higher gas dependency when the energy efficiency measures were working only in Western Europe (3B), as less demand for gas by Western Europe reduces the gas prices.

When assessing the high and low ambitions for cutting the greenhouse gases, the gas dependency decreases in both the scenarios compared to the reference. This indicates that the energy security is improved no matter how ambitious the EU climate policy is. The ETS CO_2 price and subsidies for renewables are taking their turn each on being zero in the scenarios with high and low ambitions. The dependency on Russian gas for EU30 is 24.8 percent with the lower ambitions (4A), the CO_2 price being zero and the subsidies higher than in the reference scenario. In comparison, the dependency on Russian gas is 19.9 percent in the high ambitions policy scenario (4B), with the CO_2 price being high at 45 EUR/ton CO_2 and no subsidies are paid to the renewable producers. The more surprising element in this scenario is however that the gas power production increased slightly (figure 20). The reduced gas dependency was a result of less demand by end users, an effect which is supported by the increased non-ETS CO_2 price.

Having a higher target for renewables in the energy mix decreases the gas dependency the most of all scenarios, indicating that this climate policy works well in compliance with energy security strategy. The considerable increase of the subsidies also causes total energy consumption to increase, explaining the improved gas dependency.With a higher share of renewables, more of all renewable energy production that possibly can be developed must be deployed. The higher subsidy level (of 17 EUR, see table 11) reflects this effort, which comes at a higher cost for the government having a negative net income in this scenario. The energy security improves for all countries because each country can make us of the renewable energy sources suitable for investment at their geographic location.

6 Conclusive Remarks

This study has analyzed the degree of coherence between the policies within the EU's climate and energy security policies by using the multimarket equilibrium model LIBEMOD. The term energy security is applied in a long-term perspective, where improvements in the energy security is characterized by a lower dependency on natural gas and Russian gas in particular.

I find a strong degree of coherence between the climate and the energy security policies by 2030, as the climate policy leads to a greater dispersion of energy sources. Accomplishing the climate targets implies raising both the common EU subsidies to renewables and the taxation of CO_2 emissions. Improvements in the solar and wind power producing technologies lead to a slight reduction in the deployment of gas power, but other renewable energy sources are ousted to a greater extent than gas power due to the reduction in subsidies to renewables when goal attainment of the climate policy becomes easier. The overall gas dependency for the EU is marginally affected by the additional use of renewable energy sources, compared to the reference scenario for 2030.

The degree of cohesion in climate and energy security policies is strong when implementing measures for energy efficiencies. The energy efficiency objective eased the dependency on gas significantly. Higher ambitions in the climate policies improves the energy security too, as the high CO_2 price raise the gas prices and consequently reduces the dependency on Russian gas in all countries.

The thesis has focused on describing the dynamics in the energy markets that theoretically can reduce the dependency on gas in the EU, i.e. the substitutability of fuels in the power generation and by end users of energy goods. The future energy markets may however develop fundamentally different from the assumptions in LIBEMOD. Examples could be an entry of American LNG exports to the European energy markets or an increased pace of electrification in the end user sectors. If LIBEMOD is to provide useful information for future analysis on the European energy markets, a new update of the model appear inevitable.

A secure energy security situation protects the economic welfare of a nation's citizens and the efficiency of the economy. A more thorough scrutiny of the cohesion between climate policies and energy security requires the use of a general equilibrium model. Such an approach could encompass the affordability element and total welfare impacts, which are important features of energy security too.

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Appendix

Retrieved from Aune et al. (2009) and Aune et al. (2008).

Table 14 Main sets in LIBEMOD

Countries and regions	**Group 1:** 30 endogenous model countries in Europe	Austria, Belgium, Luxembourg, Bulgaria, Cyprus, Czech Republik, Denmark, Estonia, Finland, France, Germany, Greece, Great Britain, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, The Slovak Republic, Slovenia, Spain, Sweden, Switzerland.
	Group 2: 5 exogenous countries that are not members of the European Economic Area.	Algeria, Belarus, the remaining part of former Yugoslavia, Ukraine and Russia. This study uses the extended version with Russia endogenous.
	Group 3: All other countries in the Rest of the World *row*	
	5 Large suppliers of natural gas (*row2)* acts like one, the single supplier of LNG	Algeria, Netherlands, Norway, Russia and the UK
	8 Coal-exporting countries	Australia, Canada, China, Colombia and Venezuela, Indonesia, Poland, South Africa, USA.
	3 Other regions	
8 Energy goods	Electricity, natural gas, steam coal, coking coal, lignite, oil, biofuels and biomass	
12 Time periods	2 Seasons x 2 times of day	summer and winter day and night
19 Electricity technologies	10 Pre-existing technologies 9 New technologies	Reservoir, pumped, run of river, gas, steam coal, lignite, oil, waste, wind, bio, solar, thermal and nuclear. All power technologies except lignite can be new.
5 Consumers	4 Final demand sectors 1 Intermediate demand sector	Households, services, industry and transport. Demand for fuel by fuel based electricity sector.

Source: based on table on page 34 in (Finn Roar Aune, 2008) with extensions from the 2009-update.

Electricity supply by combustion fuels in LIBEMOD

There are five power technologies for old and four technologies for new power plants in each model country; gas power, steam coal power, bio power and oil power (lignite power can only old). The supply of power form each category of electricity production is modelled as if there is one single plant with decreasing efficiencies, implying increasing marginal costs.

Costs

The capital cost of the installed power capacity K^P is sunk and subsequently should not affect behavior, it is disregarded in LIBEMOD. There are six types of costs involved in electricity from combustion fuels:

1) The *operating cost*, c^0_{ml}, is a non-fuel monetary costs directly related to the production of electricity. This cost is assumed proportionate to production and with exogenous prices this cost is constant per unit produced. When y^E_t is the production of power in period *t*, the monetary cost in each period $c^0_{ml}y^E_t$ must be summed over all periods to get the total annual operating costs.
2) *Fuel costs* are given by the price of the fuel input times the annual input quantity: $P^{XF}x^{DF}$.
3) There are *maintenance costs* of installed capacity c^M_{ml} per power unit (GW) according to the level of maintained capacity K^{PM}_{mtl}. The capital costs of installed capacity is sunk and is thus not affecting the production optimization in each period.
4) *Ramping up costs,* or start-up costs, occur if a producer decides to produce more electricity in one period than in the previous period (in the same season). These costs are expressed partly as an extra fuel requirement (i.e. included in the fuel costs) but also as a monetary cost c^S_{ml} per unit of incremental power capacity started, K^{PS}_{mtl}, in each period.
5) There are annualised *capital costs* c^{inv}_{ml} for investments in *new* power capacity K^{inv}_{ml}. Total, annual investment costs are thus $c^{inv}_{ml}K^{inv}_{ml}$.
6) Finally, there are costs of connecting the new power plants to the grid. These costs reflect that the power plants contribute in covering up the costs associated either with connection the plant to the grid or upgrading the grid in order for the connection to be possible. The model takes into account that the distance to the grid is increasing in new

capacity and that the costs of upgrading the grid is increasing and convex, the costs of grid connection, $c_{ml}^{gc}\left(K_{ml}^{inv}\right)K_{ml}^{inv}$, is also increasing and convex.

The short-run variable cost equation is therefore:

(A.1) $C^{P} = \sum_{t\in T} c^{o}\, y_t^E + P^{XF} x^{DF} + c^{M} K^{PM} + \sum_{t\in T} c_t^S\, K_t^{PS}$

Revenue

The revenue for power producers can come from two sources; regular sales to the power market at price P_t^{YE} (which varies over time) or the producer can sell reserve power capacity K_t^{PR} receiving price P_t^{KPR} from the transmitting system operator (TSO). The profit of each power producers is thus the two revenue sources less the short run variable costs and any costs of new investment:

(A.2) $\Pi^{E} = \sum_{t\in T} P_t^{YE}\, y_t^E + \sum_{t\in T} P_t^{KPR}\, K_t^{PR} - C^{P} - c^{inv}K^{inv} - c^{gc}(K^{inv})K^{inv}$

The electricity producer maximize profit subject to several constraints. The Lagrangian of the optimization problem is:

(A.3) $\mathcal{L}^{E} = \sum_{t\in T} P_t^{YE}\, y_t^E + \sum_{t\in T} P_t^{KPR}\, K_t^{PR} - C^{P} - c^{inv}K^{inv} - c^{gc}(K^{inv})K^{inv} - \lambda^{E}\{K^{PM} - K^{P}\} - \sum_{t\in T}\mu_t\{y_t^E - \psi_t(K^{PM} - K_t^{PR})\} - \eta\{\sum_{t\in T} y_t^E - \xi \sum_{t\in T}\psi_t K^{PM}\} - \sum_{t\in T}\phi_t\left\{\frac{y_t^E}{\psi_t} - \frac{y_u^E}{\psi_u} - K_t^{PS}\right\} - \pi\{\sum_{t\in T}(x^{E}(y_t^E) + v^{S}K^{PS})\} - x^{DF}$

The first constraint[15] requires that maintained power capacity K^{PM} should be less than or equal to total installed power capacity K^{P}:

(A.4) $K^{PM} \le K^{P} \perp \lambda^{E} \ge 0,$

[15] The restrictions on the optimization problem are presented in solution form, where the Kuhn-Tucker multiplier complementary to each constraint is indicated.

λ^E is the shadow price of installed power capacity. Not all pre-existing capacity have to be maintained. Maintaining however incurs a cost c^M per GW.

Second, maintained capacity can be allocated either to production of electricity or to reserve power in each period. Production is bounded by the number of hours available for electricity production in each period, ψ_t, multiplied by net power capacity $K^{PM} - K_t^{PR}$ in that period:

(A.5)

$$y_t^E \leq \psi_t \left(K^{PM} - K_t^{PR} \right) \perp \mu_t \geq 0.$$

The third constraint states that all power plants need some down-time for technical maintenance and subsequently that total annual production cannot exceed a share, ξ, of the maintained capacity:

(A.6) $$\sum_{t \in T} y_t \leq \xi \sum_{t \in T} \psi_t K^{PM} \perp \eta \geq 0.$$

Fourth, as mentioned above, start-up and ramping up costs are incurred if electricity production varies between periods in the same season. This cost depends on the additional capacity started at the beginning of each period. The start-up capacity, K_t^{PS}, must therefore satisfy the following requirement:

(A.7) $$\frac{y_t^E}{\psi_t} - \frac{y_u^E}{\psi_u} \leq K_t^{PS} \perp \phi_t \geq 0$$

where $\frac{y_t^E}{\psi_t}$ is the capacity used in period *t* and $\frac{y_u^E}{\psi_u}$ is the capacity used in the previous period $u = t - 1$ in the same season. Each produced quantity y_t^E is thus involved in two inequalities, one for period *t* and one for period *t+1*, which together imply two different non-negative start-up capacities. The maximum value of $\frac{y_t^E}{\psi_t} - \frac{y_u^E}{\psi_u}$ is K^{PM}, and hence K_t^{PS} can never exceed K^{PM}.

The fifth constraint, the fuel requirement, consists of two parts. The first is the quantity of fuel needed to produce the given quantity of electricity $x^E(y_t^E)$. This function captures the energy efficiency of the transformation process. In LIBEMOD the direct input requirement function is quadratic:

(A.8) $$x^E(y_t^E) = v^0 y_t^E + v^1 \frac{(y_t^E)^2}{\psi_t}$$

$x^E(y_t^E)$ is increasing in the electricity produced, where v^0 is a parameter for the best fuel to electricity conversion factor and v^1 is the slope in fuel to electricity conversion function. ψ_t is the number of hours in each period t. The second part is the additional fuel required to start extra capacity, or ramp up an already started power plant, which is assumed proportionate to the start up capacity by a factor v^S:

(A.9) $$\sum_{t\in T}\left(x^E(y_t^E) + v^S K^{PS}\right) \leq x^{DF} \perp \pi \geq 0.$$

First order conditions

Insert equation A.1, the short run costs, into the Lagrangian and optimize with respect to produced electricity, y_t^E, yields:

(A.10) $$P_t^{YE} - c^o \leq \mu_t + \eta + \frac{1}{\phi_t}(\phi_t - \phi_u) + \pi v_t \perp y_t^E \geq 0$$

Where $v_t = \frac{\partial x^E(y_t^E)}{\partial y_t^E}$ is the marginal inverse efficiency of period t. In each period, a positive electricity production $y_t^E \geq 0$ requires that the difference between the price of electricity P_t^{YE} and the marginal cost of production c^o should be equal the sum of suitably weighted shadow prices. The first term in this sum is the shadow price of the periodic available energy capacity restriction. $\mu_t > 0$ reflects that increased production in period t is not possible for given maintained capacity K^{PM} net of reserve power K_t^{PS}. Outside of optimum, if the left hand side of A.10 is greater than the right hand side and the restriction is not binding, it may be possible to increase maintained capacity to facilitate increased electricity production. Once optimum is reached, and holds, increasing maintained capacity is either not possible or not worth it.
The sum of shadow prices also contains the shadow price of the annual energy capacity η, and the difference (measured per hour) between the shadow price of capacity used in this period and in the following period, where $\phi_t > 0$ reflects that production in period t cannot be increased for given K_t^{PS}. The final term πv_t reflects the value of fuel input needed to produce an extra unit of electricity.

Second, the first-order condition with respect to reserve power capacity sold in each period is:

(A.11) $$P_t^{KPR} \leq \mu_t \psi_t \perp K_t^{PR} \geq 0$$

so that for positive reserve power sales the reserve power price must equal the shadow value of increasing the power capacity available to produce electricity.

Third, the first-order condition with respect to fuel input demand is:

(A.12) $$\pi \leq P^{XF} \perp x^{DF} \geq 0$$

At positive input demand, the shadow price of the input is equal to its market price.

Fourth, the first-order condition with respect to maintained capacity is:

(A.13) $$\sum_{t \in T} \psi_t \left\{ \mu_t + \eta \, \xi \right\} \leq c^M + \lambda^E \perp K^{PM} \geq 0,$$

The cost of increasing maintained capacity marginally – the sum of the maintenance cost c^M and the shadow price of installed capacity λ^E – should be equal to the value of increased annual production following from this policy. Increased maintained capacity raises both potential periodic electricity production and potential annual electricity production. Thus, in each period the value of increased production per hour is the sum of the shadow price of periodic energy capacity μ_t and the shadow price of the annual energy capacity adjusted by the maximum operating time $\eta \, \xi$.

Fifth, the first-order condition with respect to the start-up capacity is:

(A.14) $$\phi_t \leq c^S + \pi v^S \perp K_t^{PS} \geq 0,$$

In each period the shadow price of start-up capacity, ϕ_t, should be equal to the sum of the monetary start-up cost c^S and the cost of the extra fuel input πv^S. If not, the start-up capacity should be zero.

Equations A.10 and A.14 imply that *if* a plant is producing in one period, costs will increase if the plant does not also produce in the previous period because the plant will incur a start-up cost. If the marginal benefit of a start-up is positive in the period after the period in question ($\phi_u > 0$), then this allows a greater benefit of a start-up in this period. I.e. if capacity is already used in this period, one can also use it in the next period without incurring additional start-up costs.

The final FOC is for the investment decision. New technologies' total capacity is equal to investment, $K^P = K^{inv}$, and the investment criteria can be written as:

(A.15) $$\lambda^E \le c^{inv} + c^{gc}(K^{inv}) + \frac{dc^{gc}(K^{inv})}{dK^{inv}} K^{inv} \perp K^{inv} \ge 0.$$

If investment is positive, relation A.15 implies that the total annualized investment cost must equal the shadow price of installed capacity. I.e. the increase in operating surplus resulting from one extra unit of capacity.