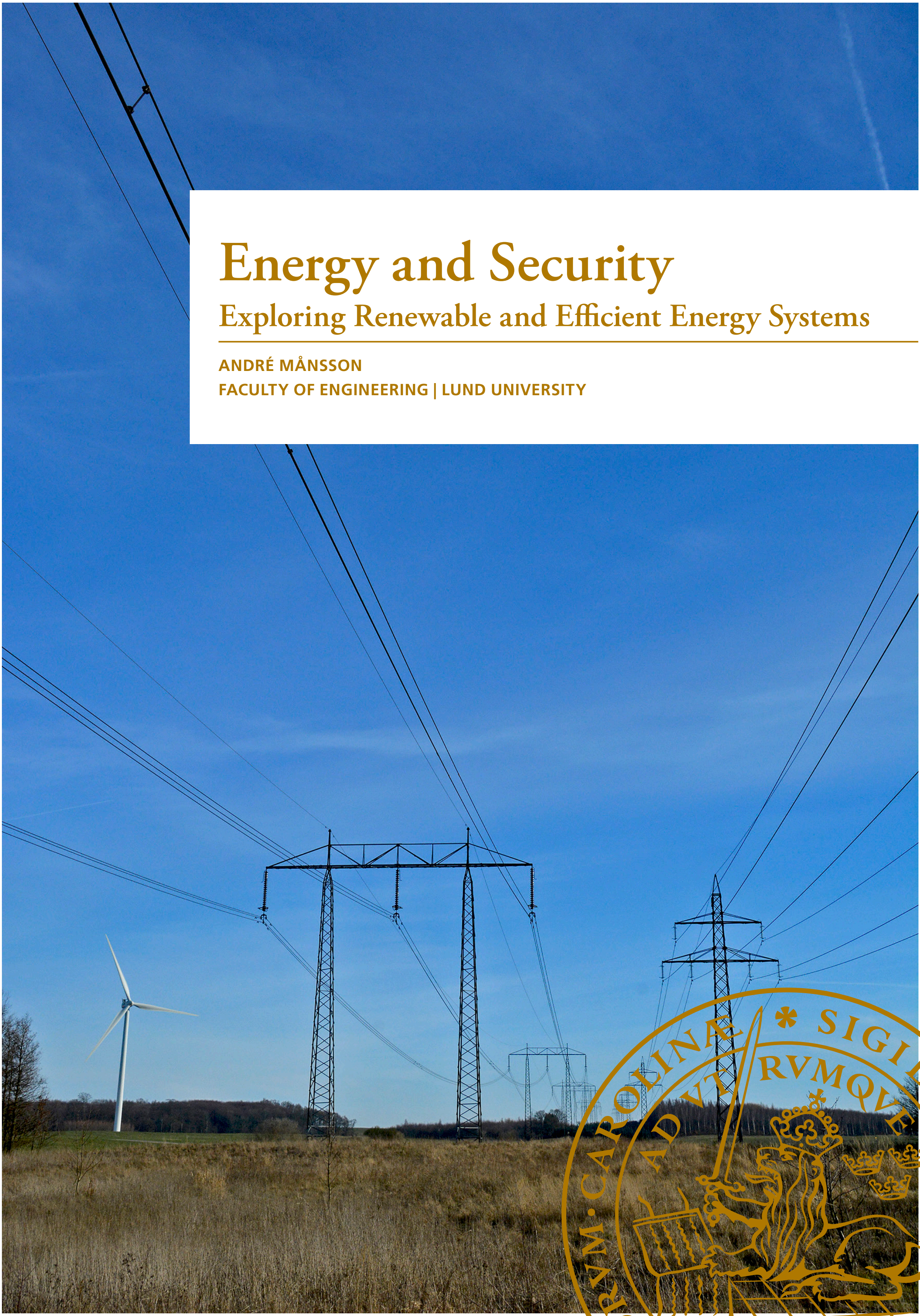
Energy and Security

Exploring Renewable and Efficient Energy Systems

ANDRÉ MÅNSSON

FACULTY OF ENGINEERING | LUND UNIVERSITY



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André Månsson

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Abstract

Mitigating climate change will affect energy systems and have consequences that reach beyond environmental policies. The studies presented in this thesis analyse how reducing emissions of greenhouse gases affect (energy) security. The focus is on strategies which improve energy efficiency or increase the share of renewable energy.

This thesis is based on five papers in which frameworks for conceptualising and analysing energy security are described and used. Two different aspects of energy security have been studied: i) security in energy systems and ii) how energy systems are related to conflicts that can threaten security.

It was found that increasing the share of renewable energy can affect threats to which the energy system is exposed, its sensitivity to disturbances, and its capacity to adapt to change. Both improvement and deterioration may result, which makes it difficult to compare the general level of security. Changes are sometimes minor because of dependencies between renewable and fossil supply chains that enable disturbances to spread. This restricts the possibility to hedge disturbances by the increased use of renewable energy. The effects on security can depend on how external factors develop and the preferences of various actors. It is suggested that energy security can be approached as a subjective concept and that (external) scenarios can be used to test the performance of different strategies. This enables the identification of strategies that are robust or adaptive to external factors, and desirable for different actors. It also strengthens the methodological integration between the fields of energy security, future studies and security studies in general.

Concerning conflicts, it was found that renewable energy has a low likelihood of triggering geopolitical conflicts as a result of abundance and low energy density. Renewable energy systems can be exploited in conflicts, for example, by withholding supplies, in the same way as fossil energy. Some bio-energy resources can trigger local conflicts due to the increased use of land and water which, for example, undermine food security.

Improving energy efficiency has many benefits with regards to security. It reduces the exposure and sensitivity to price increases and reduces competition for resources. It also enables a higher share of the demand to be met by domestic renewable resources. This increases the adaptive capacity of the energy system.

Key words

Climate change mitigation, Conflict, Decarbonisation, Energy security, Policy, Security of supply, Transition

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LUND UNIVERSITY

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Lund, April, 2016

Abstract

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Improving energy efficiency has many benefits with regards to security. It reduces the exposure and sensitivity to price increases and reduces competition for resources. It also enables a higher share of the demand to be met by domestic renewable resources. This increases the adaptive capacity of the energy system.

Populärvetenskaplig sammanfattning (Swedish)

För att nå miljömålet om begränsad klimatpåverkan måste användningen av fossil energi minska kraftigt. I denna avhandling undersöks om detta går att förena med mål om en trygg och säker energiförsörjning.

Dagens användning av fossila resurser är ohållbar eftersom resurserna är ändliga och användningen orsakar miljöproblem. I synnerhet bidrar de fossila bränslena till klimatförändringen. För att den globala uppvärmningen inte ska bli större än 2°C, en nivå som ledare för världens länder enats om inte ska överskridas, krävs att utsläppen halveras till mitten av detta århundrade samt närmar sig noll mot seklets slut. En sådan minskning skulle kräva en kraftig omställning av energiförsörjningen som även påverkar samhället i stort.

Under senare år har kopplingen mellan energi och säkerhet kommit att diskuteras allt mer. Diskussionen handlar både om en oro för att försörjningstryggheten hotas och att energi kan utnyttjas som verktyg för staters säkerhetspolitiska strävanden. Båda dessa aspekter blev tydliga i ett och samma problemkomplex, Rysslands (energi)relation med Ukraina. I Sverige har frågor kring leveranssäkerhet präglat diskussionen om elsystemets utveckling samtidigt som distributionens sårbarhet vid oväder och konsekvenserna vid strömavbrott tydliggjorts i samband med stormar. En annan fråga som rönt stor uppmärksamhet är minskad tillgång till oljeresurser som kan utvinnas till låg kostnad och samhällets sårbarhet för stigande och fluktuerande energipriser som kan följa av detta. Även minskat antal exportörer och deras instabilitet har kommit att uppmärksammas då konflikter har begränsat exporten av olja.

Att energisäkerhet är en viktig fråga i energipolitiken märks inte minst genom att försörjningstrygghet är ett av tre övergripande mål för EU:s energipolitik, tillsammans med konkurrenskraft och hållbarhet. Ibland används förbättrad energisäkerhet som argument för att motivera en klimatomställning. Andra väljer istället att belysa problem med förnybar energi som hotar att försämra energisäkerheten. Anledningen till dessa motstridiga slutsatser är bland annat att begreppet energisäkerhet är luddigt och det är oklart vilka aspekter av säkerhet som avses.

Syftet med denna avhandling är att undersöka kopplingen mellan energi- och säkerhetsfrågor samt visa på konsekvenserna av en omställning. Fokus ligger framförallt på ökad användning av förnybar energi och energieffektivisering. Dessa åtgärder är tillsammans med koldioxidlagring, ökad användning av kärnkraft och beteendeförändringar som minskar efterfrågan på energitjänster, de möjligheter inom energiområdet som främst står till buds för att minska klimatpåverkan.

I denna avhandling undersöks två perspektiv på säkerhet. Den första är försörjningstrygghet, där målet är att säkerställa ett kontinuerligt flöde i energisystemet till en stabil kostnad. Genom en litteraturstudie utvecklas en metod där försörjningskedjans exponering, sårbarhet och förmåga till anpassning analyseras. Det andra säkerhetsperspektivet som används här är när energiförsörjningen bidrar till (o)säkerhet. Ett ramverk utvecklas för att analysera hur energisystem påverkar möjligheten till olika former av konflikter.

Denna studie visar att förnybara energiresurser inte motiverar mellanstatliga konflikter som är kopplade till resursknapphet och staters geopolitiska ambitioner i samma utsträckning som fossila resurser. Detta beror på att förnybara resurser är mer jämnt utspridda över stora geografiska områden och produktionen täcker större ytor. Detta gör det svårt för utomstående aktörer att ta kontroll över en ansenlig mängd förnybara resurser till en låg kostnad. Jämnare geografisk fördelning möjliggör även ökad självförsörjning och ett minskat beroende av enstaka exportörer så väl som internationella marknader.

Effektivisering har flera fördelar ur ett energisäkerhetsperspektiv. Lägre energianvändning gör att en stat eller annan aktör blir mindre sårbar för prisförändringar. Det ökar även staters handlingsutrymme eftersom en lägre energianvändning ökar möjligheten till självförsörjning och konkurrensen om fossila och förnybara råvaror minskar. Självförsörjning är främst värdefullt om möjligheten till import skulle minska under en längre period, exempelvis till följd av långvarig avspärrning eller konflikt.

Vissa försörjningskedjor för förnybar energi påverkas idag av tillgängligheten på fossil energi. Som exempel kan nämnas när fossil energi ingår som insatsvara vid produktion av biodrivmedel. Detta innebär att förnybara försörjningskedjor inte är oberoende av vad som händer på de fossila marknaderna och att användare av förnybar energi påverkas av störningar som härrör från de fossila energimarknaderna.

Utvinning av vissa förnybara energikällor, inte minst vindkraft och solenergi, uppvisar variationer över dygnet respektive mellan olika årstider. Detta kan skapa problem och ställer större krav på exempelvis elsystemet vad gäller ökad flexibilitet i försörjningskedjan genom annan produktion, energilagring, eller efterfrågestyrning. En annan nackdel är att vissa former av förnybar energi genom sitt stora anspråk på mark och vatten påverkar bland annat livsmedelsförsörjningen negativt.

Det ökade beroendet av tillförlitlig elförsörjning, som troligen kommer ske oavsett omställning av energisystemet, ökar samhällets känslighet vid avbrott.

Smarta distributionssystem framhålls ibland som lösningen för att öka flexibiliteten men dessa ökar även systemens komplexitet. Komplexiteten kan i sig resultera i att systemen exponeras för fler tekniska riskfaktorer och ökar möjligheterna för attacker på systemet.

Det är inte möjligt att veta exakt hur en framtida omställning av energisystemen kommer påverka energisäkerheten. Säkerhet är inget absolut tillstånd och är svårt att beskriva dess innebörd objektivt. Värderingen av säkerhet och vad som upplevs som hot kan även skilja sig mellan olika personer. Vilka strategier en beslutsfattare ska välja beror också på vilken vikt som energisäkerheten ska ges i förhållande till andra samhällsmål. Dessa preferenser, likväl som hotbild och systemens förmåga att hantera störningar förändras över tiden. I denna avhandling har metoder utvecklats och testats som syftar till att ta hänsyn till detta när olika systemlösningar och strategier ska värderas. Det blir då tydligt att aktörers olika preferenser innebär att strategier som vissa uppfattar som bra uppfattas som dåliga av andra.

Det finns strategier som bara fungerar tillfredsställande när omvärlden utvecklas på ett visst sätt men inte annars. Om man förlitar sig på en sådan strategi som förväntas ge ökad säkerhet och omvärlden utvecklas på ett annat än man trott kan konsekvensen bli en försämrad säkerhet. Jämfört med strategier där användningen av förnybar energi ska öka framstår ökad energieffektivitet som den strategi som är mest fördelaktig. Detta med hänsyn tagen till både ovisshet om hur omvärlden och aktörers preferenser kommer utvecklas. För att nå klimatmålen räcker det inte med enbart effektivisering. I avhandlingen identifieras därför även hur olika strategier med förnybar energi kan komplettera varandra vilket gör att de sammantaget fungerar i olika situationer.

List of publications

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

I Månsson, A., Johansson, B., Nilsson, L.J., 2014. Assessing energy security: An overview of commonly used methodologies. *Energy 73*: 1-14.

II Månsson, A., Sanches-Pereira, A., Hermann, S., 2014. Biofuels for road transport: Analysing evolving supply chains in Sweden from an energy security perspective. *Applied Energy 123*: 349-357.

III Månsson, A., 2014. Energy, conflict and war: Towards a conceptual framework. *Energy Research & Social Science 4*: 106-116.

IV Månsson, A., 2015. A resource curse for renewables? Conflict and cooperation in the renewable energy sector. *Energy Research & Social Science 10*: 1-9.

V Månsson, A., Energy security, uncertainty and climate change mitigation: A quest for robust and adaptive mobility strategies. *Submitted*.

My contribution to the publications

I. I was responsible for the design of the study and the analysis. I wrote the paper together with the co-authors.

II. I was responsible for the study design, the development of the method, the security analysis and writing the main part of the paper. Alessandro Sanches-Pereira was responsible for compiling and writing the parts on current biofuel use, the composition of Sweden’s vehicle fleet and development trends in Swedish demand for biofuels. Sebastian Hermann assisted Alessandro and commented on the final text.

III. I was the sole author.

IV. I was the sole author.

V. I was the sole author.

A list of related publications by the author, not included in this thesis, can be found at the end of this thesis.

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1. Introduction

Current energy systems are environmentally unsustainable and affect security. The implementation of strategies that reduce the contribution to climate change will affect the relationship between energy systems and security. The work presented in this thesis is concerned with how these changes can be studied, and the effects they will have.

This chapter starts by providing some background to the topic and previous research. The research objectives and research questions are then discussed.

1.1 Energy as a security issue

The provision of energy services, e.g. for lighting, heating and transport, requires some form of energy system that connects natural resources and energy users. An energy system is made up of the physical energy supply chain and its governing institutions. Therefore, energy systems can be seen as socio-technical systems. These systems have co-developed with societies over time. Increasing demands for energy services have been met by using new resources and by developing new distribution systems.

Energy has a dual relationship with security: the objective may be to secure energy flows and protect them from threats, while energy systems can also cause security problems leading to danger in society (Johansson, 2013a). Threats change over time, as does the capacity of energy systems to respond to disturbances. However, perceptions of what constitutes security, and for whom, also change. According to Dannreuther (2015) "the dominant articulations of the threat to energy security are generally promoted by those experiencing negative shifts in the distribution of power in the energy value chain".

There are many historical examples of past threats to energy security. Deforestation was deemed a threat to the availability of energy resources during the 18th century in Sweden, which spurred the development of the energy-efficient tiled stove. There are early records from Germany, where rivers were used to transport logs, of upstream suppliers cutting off the supply of logs during political and trade disputes (Högselius et al., 2015; Radkau, 2008), while striking coal miners caused energy security concerns in England during the 1970s (Butler et al., 2013). Access to oil was important for the armed forces during both World Wars (Yergin, 1991), and the oil crises during the 1970s underlined the dependence of the transport sector on oil products, and the vulnerability of society to disruptions and price volatility (Deese and Nye, 1981; Hamilton, 1983).[1] This initiated a debate on how the relationship between energy security and foreign policy could be understood in countries that were dependent on, or independent of, energy trading (Miller, 1977).

Energy imports and international trade are sometimes still considered to be a security issue.[2] For example, the import of natural gas from Russia has been regarded as a security concern in the EU since the late 1990s (Casier, 2011). A secure energy supply constitutes one of the main pillars of EU energy policy, together with competitive energy markets and environmental sustainability.

Today’s energy systems are reliant on other forms of infrastructure, such as those providing communication, and energy supply chains can stretch over long distances. Most sectors in society are dependent on reliable sources of electricity, making the power grid a critical infrastructure. It can be important to prevent large blackouts, as these affect so many people and societal functions (Bo et al., 2015). The US military, an early adopter of nuclear-powered vessels, now has the goals of developing drop-in synthetic fuels and solar-powered military bases, and increasing energy efficiency in the field, to improve their energy security (Alic, 2015). Increased geographical concentration of resource extraction, flow rates and net energy yield have been portrayed as future threats to security and economic growth (Dale et al., 2012; Hall et al., 2014; King, 2015).

In parallel with these developments, increased environmental awareness is becoming a factor that affects the evolution of energy systems. If history provides some idea of the future, energy and security will continue to interact, but the way in which they interact change over time. Some of the currently perceived threats may become less important, while as new ones will emerge.

1.2 Contribution of energy systems to climate change

Technological progress, combined with an increase in the use of energy, has enabled the human population to increase and economies to grow (Kümmel, 2011). However, this growth places pressure on the environment that can

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[1] The oil crises started when the Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo in response to US involvement in the Yom Kippur War. The embargo coincided with a decline in oil extraction in the USA, which had a reinforcing effect.

[2] International energy trade (mainly crude oil, oil products and coal) make up more than 44% of all seaborne trade (Stopford, 2009:44).

undermine human livelihoods in the longer term. Several environmental problems can be seen as symptoms of unsustainable societies. One of these problems, connected with several others, is anthropogenic climate change.[3]

It has been agreed that global warming should be kept below 2°C compared with the preindustrial level (UNFCCC, 2015). To achieve this requires stabilising the concentration of carbon dioxide in the atmosphere below 450 ppm (IPCC, 2013). This requires that cumulative carbon dioxide emissions between 2011 and 2100 remain below 1240 Gt (Giga ton). For this to be achieved, the emission of carbon dioxide in 2050 must be 40-70% lower than in 2010, and close to zero at the end of the 21st century, according to the IPCC (2014b).

Meeting the target of lower emissions will affect energy systems since the energy sector is a major emitter of carbon dioxide. A number of measures can be taken to reduce emissions and mitigate anthropogenic climate change. These include technological changes, such as replacing fossil fuels with renewable energy or nuclear power, carbon capture and sequestration (CCS), increased efficiency, and behavioural changes to reduce the demand for energy services.

Developments during recent decades provide both hope and despair concerning the prospect of mitigating climate change. Targets for temperature increase have been agreed upon internationally, but there is as yet no agreement on the necessary emission reductions (UNFCCC, 2015). Many local, regional and national actors are taking voluntary measures to reduce their environmental impact. Some of these provide synergies or trade-offs with other policy goals. Energy security is a goal that is frequently mentioned as interacting with climate change mitigation policies (e.g. (Bauen, 2006; Bollen et al., 2010; IPCC, 2014b)).

1.3 Previous research on energy security and climate change mitigation

Recent years have witnessed an increase in research into how climate change mitigation policies affect energy security. An overview of the current state of this research is presented below. In-depth reviews can be found in previous publications (e.g. (Johansson, 2013b; Jonsson et al., 2013; King and Gulledge, 2013)).

Several studies have used global energy models to assess how climate mitigation policies would affect, for example, the composition of the global energy mix, and the dependence on imports and trade between different regions (Bollen et

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[3] Apart from climate change, earth system scientists have identified eight other “planetary boundaries” (e.g. ocean acidification and the biochemical flow of nitrogen and phosphorus) that can change the stable conditions of the Holocene (Rockström et al., 2009; Steffen et al., 2015).

al., 2010; Jewell, 2013; Kanudia et al., 2013; Matsumoto and Andriosopoulos, 2016; McCollum et al., 2013; Turton and Barreto, 2006). These studies use quantitative indicators as proxies for the level of security, and compare the results with other development pathways, e.g. business-as-usual scenarios. The effects of climate mitigation policies on national energy systems have also been studied, for example: ways in which mitigation policies can hedge fuel price volatility related to oil imports (Criqui and Mima, 2012; Escribano Francés et al., 2013; Hedenus et al., 2010), effects on diversity of fuel mix and import dependence (Chalvatzis and Rubel, 2015; Schwanitz et al., 2015; van Moerkerk and Crijns-Graus, 2016; van Vliet et al., 2012), and ways in which the effects of climate mitigation policies on energy security differ depending on the time horizon and input variables (Guivarch et al., 2015).

Diversity is often seen as a general hedge of uncertainty that increases security. The extent to which mitigation policies increase diversity has been estimated using diversity indexes (Grubb et al., 2006) and mean-variance portfolios (Awerbuch et al., 2006). It has also been shown that climate change mitigation policies can increase the diversity of, for example, electricity generation technologies (Li, 2005).

Infrastructure has also been analysed with regard to technical reliability, especially balancing of (national) electricity grids with variable production. Examples include the assessment of power system reliability in providing continuity of energy supply with stochastic renewable electricity production (Abdullah et al., 2014), supply adequacy with various shares of variable renewable production (Grave et al., 2012), and the use of vehicle-to-grid technology to balance wind power (Haddadian et al., 2015). Others have analysed how the implementation of climate policies affects the capacity of infrastructure to respond to, and cope with, short-term physical disruptions (Skea et al., 2012). In one study, the supply security of local biomass used in combined heat and power plants was analysed (Karhunen et al., 2015). They found that supply security could be improved by integrating the decentralised supply chains in a national network.

Production data have been compared in a number of case studies, leading to the identification of new sources of risk such as drought and variability, as renewable energy systems may be more dependent on natural flows (Eaves and Eaves, 2007; Mullins et al., 2014; Pimentel, 1991; Sáenz et al., 2014). This dependence results in seasonal variability and short-term intermittency of energy production. Studies have also been carried out to assess how the incentive of terrorists to attack energy systems is affected when the share of renewable energy is increased (Lilliestam, 2014; Stegen et al., 2012).

A handful of studies have been performed to elucidate the effects of climate change mitigation and renewable energy systems on international relations, and the possible geopolitical implications. The implications were found to differ depending, for example, on whether the country is a net importer or exporter of fossil fuels, and its level of economic development (Bradshaw, 2014). Various approaches have been used, including modelling of international trade flows (Andrews-Speed et al., 2014), “thought experiments” (Scholten and Bosman, 2016), and using the economic interdependency of exporters and importers to estimate the stability of the trade relationship (Lilliestam and Ellenbeck, 2011).

Politically oriented analysis on the national or subnational level is not as common in the literature. One exception is the study by Eisgruber (2013), who investigated the likelihood of renewable electricity export developing into a “resource curse” for the exporter.

Applied policy analysis has been used to assess the interactions and coherence between energy security and other energy policy fields in an existing situation (Strambo et al., 2015) and under different development pathways (Jonsson et al., 2015). One study analysed the way in which “greening the energy system” became the answer to the challenges to protect climate and to strengthen energy security in a country that imported fossil fuels (Hillebrand, 2013). A number of qualitative studies have also been performed with the aim of analysing stakeholders’ conflicts of interest using, for example, discourse analysis to understand the relationship between the discourse and material interests (Bang, 2010; Fischhendler et al., 2014; Michaels and Tal, 2015; Rogers-Hayden et al., 2011; Toke and Vezirgiannidou, 2013). These studies have shown that investments in low-carbon energy sources and renewable energy policies are sometimes rejected when they are perceived to be in conflict with national security. In other situations, the incumbent actors have used energy security as an argument to promote a certain low-carbon technology. There are also examples where energy security has been used as an argument to legitimize and prioritize increased domestic extraction of fossil resources which goes against climate change mitigation policies (Nyman, 2015).

1.3.1 Research gaps addressed in this thesis

There is a need to improve the methodologies used to assess energy security so they that capture different types of uncertainties. Such improvement is particularly valuable when the object to secure is in a future setting. This is because there are so many factors that change over time, although the way in which they change is unclear, and it can be difficult to trace their causality. Performing more thorough analysis of different uncertainties enables identification of the strategies that are sensitive to external factors and should be avoided by an actor who is averse to risk in uncertain situations. Currently, certain characteristics, such as self-sufficiency, are virtually always considered to strengthen security, which is not necessarily the case. Analysing uncertainties can also enable the detection of trade-offs, for example, between stability and flexibility.

In terms of empirical research gaps, there is a need to improve our understanding of how different sectors and the provision of certain energy services are affected. This is particularly the case for transport. The road transport sector is currently dominated by the use of fossil fuels in vehicles. Breaking the dominance of oil-based fuels may increase the number of energy carriers and transport modes, and lead to changes in spatial planning.

There has been little research into the effects of emission reductions on security in general. Fossil energy systems have been claimed to render insecurity for a number of reasons, e.g. their political and economic value (Johansson, 2013a). The extent to which this may also be the case for renewable energy has not been thoroughly assessed. This topic warrants closer scrutiny, considering how current energy systems are linked to political power relationships, the importance of energy export revenues for many countries, and the differences between existing fossil supply chains and renewable supply chains.

1.4 Research objectives

The overarching aim of the work presented in this thesis was to improve our understanding of how security and energy systems are interlinked, and how this relationship is affected by the implementation of climate change mitigation policies. To achieve this aim requires a deeper understanding of which methodologies can be used to study energy security, and their respective strengths and limitations, as well as the underlying causes of security issues and how the relative importance of these factors changes as a result of the implementation of climate change mitigation policies.

The point of departure was the assumption that mitigating anthropogenic climate change is possible, and that it will require major changes in current socio-technical energy systems. At the same time, societies are constantly evolving. Some of these changes are dependent on, and interact with, the energy system, while others are not. Although it is difficult, if not impossible, to predict what will happen, we should, nonetheless, make an attempt to anticipate the challenges and identify proactive strategies for managing them

1.4.1 Research questions

The following overarching research question was formulated to guide the research process: *How will the introduction of low-carbon energy systems affect security?*

This question was broken down into the following questions:

1. How can security be assessed in evolving energy systems?
2. How will the transition to a fossil-fuel independent road transport fleet affect the security of transport services?
3. How are renewable energy systems related to conflicts?

Energy security is a broad field. Answering the first question will provide insight into which methodologies are used to assess energy security, including their strengths and weaknesses. This knowledge will be useful when studying the security of current energy systems, as well as that of evolving and future systems.

The second question focuses on one sector, i.e. road transport, using Sweden as the case to be scrutinised. There are several reasons for this. The transport sector is currently dominated by road transport, using vehicles that depend on fossil fuels (diesel and petrol). As only a handful of countries export oil, and the transport sector is sensitive to disturbances, the transport sector is often at the centre of energy security discussions.[4] There is uncertainty in the future supply and availability of oil, as well as which energy carrier, or carriers, that will replace oil. As is the case in most other Western countries, the transport sector in Sweden is dependent on imported oil. The results of this study may therefore be relevant in many other countries.

The third question frames the energy system as a contributor to insecurity. This relationship is often neglected in studies on emission reductions, as discussed in Section 1.3.1. Conflicts are subjected to closer scrutiny as they are often linked to security.

1.4.2 Delimitations

A transition to low-carbon energy can take various forms and involve different technologies. In this thesis, the reduced use of energy, through increased efficiency and conservation, and the introduction of renewable energy were considered. Nuclear power and CCS were not considered. The main reason for this is that the combination of renewable energy and the reduced use of energy is assumed to result in larger structural changes with greater implications for security.

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[4] Several studies have focused on the dependence of the transport sector on oil products, the scarcity of conventional oil and the possibility of replacing oil (see e.g. (Friedemann, 2016; Hirsch, 2008)).

It should be noted that interactions between security and emission reductions are analysed, but no assessment is made of the likelihood that such emission reductions will take place.

1.5 Outline

The second chapter of this thesis introduces various perspectives of environmental sustainability and the ways it relate to the conversion of energy. This provides an introduction intended mainly for readers who have no detailed knowledge of environmental science or the ways in which climate change mitigation policies affect energy systems. The third chapter provides an introduction and overview of energy security.

The following chapter provides the theoretical and methodological foundation of this work. It is divided into three parts: socio-technical system studies, security studies, and studies of alternative futures with a focus on scenario methodology and managing uncertainty.

The fifth chapter summarises the results presented in the papers, and relates them to the research questions. The findings are discussed in Chapter six. Chapter seven presents concluding remarks. Chapter eight provides suggestions for further research.

2. Environmental sustainability as a driver of change

This chapter provides a brief introduction to environmental sustainability, climate change, and the effects of strategies to reduce emissions of greenhouse gases on energy systems.

2.1 Perspectives on environmental sustainability

Natural resources are necessary for human activities, but human activities can also have negative effects on the environment. This dual relationship has been known and studied for centuries(see e.g. Marsh (1864)). The use of natural resources enables humans to produce other forms of (man-made) capital. Opinions differ as to what is sustainable and what is not, depending on assumptions regarding the substitutability of different kinds of resources and capital, nature's own capacity to regenerate itself following environmental degradation, and assumptions on the capacity of mankind to innovate and anticipate the future (Brown et al., 2014; Nekola et al., 2013).[5] As a result of these differences, researchers reach diverging conclusions on the need to take any precautionary action, and if so, what it should be.

This has resulted in much debate on resource availability and its implications for society. Examples of researchers who foresee resource limitations are (Barney, 1980; Carson, 1962; Ehrlich and Ehrlich, 1968; Jefferson, 2015; Meadows et al., 1972; Turner, 2008) while those who do not, include (Lomborg, 2013; McAnany and Yoffee, 2009; Radetzki, 2010; Simon, 1981).[6] Researchers who do not believe

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[5] Further differentiation can be made depending on whether the environment is believed to have an intrinsic value (ecocentric) or only provide benefits to humans (anthropocentric) (Gagnon-Thompson and Barton, 1994).

[6] The "Limits to Growth" project by Meadows et al. (1972) is one of the most disputed studies on environmental sustainability. They concluded that: i) limits on growth of the present kind will be reached within the next 100 years, ii) a sustainable future is possible but requires proactive measures due to delayed feedback, and iii) if the growth trajectory is left unabated an uncontrollable and sudden decline in population and industrial production is likely to follow.

that natural resources will limit the prosperity of society have argued that unconventional fossil resources (shale oil, shale gas, tar sand, etc.) can increase energy security, obviating concerns of resource scarcity and increased marginal extraction cost (see e.g. (Lomborg, 2013; Radetzki, 2010; Yergin, 2011)). Responding to unsustainability by developing new technologies can increase the levels of complexity and specialisation of society leading to new risks of which the responsibility is unclear (Tainter and Taylor, 2014). This has been referred to as the *risk society* (Beck, 1992; Giddens, 1999). Some researchers therefore believe that developing unconventional resources will at most provide temporary relief of resource scarcity symptoms, rather than address the underlying causes of unsustainability (Bardi, 2011; Becker, 2013; Friedrichs, 2013; Turner, 2008). It is unknown how long it will be possible to compensate degraded natural capital by an increase in other capital. Actors may value this risk-reward trade-off differently -depending on, for example, their knowledge of the subject (Tversky and Kahneman, 1974) and their socially embedded values (Douglas, 1985; Luhmann, 1993).[7]

In this thesis, climate change is regarded an issue of environmental unsustainability. Strategies to reduce emissions that contribute to global warming are analysed from an energy security perspective. Some strategies target the cause of unsustainability, such as changing practices to conserve energy, while others only address the symptoms, such as substituting fossil fuels with renewable resources that are associated with lower emissions of carbon dioxide.

2.2 Climate change

Greenhouse gases (e.g. water and carbon dioxide) occur naturally in the atmosphere, and they are necessary for creating a stable climate in which species can live. The climate is subject to natural variations over long periods of time. For example, the inflow of solar radiation changes with variations in the earth’s orbit (Hays et al., 1976). Apart from these natural variations, human activities can also affect the climate, and this is referred to as anthropogenic climate change.

The rate of emission of carbon dioxide and other greenhouse gases from human activities is higher than the rate of absorption by carbon sinks. Total emissions of greenhouse gases in 2010 corresponded to 49 Gt CO_2 equivalents, of which 62% resulted from the combustion of fossil fuels and industrial processes, and 13% from forestry and land use changes (IPCC, 2014b). Concerning global energy supply, coal and oil account for almost a third each (see Figure 1).

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[7] Hume (1739) was one of the first to point out that humans care less about environmental problems that are remote (in time and space) than proximate.

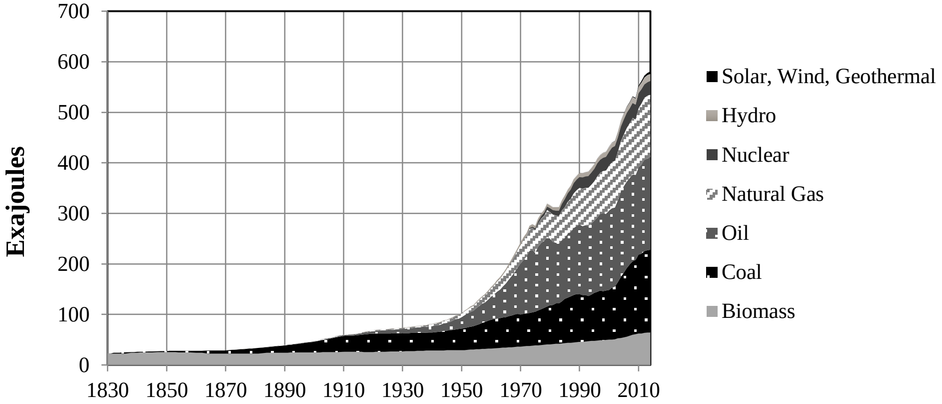

Figure 1.
World total primary energy supply 1830-2014 (exajoules). The figure illustrates global energy resource additives occurring during the 20th century (from Smil (2010:154) with updated data from BP (2015)).

Between 1750 and 2011, 880 Gt of carbon dioxide were accumulated in the atmosphere as a result of human activities (IPCC, 2013). This increased the level of carbon dioxide in the atmosphere (from 280 to 400 ppm). During the period from 1880 to 2012 the global average temperature increased by 0.85°C (IPCC, 2013), see Figure 2. This is commonly referred to as climate change or global warming. However, the term global warming falls short in representing all the aspects of climate change, since not only the global average temperature is changing, but also the stability and predictability of the climate system itself.

Some of the effects of climate change on ecosystems and people may be irreversible, such as more frequent droughts, floods and heatwaves (IPCC, 2014a). These can pose a threat to security in vulnerable societies such as increased likelihood or severity of conflicts. [8] In other words, although climate change itself does not cause conflicts, it can be seen as a catalyst of conflict and a threat multiplier (see e.g. (CNA, 2007, 2014)).[9] It is difficult to estimate the environmental cost of climate change, but according to Stern (2006) it exceeds the cost of inaction.

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[8] Studies of early civilisations have indicated that some societies had difficulties in adapting to changes in climate (Hsiang et al., 2013; Zhang et al., 2011).

[9] It should be noted that some researchers question the hypothesis that climate has an impact on conflicts, or argue that it prevents violent conflicts (Salehyan, 2008; Slettebak, 2012).

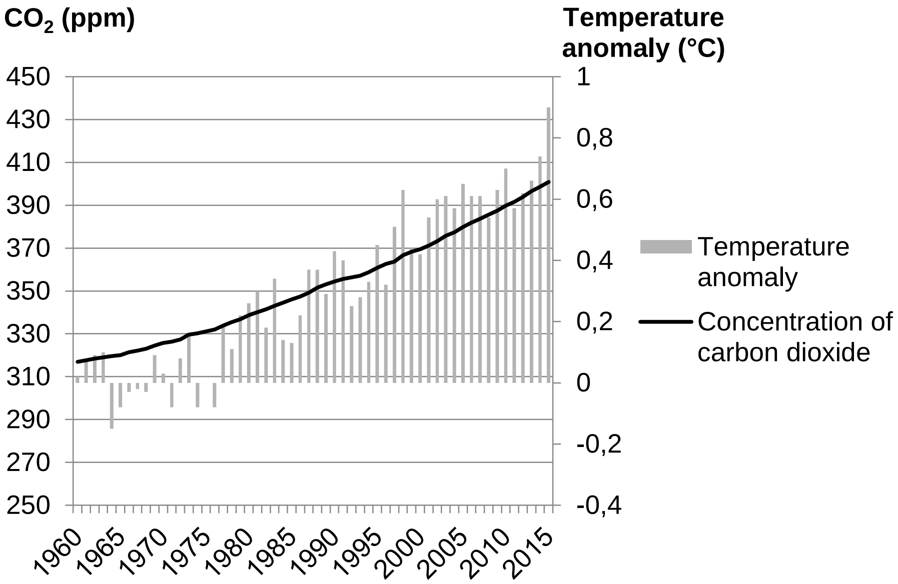

Figure 2.
Trend curve for atmospheric concentration of carbon dioxide (ppm, left axis) and temperature anomaly (°C, right axis) with respect to the average durring the 20th century (1901-2000) over the period 1959-2014 (data from (ESRL, 2016; NCEI, 2016)).

The negative effects of climate change increase non-linearly as the temperature increases. Political leaders have agreed that the average increase in global temperature should be kept below 2°C to prevent major negative effects, and “pursue efforts” to limit the increase to 1.5°C (UNFCCC, 2015). Reductions in emissions from today’s levels will be required to achieve these goals. In order to achieve a greater than 66% likelihood of not exceeding a 2°C increase in temperature, the cumulative emission of carbon dioxide after 2015 would have to be in the range of 590-1240 Gt (Rogelj et al., 2016). According to the IPCC (2014b), emissions in 2050 would have to be between 40% and 70% lower than in 2010, and close to zero at the end of the 21st century, to avoid a 2°C increase in temperature. It is theoretically possible to postpone the emission peak, but this would require more rapid reductions at a later point in time, combined with sequestration and storage of carbon previously released into the atmosphere.

It should be noted that the total amount of emissions must be reduced, since climate change is a global problem. Industrialised countries will have to reduce their emissions more if developing countries were allowed to increase their emissions. The European Commission (2011) estimates that emissions from the European Union would have to be reduced by 80-95% by 2050, compared with 1990, and approach zero at the end of this century.

2.2.1 The effect of emission reductions on the energy system

Climate change mitigation will affect the energy sector, since it is the major source of anthropogenic greenhouse gases. There are three main approaches to mitigating climate change that affect the energy sector.

1. Reduction in the use of energy: for example, switching to technologies with higher efficiency, behavioural changes that conserve energy, leading to reduced energy demand, or population decline (lower birth rate).
2. Shifting to technologies that have lower emissions: for example, replacing fossil resources with renewable resources or nuclear power.
3. Implementing end-of-pipe technologies that capture and store emissions.

Considerable time is required to change energy systems due to the large capital stock and long turnover time. Therefore, the implementation of climate mitigation policies must start early so that the technology can mature and decisions on investments are affected such that society’s fossil energy lock-in is broken. There is an abundance of literature on the ways in which energy systems are affected by climate mitigation policies. The findings differ slightly depending on the assumptions made regarding potential resources, future cost, demand, etc. The overall energy mix assumed is similar concerning improved efficiency, increased use of renewable energy and reduced use of coal and oil. One example that illustrates this is that given by the IEA (2015). Table 1 presents the energy mix in 2040 projected by the IEA with and without the implementation of a stringent restriction on the concentration of carbon dioxide in the atmosphere of 450 ppm.

Table 1.

Example of how the total primary energy demand (EJ/year) from different sources could change in 2040 as a result of climate mitigation policies. 2013 is used as the reference point. A scenario with stringent climate mitigation polcies (“450ppm scenario”) is compared with a business-as-usual projection (“Current polcies scenario”) (source IEA (2015)).

	2013	**2040**	
		450 ppm scenario	Current policies scenario
Coal	164.5	104.5	235.2
Oil	176.6	140.3	223.9
Gas	121.5	139.6	193
Nuclear	27.0	68.1	43.4
Hydro	13.6	24.6	21.2
Bioenergy	57.6	97.6	76.6
Other Renewables	6.7	61.5	29.0
Total	567.6	636.3	822.4

As can be seen in the example above, climate mitigation policies would reduce the share of fossil fuels. Coal is reduced most, since it is more carbon intensive than natural gas. The use of renewable energy (mainly bioenergy, wind power and solar photovoltaic (PV)) increases in both relative and absolute terms. Energy efficiency is also increased, meaning that less energy is required to produce one unit of gross domestic production. This is partly the result of increased electrification of transport and industry.

Climate mitigation policies require the development of new supply chains, i.e. technologies to produce/convert renewable resources into energy carriers, distribution technologies and efficient technologies for final energy use. Stringent carbon dioxide restrictions will also require that fossil resources are left in the ground rather than being extracted. As renewable resources have a different spatial distribution from fossil resources, new trade patterns will develop.

Climate change has been described as a “(super) wicked problem” (Lazarus, 2009; Levin et al., 2012). This means that it covers multiple policy spheres, is long term and large scale, there are uncertainty and diverging opinions and framings of the problem, and the problem can be a symptom rather than the actual cause (Rittel and Webber, 1973). Therefore, reducing emissions will not only have implications on the energy sector, since societies and energy systems co-evolve. This can be seen as both a threat and an opportunity. For example, emission reductions may bring co-benefits such as reduced local air pollution, traffic congestion and ocean acidification (IPCC, 2014b). The way in which climate change mitigation affects security is the subject of this thesis.

3. Energy and security

This chapter presents perspectives on energy security found in contemporary research. The chapter is structured according to what is assumed to be secured as “energy” and “security” can have two different relationships. These are: i) whether the energy system is (considered) a referent object that is to be secured or, ii) a subject that generates (in)security or is perceived to do so (Johansson, 2013a).[10]

3.1 The energy system as a referent object

Energy security is with this perspective concerned with securing the energy system. However, energy systems usually do not usually have an intrinsic value that makes them valuable for their own sake. It is rather what energy systems can provide, i.e. energy services, that is the underlying reason why actors take an interest in securing their function. Examples of energy services are personal mobility, transport of goods, indoor heating and lighting.

The entire energy system, from resources to final energy use, must function satisfactorily. Disturbances can affect all the different stages, resulting in physical disruptions of energy delivery and/or price increases for energy users. The further downstream the disturbance occurs, the more likely it is to result in a physical disruption for users, assuming that there is a market to balance supply and demand. A physical disruption will have a higher cost than that indicated by the mere cost of energy due to the discrepancy between energy’s share in total factor cost and output elasticity (Kümmel et al., 2015). In other words, energy is required to enable economic activity and its total value is not fully reflected in its cost. Furthermore, in the short term, it can be difficult to replace certain energy carriers with other carriers as well as replace energy in general with natural or man-made capital.

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[10] A similar relationship can be found in the risk literature on the relationship between a risk object, e.g. a threat, and an object at risk that is to be protected (see (Boholm and Corvellec, 2011; Hilgartner, 1992)).

3.1.1 Conceptualising and defining energy security

Some researchers define and assess energy security using multiple dimensions such as available, accessible, affordable and reliable supply of energy (Kruyt et al., 2009; Luft et al., 2011; Sovacool and Mukherjee, 2011). The exact levels of these parameters required in order for the supply to be considered secure is usually not defined, but security, or insecurity, is regarded as a physical state that can be measured objectively using scientific methods.

This multidimensional conceptualisation has been criticised by those who argue that the dimensions overlap (i.e. they are not independent which may result in double counting), and that a multidimensional definition obscures differences between goals (security), means (ways of increasing security) and threats (that which compromises security) (Cherp and Jewell, 2014; Lilliestam and Patt, 2012; Winzer, 2012). However, these critical authors maintain that energy security can be described by a single, all-encompassing definition, and they propose definitions such as “continuity of energy supply relative to demand” (Winzer, 2012) and “low vulnerability of vital energy systems” (Cherp and Jewell, 2014). One drawback of a single definition is that the level of abstraction is not reduced compared to the use of multidimensional conceptualisations of energy security. Instead, it creates a need to conceptualise what a vital energy system is, what low vulnerability is, who should decide this, etc. For example, different actors may have different perceptions of whether an energy service is “necessary” or “desirable”, as well as whether the system that provides the service is vital or not.

There are energetic differences between energy flows. Rosen (2002) and Shaw et al. (2010) suggested that “energy security” is a misnomer since it focuses attention on the gross supply of primary energy. This may underestimate the role of efficiency improvements and disguise inherent differences in energetic quality between energy resources (e.g., energy balances, intermittency, etc.). Therefore, these authors proposed that emphasis should be placed on energy that can be used to do useful work (i.e., “exergy security” or “secure net energy”).

Chester (2010) suggested that energy security is “polysemic in nature” and “capable of holding multiple dimensions”. However, instead of proposing one set of metrics to be used as “one-size-fits-all”, she argued in favour of making the underlying assumptions explicit. Both policy makers and researchers should thus be transparent regarding what they mean when they refer to energy security.

3.1.2 Style of action – responding to change or controlling it?

Approaches to studying and strengthening energy security can focus on (preventing) threats and/or (developing) the system’s capacity to withstand and respond to a threat. Stirling (2014) refers to this as *control* and *respond*. For *control* to be effective, intervention must be possible as well as desirable, and the drivers of change causing the threat must be traceable and well understood. This requires firm knowledge and high predictability, neither of which may be possible in all situations. For example, the sheer number of “black swans” (i.e., tail events that each have a low probability of occurring, but will have high impact if one does) may be so high that it is plausible that one of these events will occur, but it is not possible to know which one (Taleb, 2009).

The *Respond* perspective can be taken one step further by assessing how energy services can be secured rather than particular energy flows (see e.g. (Caballero-Anthony et al., 2012; Jansen and Seebregts, 2010). These differences may appear to be semantic, but the choice of approach determines which strategies can be proposed to increase security. Focusing on threats is more likely to legitimize protection (of the status quo), whereas focusing on response can promote capacity development, increased resilience, transformation, etc. This can take place at different levels, for example, access to energy services is a cornerstone in enabling human security and development (Karlsson-Vinkhuyzen and Nigel, 2013).

3.1.3 Temporalities of vulnerabilities

Energy systems have different vulnerabilities in the short- and long term (Boston, 2013; Gracceva and Zeniewski, 2014; Stirling, 2014). Stirling (2014) refers to this as temporality of change, and differentiates between *shocks*, which are transient disruptions (e.g. weather events), and *stresses*, which are enduring shifts (e.g. resource depletion).

It may be necessary to know whether a disturbance is transient or enduring to be able to formulate a strategy that improves security. Trade-offs between may also be possible. For example, investing in emergency stock provides a buffer that will reduce transient disruptions, but this may reduce the capacity to respond to enduring shifts due to increased technological lock-in.

3.1.4 Energy security strategies

Combining the style of action and temporality of change results in four generic strategies to increase security, which Stirling (2014) refers to as *stability*, *durability*, *resilience* and *robustness*. What Stirling refers to as *robustness* is in this thesis referred to as *transformability* (see Figure 3). This term is used because it is consistent with the scenario analysis and planning nomenclature used in this thesis (see Section 4.3). In scenario analysis, a strategy that is robust, is stable and durable in the face of different changes, and it therefore performs satisfactorily in several settings.

It should be noted that the four different groups of strategies have different strengths and weaknesses which make them complementary and useful in different situations. According to Stirling (2014) incumbents have a preference for controlling while as responding tend to be better in situations where there is a lack of knowledge on how to supress or control threats.

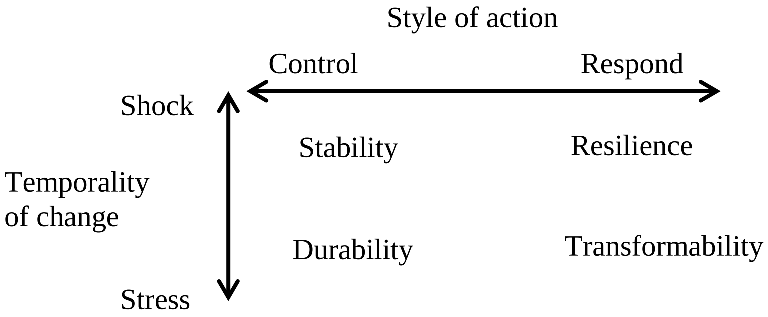

Figure 3.
Typology of governance strategies that can be applied to energy security. Adapted from Stirling (2014).

Stability refers to a system’s ability to withstand transient shocks. This feature can be important for critical energy infrastructure such as the national electricity grid (Gracceva and Zeniewski, 2014). Stability requires regular maintenance so that the functionality and predictability of technical components is maintained, and sufficient investment ensuring that the system has a (maximum) capacity that is adequate to meet demands at all times.

Durability refers to a system’s ability to withstand stress over time. Examples of durability strategies are to increase the height of a hydropower dam so it can sustain higher water levels, and to extend the lifetime of old electricity production plants.

Resilience refers to a system’s ability to bounce back after a shock, at low cost, to buffer and maintain a desired function during a strain, or to adapt in reaction to a disturbance and continue along the preferred and pre-defined development trajectory (Becker, 2014; Pendall et al., 2010; Walker and Cooper, 2011). These three perspectives originate from different assumptions regarding what is a desired system state, and if one or several stable equilibria exist. The ability-to-bounce-back mind frame assumes that systems have one stable state (equilibrium) that is desired, and resilience is the ability of that system to rapidly bounce back to the same equilibrium at a low cost, e.g. as a result of redundancy. This is also referred to as engineering resilience. The “buffer perspective” assumes that a system has multiple stable equilibria to which the system can bounce back, e.g. as a result of flexibility. Resilience as the "ability to adapt" departs from the assumption that there is no equilibrium as the system is constantly changing, and resilience is then the ability of a system to retain the same function (i.e. continue along its development trajectory) when exposed to a strain. Several characteristics of energy systems affect resilience, including diversity, redundancy and organisational structure (Molyneaux et al., 2016).

Transformability is concerned with dealing with and avoiding lock-in (Blum and Legey, 2012). Improving this characteristic requires strategies that perform satisfactorily within long-term constraints defined by the system's technical, political and economic environment (Gracceva and Zeniewski, 2014; Stirling, 2014). This is an emergent property that is dynamic in nature since it implies that the system must be able to adapt and follow new development trajectories when contextual boundaries change, e.g. the preferred development trajectory (Folke et al., 2010; Walker et al., 2004). This differentiates it from third-order resilience strategies ("ability to adapt"), since those strategies strive to retain the same function and continue along the same development trajectory.

3.2 The energy system as a subject

As a security subject, the energy system has a dual relationship with security. It can be a security threat, e.g. a risk source, but it can also enable security. According to Johansson (2013a), energy systems can generate three causes of insecurity as a result of: political or economic value, technological risk factors, and environmental risk factors.

The first is due to the political and economic value (or perceived value) of energy. Examples of this include the "resource curse" and geopolitically motivated struggles for scarce resources. It should be noted here that different theoretical perspectives provide diverging, and sometimes even contradictory, explanations of the ways in which energy trade interacts with conflicts. Two of the more prominent schools within the field of international relations, liberalism and realism, employ different assumptions of the rationale and ability of states to trust other states. This has implications for security and strategies to improve it (Ciută, 2010; Sonnsjö, 2014). Assuming that states value relative gains, i.e. they strive to improve their position relative to other states, and that they do not trust others (as a result of anarchy of international politics), the policy implication is to aim for increased self-sufficiency, since dependence on others hampers foreign policy autonomy. Assuming that states value absolute gains and trust others, results in strategies that strengthen interdependence on other states and (complex) interdependence with the international community. There are historic (empirical) examples that support both hypotheses of whether, and how, energy trade interacts with conflicts. An example that illustrates how energy interdependence can contribute to more friendly international relationships is the European Coal and Steel Community (ECSC). This was the predecessor of the European Union, and helped to unify European countries after the Second World War by enabling the trade of energy between countries that had previously been at war. This can be seen as an example of how energy (trade) can enable security.

Examples of technological risk factors include explosive energy carriers, such as natural gas and hydrogen, and nuclear proliferation. Antagonistic threats can exploit these risks rendering insecurity. Technical failures, such as malfunction due to aging or natural hazards may also trigger an event. Some accidents can also be regarded as safety issues for those working at the production plant (see e.g. Sovacool et al. (2016)).

Environmental risk factors include conflicts that result from competing land use, climate-change-induced risks such as migration, air and water pollution, and threats to biodiversity. The production, distribution and use of energy can contribute to these security issues, which are generally unintentional side effects, i.e. groups in society that have an interest in maintaining practices that cause insecurity, but not usually in maintaining the insecurity itself (for an analysis of the differences between these situations, see Martin (1996)).

4. Theoretical and methodological perspectives

4.1 Socio-technical (energy) systems

Energy systems can be seen as socio-technical systems. Socio-technical systems consist of technical components, such as infrastructure, and people who interact with the technical system (Hughes, 1983; Kaijser, 2005). The organisation of people, their practices and the (formal and informal) institutions co-evolve with the technical system. For a researcher, the social and technical parts of a system can be so interlinked that both of them must be considered and studied in order to understand how the system functions.

A coherent configuration of a socio-technical system has been referred to as a socio-technical regime (Elzen et al., 2004). In a certain period in time one regime tends to dominate the provision of a certain service. The regime is sometimes described as stable, and will change following an interruption that triggers a shift to another stable regime (Truffer et al., 2010). The process of moving between two equilibria is referred to as a *transition*. Others regard the process of change as a more gradual modification of the direction of development, i.e., a process that is open-ended, and is referred to as *transformation* (Schreuer et al., 2010; Stirling, 2014). Both the concepts of *transition* and *transformation* are used in this thesis. *Transition* is used to describe an end state, such as the energy system in 2030, while *transformation* is used when referring to a process or pathway that depart from business as usual. However, it should be noted that these two concepts are often used interchangeably in the literature. For example, Markard et al. (2012) described sustainability transition as a “transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption”.

In this thesis, the technical part of the system is seen as the supply chain, which stretches from the initial upstream stages involving primary resources, through conversion, to the later downstream stages involving distribution and final use. The social part involves actors as well as the institutions in which they operate, organise and interact with the energy supply chain.

In Paper I, the analysis of previous research was structured in accordance with the energy supply chain (from upstream supply to downstream use). Paper II presents a framework and analysis of a biofuel supply chain using different stages of the supply chain to structure the analysis. These papers focus mainly on the technical part of energy systems. A framework for the analysis of energy conflicts is developed and adopted in Papers III and IV. The characteristics of different parts of energy systems were used in the analysis of previous research and theories, and to construct the framework. The study presented in Paper V develops and analyse scenarios of future (socio-technical) energy systems.

4.1.1 Theoretical and methodological pluralism

A system perspective enables a holistic view, as well as the study of multiple interpretations of a phenomenon. This allows for methodological pluralism. Methodological pluralism can be used to check the robustness of the results (Thorén and Persson, 2013) and to increase the researcher's reflexivity throughout the research process (Alvesson and Sköldberg, 2010). It also provides a means of responding to uncertainty, for example, in scenario studies, since the different perspectives provide the different insights that are required to understand complex issues (see e.g. (Heylighen et al., 2007; Rescher, 2009)).

The level of disciplinary integration tends to evolve as a research field matures (Jantsch, 1970). The lowest level of integration is multidisciplinary, in which there is no cooperation between the disciplines. The interdisciplinary level of disciplinary integration requires that there is coordination through higher levels of concept, such as common axiomatics. Transdisciplinary is the highest level of disciplinary integration, and requires that stakeholders are involved in the research process.[11]

Theories and methodologies from different fields have been used in this work. Paper I provides a methodological overview, and it is concluded that the methodologies have different strengths and weaknesses, that they can be combined to complement each other, and that the level of disciplinary integration can be characterised as multidisciplinary. In Paper II, scenarios and methods from industrial economics were used to measure (dual) diversity. A framework for the relationship between energy systems and conflicts, drawing from theories from different disciplines, is presented in Paper III. This framework was used for analysing renewable energy systems in Paper IV. The methods derived from scenario planning were adopted in Paper V to explore uncertainties.

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[11] Other nomenclatures can be used to describe the levels of integration. For example, Jantsch (1970) included pluridisciplinarity and crossdisciplinarity as intermediary steps between multi- and interdisciplinary.

4.2 Security studies

Many different issues can pose a threat to security. Different actors may also have different perceptions of what constitutes security, and may perceive the danger of a threat differently. These differences influence how security is defined and approached in research. According to Buzan and Hansen (2009), security studies can be separated at the meta-level into three different aspects:

1. the level of analysis,
2. the width of analysis, and
3. the epistemology.

4.2.1 The level of analysis

The level of analysis determines what constitutes the referent object, i.e. it asks the question, “What is to be secured?”. The three most common levels analysed are human, national and international. Some researchers have also directed their attention to intermediate levels, such as the regional level, emphasizing the importance of including these levels in order to understand the interactions with levels above and below (Buzan and Waever, 2004). Through a traditional state-centric lens, i.e. ‘national security’, the state is viewed as the object to be secured, and it is also the guarantor of security for its citizens through the use of power. According to Buzan (1991) those who define what constitutes a threat to national security are the ruling elite, who generally have an interest in maintaining the current situation as they benefit from it. An alternative mind frame is provided by the human security paradigm, which questions the traditional notion of the state as the referent object that is to be secured (UNDP, 1994). Instead, the focus is on the level of security of individuals, emphasizing their well-being and access to basic necessities. If the frame of analysis is human security, rather than national security, the state may be a threat to security rather than the guarantor, since it can be in the interest of the state to supress the population.

4.2.2 The width of the analysis

The width of the analysis defines which threats to security are included, i.e. it poses the question, “Secured from what?”. The traditional realist interpretation of security originated from the field of international relations. It is a state-centric view of what should be secured, but it also places an emphasis on physical, mainly military, threats (i.e. “high politics”) from other states in an anarchical global world order. Structural defensive realists even argue that the behaviour of states in foreign relations can mainly be explained by their desire to maximise their security in response to military threats (see e.g. Waltz (1979)). Towards the end of the Cold War scholars began to argue in favour of expansion of the concept of security, as they perceived that other threats had become important for security (Ullman, 1983).

In their seminal book, Buzan et al. (1998) proposed that the concept of security should be expanded by a sectoral widening of the concept (they also included different levels, but the "unit" of their analysis was mainly state-centric). The authors argued that security should be understood in relation to how a threat is interpreted to impact a sector, in other words, perceptions of consequences. These authors identified five sectors that could be relevant for security: military, environmental, economic, societal and political. As pointed out by Belyi (2003), energy (security) spans across all these sectors. For example, access to energy can be perceived as a necessity due to its importance for both economies and the military. There is also a wide range of threats, such as capabilities to implement blockades that affect energy trading, and environmental degradation that reduces the potential for renewable energy.

4.2.3 The epistemology

The epistemology influences the study approach. According to Buzan and Hansen (2009:33-35) security can be approached as an objective, subjective or discursive conception.

When security is approached as objective it is assumed that it is possible to choose and generalise how to value security on the basis of certain physical characteristics. This makes it easier to compare the level of security over time and space, and to use quantitative methods. Concerning energy security, the objective approach is often adopted by researchers who have a background in engineering or economics. These researchers tend to be positivistic and strive to scientifically measure, quantify and compare energy security objectively using various indicators and indexes. This approach assumes that there is a dichotomy of facts and values. An example is given by Cherp and Jewell (2013), who argue that it is possible to separate *perceptions* of what constitutes an energy security issue from objective *facts*.

If security is approached as subjective, it is assumed that the context is important as it influences what is considered to be security, a threat, etc. Researchers who adopt a subjective approach can study how a subject perceives a threat regardless of whether an objective threat exists or not, or how subjects perceive threats differently as a result of their interests, experiences, beliefs and power positions etc. In other words, security has an objective threat-element, but its valuation is context-dependent (Wolfers, 1962). From this perspective it is important for the researcher to be reflexive and open-minded, and to consider how the contextual factors differ, influence perceptions and evolve over time. The subjective approach has been adopted by researchers in studies of energy security in order to try to understand what certain actors perceive as security issues. This approach seems to be more common among researchers with a background in the social sciences. Examples can be found that emphasize how contextual factors (e.g. economic development, culture, etc.) affect which material factors (e.g. import dependence) are perceived as energy security issues, and how these are valued (Bradshaw, 2014; Dannreuther, 2015; Knox-Hayes et al., 2013; Sovacool, 2011).

If security is approached as a discursive conception it is assumed that it is socially constructed and originates from a securitization process. In this process an actor speaks out about something, declaring that it is a security issue, raising it above everyday politics and justifying the use of other means (Waever, 1995). The researcher collects data from the discourse (e.g. published statements and speeches) and analyses who determines what constitutes a threat to security, how and when, i.e. the intersubjective process. The discursive approach to energy security has been used by researchers to understand when and how energy politics is moved up on the political agenda and becomes a security issue. Several researchers have analysed how different interest groups, with conflicting agendas and underlying motives, try to shape, or “manipulate”, the public energy policy discourse by proposing security strategies that primarily benefit their own self-interests (Fischhendler and Nathan, 2014; Littlefield, 2013; Rogers-Hayden et al., 2011; Teräväinen et al., 2011).

Further epistemological differentiation can be made between negative and positive security studies (Hoogensen Gjørv, 2012; Roe, 2008). Negative security studies emphasize fears and threats to security, whereas positive security focuses on factors that enable security, such as capacities, capabilities and trust between actors. These two different approaches can lead to different conclusions regarding responses and ways of increasing security. For example, negative security studies are more likely to promote efforts to protect systems, e.g. legitimize military intervention and deterrence (Hoogensen Gjørv, 2012). Positive security studies emphasize actions that enable security, such as capacity development. The concepts of positive and negative security have previously not been adopted in energy security research.

4.2.4 The approach to security in the present work

Different relationships between energy and security have been analysed in the present work. In Paper III, a framework is developed to analyse energy conflicts, i.e. how energy systems are related to conflicts that render insecurity. This framework can be used to analyse conflicts at multiple levels, ranging from the individual to the global level. The framework is used in Paper IV to analyse at which level renewable energy conflicts are likely to occur.

Both positive and negative approaches were used in this work. The negative approach was used to identify threats and exposure to those threats, whereas as the positive approach was used to identify how capacity can be developed to respond to threats, e.g. adaptation and transformation. The motivation for using both these perspectives is that they complement each other. Analysing only threats can reinforce path dependency and lock-in, as it legitimizes strategies to protect the current system. However, there is a need to understand the threats that may arise in order to understand which capabilities should be developed. In Paper IV it was suggested that incentives for energy trade and collaboration can build trust and enable (positive) security, while energy conflicts fall under negative security.

An objective approach to energy security was adopted in Papers I and II. This means that security can be measured quantitatively and compared over time, while as a subjective approach was used in Paper V. As a result of this, Paper V identifies emission reduction strategies that some actors perceive as improving the transport system, while others perceive this strategy as undesirable.

4.3 Analysing the future and uncertainties

Future studies constitute a wide and multidisciplinary field of research in which current knowledge is used to develop forecasts, study plausible future(s), perceptions of the future, and ways in which future events can be shaped or responded to. One of the pioneers within the field, Herman Kahn, described it as “thinking about the unthinkable” (Kahn, 1962). Apart from mere curiosity, assessments of how some aspects may evolve in the future, and how we should respond to them can be used for decision-making and planning. For example, a transmission system operator needs forecasts of production and demand to plan future infrastructure investments.

4.3.1 Types of uncertainty and responses to them

An obvious challenge in future studies is that our ability to predict the future is limited, and therefore the future is uncertain. Uncertainty can be classified as aleatory, ontological, or epistemological, or in terms of ambiguity (Der Kiureghian and Ditlevsen, 2009; Rescher, 1998; Stirling, 2014).

Aleatory uncertainty refers to a system with stochastic properties, i.e. random, but all possible outcomes and their distribution are known. Examples are tossing a coin or rolling a dice. It is impossible to know what the outcome will be each time, but the possible outcomes are known, as well as their probabilities. In energy planning this form of uncertainty has been analysed by changing input parameters while maintaining the structure of the energy model (see e.g. Thangavelu et al. (2015) who changed input variables using a stochastic optimization method).

Ontological uncertainty originates from the nature of the world that in some aspects lacks lawful regularities as a result of complexity. It can also have properties that are emergent and evolve over time. This can make it difficult to test hypothesis in the real world in the same way as in a laboratory where it is possible to control the environment. If there is a total lack of regularities or knowledge, then ignorance prevails. In such situations, the best response is to diversify, in order to spread the exposure to sources of risk as much as possible, and increase the capacity to respond to disturbances (Stirling, 1998).

Epistemological uncertainty is a result of our inability to describe the world and construct one representative and valid model of it. For example, current theories may be inaccurate, but we are unable to comprehend this because we can only observe events and their correlations, while the underlying causation is beyond our reach. Therefore, we formulate hypotheses that are assumed to be valid until proven false. This type of uncertainty can be either static or dynamic (Dreborg, 2004; Strangert, 1974). Static uncertainty is constant over time, while dynamic uncertainty will decrease over time as more knowledge is obtained. As a result, the strategies for coping with static and dynamic uncertainty differ. Static uncertainty is typically managed by formulating strategies that perform satisfactorily in several settings, i.e. they are robust. Dynamic uncertainty, however, is managed using strategies that can be modified as time progress, i.e. they are adaptive. However, it should be noted that it is not always possible to know beforehand whether the uncertainty is static or dynamic.

The last kind of uncertainty, *ambiguity*, is related to *epistemological* uncertainty. Ambiguity is a result of the existence of several theories that are each scientifically valid within their own knowledge paradigm, but provide conflicting interpretations of a phenomenon, it is not possible to know if any of the theories is correct and which one that is (Dreborg, 2004). An example of this is the previously discussed concept of sustainability, where some researchers conclude that there is no need to take precautionary action, while others argue that there is. Ambiguity can be managed, but not resolved, by adopting different approaches and theories when studying a question and expanding the debate to include conflicting interests and perspective.

4.3.2 Scenarios as a tool to study the future

In order to study the uncertain future, methods of constructing representations of possible futures that can be used as empirical material are required. Scenario methodology is one such formalised approach that enables the structuring of uncertainty and the study of situations and development processes that have not yet occurred. According to Börjeson et al. (2006) scenarios are either predictive, explorative or normative. *Predictive scenarios* are used to answer the question of what is most likely to happen (forecast), or most likely under the condition that a certain event unfolds (what-if scenario). To be relevant and useful, these types of scenarios require sound knowledge of the structure of the system being studied, and they generally have a short time frame. *Explorative scenarios* answer the question of what can happen. In these scenarios the structure of the system may evolve into something rather different from the current one. The third type of scenarios, i.e. *normative scenarios*, is used to find how a specific target can be reached, either through preserving the status quo or by envisioning a transformation of the system being studied (back-casting). Predictive, explorative and normative scenarios are typically used in future studies, but it should be noted that counterfactual scenarios can also be used to explore what could have happened.[12]

A scenario is a description of a storyline or an end state. It is therefore common to construct several scenarios that differ depending on how certain driving forces develop. For example, one scenario assuming high economic growth and one assuming low growth (see Figure 4). The scenarios used cover a defined scenario space, and therefore, scenario studies do not cover events that fall outside or between these discrete scenarios.

Predictive scenarios require that the analyst is able to provide information of what can happen and its probability (see e.g. Weidmann and Ward (2010)). Thus, ontological and epistemological uncertainties are assumed not to have a decisive influence. Explorative scenarios can instead be used to identify how the dynamics in the system may develop over time and to anticipate some of the implications (see e.g. Bakker (2012)). This is mainly a response to ontological uncertainty. However, it can be part of a multidisciplinary approach in which different theories or mind frames are used for interpretation, which then also takes into account ambiguity.

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[12] Colgan (2013) used counterfactual scenarios to assess whether international conflicts would be less plausible in oil-producing countries if they had no oil.

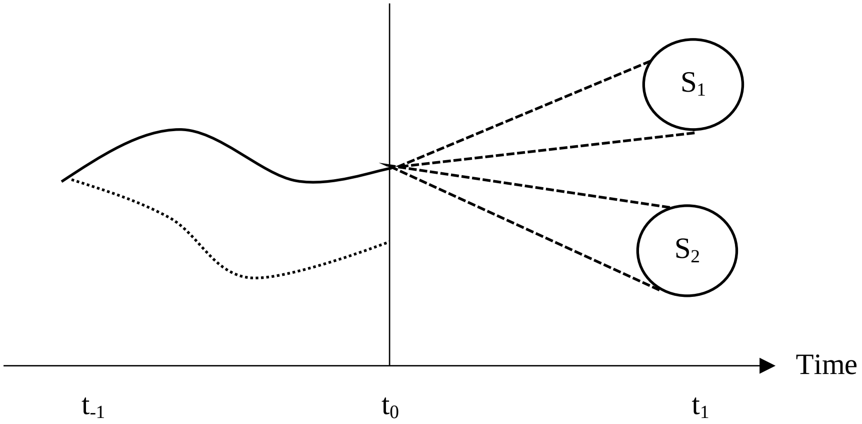

Figure 4.
Conceptual illustration of the relationship between the system, time and scenario space. The system has evolved along a development trajectory (solid line) as a result of various events and is currently at t_0. Each scenario (S_1 and S_2) describes a storyline that leads to a future system at t_1. The dotted line is a counterfactual development trajectory that illustrates what could have happened if an event at t_{-1} had played out differently.

The elements of ontology are not always stated explicitly in scenario and future studies, but should include at least two different aspects. The first is which factors that are included, and the second is how they are connected and influence each other, i.e. their causal relationships (Poli, 2011).

4.3.3 Scenario development and assessment

Scenario assessment was adopted and institutionalised by American military planners during the 1950s and 1960s to assist in decision-making. Herman Kahn, working at the RAND Corporation pioneered the development of scenarios as a means of describing the future and structuring what is assumed to be predictable and what is highly uncertain (Cornish, 1977; Kahn and Wiener, 1967). In the private sector, the oil company Shell (Royal Dutch Shell) is famous for adopting explorative scenarios in their business planning in the late 1960s (Wack, 1985). This increased Shell's capacity to respond swiftly to the oil crises during the 1970s which put them in a better position relative to their competitors (Moniz, 2006). [13]

Researchers and planners can use similar methods to develop scenarios. Both are interested in structuring uncertainty, and learning about and identifying plausible future trend breaks. However, planners are mainly interested in

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[13] Some of the developments Shell anticipated were a shift from a buyer's market to a seller's market, the lack of spare capacity, that the influence of oil producing countries in the Middle East would increase, and that a period of low economic growth was likely (Wack, 1985).

improving their organisations position, while researchers may be interested in developing the methods that are used in the process and identifying conflicts of interest between different actors if a certain scenario should materialise.

4.3.3.1 Top-down and bottom-up approaches to generate qualitative scenarios

Scenarios can be constructed using top-down or bottom-up approaches, also referred to as deductive and inductive approaches, respectively (Dreborg, 2004; Konno et al., 2014).

The *top-down* approach starts by identifying a limited number of driving forces, which are then combined to construct scenarios. It is common to use two main driving forces as this enables them to be used as two axes and a skeleton to construct four scenarios (by combing high and low values of each factor) (see e.g. Schwartz (1996)). Schwartz (1996) states that the factors that are most important (i.e. those that have a decisive impact) and most uncertain should be used, but it is left to the scenario developer to decide which these factors are. The two drivers selected are assumed to be independent, and the state of all other drivers is deduced from a combination of these two (van ’t Klooster and van Asselt, 2006).

The *bottom-up approach* starts with a large sample of driving forces, all of which can be interdependent. The scenario developer is here assumed to have sufficient knowledge of the relationships between the driving forces to be able to classify the causality (reinforcing, neutral or negative) and strength (weak, strong, etc.) of each. Taken together, the driving forces and their relationships represent the scenario ontology. The number of system states, i.e. the values that a driver can take, increases exponentially as more drivers are included. This makes it impractical to use the bottom-up method without the assistance of computer programs. One such method is cross-impact balance analysis, also referred to as cross-impact analysis matrix (Amer et al., 2013). This method utilises an algorithm to construct scenarios that are consistent. It should be noted that the scenarios are both internally and externally consistent, since they share a common set of drivers and relationships. Therefore, this method does not capture uncertainty derived from ambiguity, since ambiguity mean that there is one or more contradictory interpretations of causality.[14] It is proposed in Paper V that this can be managed by using scenarios that are internally but not external consistent.

The number of scenarios is a compromise between a few scenarios, providing an overview, and many scenarios, providing variety. Three to five scenarios is generally regarded as providing a good balance between the two (Alcamo, 2008; Schnaars and Ziamou, 2001). After the number of scenarios and their logic has been decided, the scenario developer then formulates a story-line or narrative that describes the future as an end state and/or the pathway to it.

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[14] If deep uncertainty prevails (“ignorance”) it is preferable to use different models to include different structural representations of the real world (see Walker et al. (2010)).

4.3.3.2 Scenario assessment

The next step involves exploring the implications for the issue investigated if the different scenarios were to materialise, for example, assessing the performance of one or several strategies in different scenarios. The aim here is to identify which strategies are sensitive to the development of external factors, and if any of these strategies is robust. It is also possible to iterate, modify and improve a strategy and assess which portfolio of capabilities should be developed to provide a better starting point if the different scenarios were to materialise (Davis and Dreyer, 2009). An issue that is not usually addressed at this stage is that the values that determine how the outcome of a strategy in a certain scenario is perceived differ among actors and can also be subject to development over time (Störmer et al., 2009). An example of this shortcoming is the use of the Delphi technique to establish consensus in the assessment of the performance of a strategy in a scenario. This masks conflicting values. Cagnin and Keenan (2008) proposed that it is more useful to understand the plurality of opinions and how they are related to underlying values and opinions. According to them, this is particularly useful if scenarios are used to study a transformation, since the established paradigm and its related values may then change.

When considering only static scenarios, events that may take place in other situations will be overlooked, as the scenarios are discrete and do not consider what happens if development falls outside the scenario space. Adaptive strategies, policies and foresight have been proposed as a means of addressing this (Eriksson and Weber, 2008; Walker et al., 2010). Adaptive strategies are especially preferable when there is limited knowledge on: i) how the future will develop; ii) the system studied; and/or iii) the value system, i.e. how various outcomes are ranked (Marchau et al., 2010; Walker et al., 2010).

4.3.4 The use of scenarios in this thesis

Several of the studies included in this thesis make use of scenarios. In Paper II, normative scenarios of a low-carbon transport system in Sweden are analysed from an energy security perspective. Those scenarios were adopted from an earlier study. Several previous scenario studies were used to identify and decide which technologies and resources should be included in the study described in Paper IV. Data on the potential for, and trade of, renewable energy from previous scenario studies are also used in that study.

In Paper V the aim was to analyse the robustness and adaptivity of strategies to reduce the use of fossil fuels in the road transport sector. Five scenarios were constructed using the bottom-up approach, and cross-impact balance analysis was applied. The scenarios were used to study energy security of five different oil-reduction strategies. This study also included diverging preferences.

5. Contributions of this work

This chapter summarises the results presented in the five publications. The research questions are discussed in the context of the papers, after which the answers to the questions are presented.

5.1 The research questions addressed

The overarching question addressed in this thesis is: *How will the introduction of low-carbon energy systems affect security?* This was divided into three research questions that were addressed in the five publications. Table 2 provides an overview of the questions addressed in each paper.

Table 2.
Overview of the research questions addressed in the papers.

	Q1: How can security be assessed in evolving energy systems?	**Q2: How will the transition to a fossil-fuel independent road transport fleet affect the security of transport services?**	**Q3: How are renewable energy systems related to conflicts?**
Paper I	The paper provides an overview of previously used methodologies.		
Paper II	A method is developed to assess evolving biofuel supply chains.	Swedish biofuel supply chains are analysed.	
Paper III	A framework is developed to analyse energy conflicts.		
Paper IV			Renewable energy (hydro, wind, solar PV and biomass) is analysed.
Paper V	A scenario method is developed to analyse evolving energy systems.	Energy security is expanded to include transport services. Security is analysed using a subjective approach.	

The first research question is addressed in Paper I, where a review is given of the methodologies used previously to assess energy security. Studies published in scientific journals and some reports from research institutes and think tanks were included in the study. The methodologies were classified according to a framework that reflects the flow of energy in the supply chain.

A framework is presented in paper III that can be used to study the relationships between energy systems and conflicts. The framework uses both energy system characteristics and contextual conditions as building blocks. The theoretical origins of the different explanations of conflicts are also presented. The theoretical explanations range from realism and geopolitics, which provide interpretations of states involvement in conflicts, to political ecology and development studies, which provide interpretations of why actors such as groups of people are involved in conflicts.

Paper II addresses both the first and second research questions. The aim in this study was to develop a method to analyse and compare energy supply chains from an energy security point of view, and to apply the method to assess the security of the Swedish biofuel supply chain for road transport. An assessment was carried out of the current situation using publically available data from, for example, the Swedish Energy Agency, Statistics Sweden (SCB) and the International Energy Agency (IEA). The situation in 2030 was analysed using previously developed scenarios.

The study presented in Paper IV is based on the framework developed in Paper III, and the ways in which renewable energy systems affect the likelihood of conflicts are analysed. The procedure used was to compare the characteristics of renewable energy systems with characteristics that, according to the framework, increase the likelihood of conflicts. Bioenergy and renewable electricity from wind, hydro and solar PV was analysed, since previous studies have proposed that these will make up the largest share of renewable energy in low-carbon energy systems. Data on, for example, land requirements for these forms of renewable energy, their technical potentials, the effects of climate mitigation policies on the energy mix, trade flows etc. were gathered from previous studies.

The first and second research questions are addressed in Paper V. The paper presents an analysis of how a fossil-fuel-independent road transport system in Sweden will affect the security of transport services. Rather than only analysing the security of specific energy flows, as in Paper II, this study broadens the framework of the analysis to the field of critical infrastructure and physical planning. The study starts by analysing how five different strategies to reduce the use of fossil fuel may affect the exposure, sensitivity and adaptive capacity of the transport system. The five strategies analysed are: i) development of urban areas to reduce the demand for transport, ii) investments in infrastructure and modal shifts, iii) an increase in fuel efficiency, iv) an increase in the use of biofuels, and v) electrification of road transport. Uncertain driving forces and their relationships were identified from previous studies. These were used to construct four consistent qualitative scenarios using cross-impact balance analysis. These strategies were then exposed to the external scenarios to identify the conditions under which different strategies would be unable to deliver the required transport services.

5.2 Assessing the security of evolving energy systems

Two different frameworks are developed to answer the first research question. The first was used when the energy system is the referent object to be secured, and the second when the energy system causes insecurity in the form of conflicts. The first framework adopts and integrates methodologies that have been used to study energy security, scenario planning and risk management. The second framework draws mainly from theories in the fields of international relations, political economy and geopolitics. Both start by defining the issue at hand, i.e. what is to be analysed.

5.2.1 Defining the issue

The first step is to define what is to be assessed. This includes defining the system boundaries.[15] In Paper II, biofuel supply chains were analysed and boundaries defined that included feedstock, imports from upstream market, production, distribution, and final use (see Figure 5).

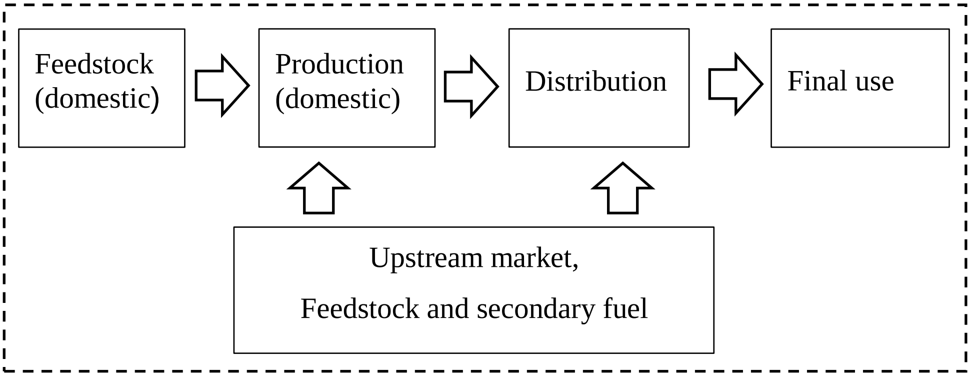

Figure 5.
Illustration of system boundaries that determine which stages of the energy supply chain are included in the assessment (from Paper II).

The importance of including the entire supply chain is stressed in Papers I and II, since a chain is no stronger than its weakest link. Therefore, the final use of

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[15] This is consistent with the workflow found in system analysis (see e.g. Quade and Miser (1985)).

energy was included a as stage of the supply chain in both Papers II and V. This enabled the analysis of the impact of climate mitigation policies, the use of different energy carriers and the capacity of final users to respond to disturbances.

It is important to be consistent regarding what is included in the analysis and what is not. An example of this can be found in Paper II. In that study, imports of both feedstock and renewable energy carriers were included. If only the import of energy carriers had been included, then imported feedstock would have been evaluated as a secure supply which is not the case.

5.2.2 Steps in the energy security assessment

In this thesis, the security assessment was regarded as a process involving four stages: identification of threats, characterisation of the vulnerabilities and capabilities of the energy system, estimation of the consequences, and valuation, as illustrated in Figure 6.[16]

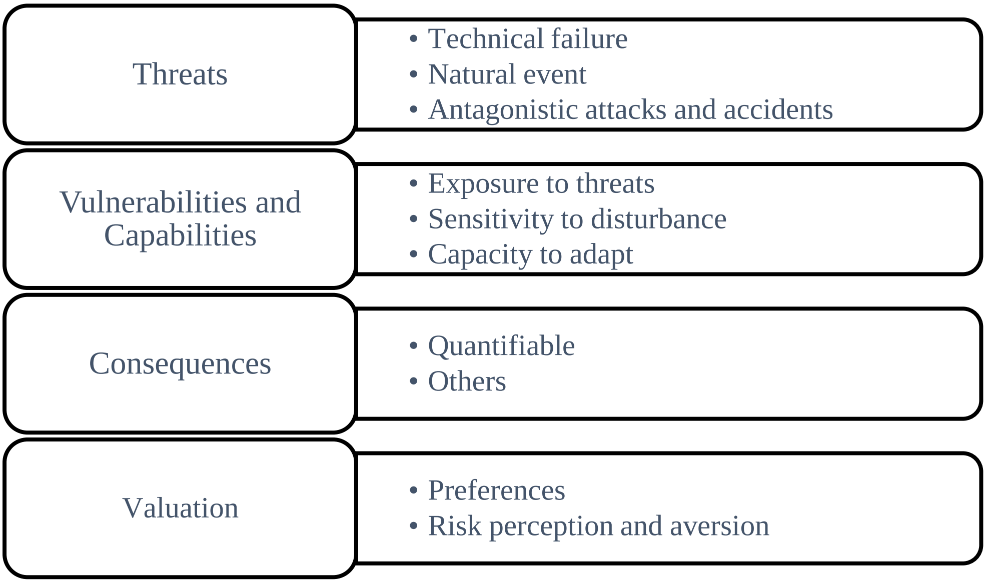

Figure 6.
Illustration of the stages included in the energy security assessment, with examples for each stage (adapted from Papers I and V).

It is possible to conduct a comprehensive assessment including all the stages. The workflow would typically be linear, beginning with the identification of

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[16] Other assessment frameworks have been used in previous studies (see e.g. (Augutis et al., 2012; Cherp and Jewell, 2013; Escribano Francés et al., 2013; Gracceva and Zeniewski, 2014)).

threats. However, it was found in Paper I that some of the methods used previously focus mainly on one step, for example, estimating the consequences of a black-out. It is also possible to use an iterative procedure in which the valuation process provides input regarding which capabilities should be developed to ensure acceptable consequences.

5.2.2.1 Threats

The first stage, identifying threats, involves the analysis of the events to which the energy system is exposed, e.g. technical, natural and antagonistic threats.[17] In Paper V it is suggested that scenarios can be used to facilitate this. Each scenario describes a situation in which there are threats of short or long duration. An advantage of scenarios is that it is possible to consider threats that change over time, i.e. some threats emerge while others become less noticeable. Scenarios can also include (desirable) situations to which the system may be exposed, such as the rapid cost reduction of new technology.

This method also acknowledges the fact that development trajectories can be external to the energy system. In other words, some threats develop independently of the energy system. A case in point is the previously mentioned cost reduction that can result from technological progress in other countries. Other examples are blockades and similar political events which will affect all international trade.

A further advantage of the use of scenarios is that the threats included are plausible. In other words, there is an element of uncertainty that is recognised and made explicit.

5.2.2.2 Vulnerabilities and capabilities

Assessing the vulnerability and capability involves determining how a particular energy system will be affected by a particular threat at a certain time. The properties of the energy system are analysed at his stage. In Paper V, a topology was adopted in which three different properties were specified: exposure to threat, sensitivity in the case of a disturbance, and capacity to adapt. This topology integrates the perspectives of negative security (exposure to threat) with positive security (capacity to adapt).

Exposure denotes the relationship between the risk source, e.g. a threat, and the energy system. If and when a threat materialises into an event that causes a disturbance is always subject to some type of uncertainty. Measures to reduce

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[17] Some previous studies have categorised these into groups of root causes of insecurity (Greenleaf et al., 2009), risk (Cherp and Jewell, 2014) or primary energy risk (Escribano Francés et al., 2013). It is, however, more correct to describe them as threat or source of risk rather than simply a risk, since risk should be related to something that is valued. See e.g. Kaplan and Garrick (1981), who defined risk as “a set of triplets”: What can happen?, What is the likelihood?, What are the consequences if it happens?

exposure are implemented to increase reliability, suppress threats and provide stability.

Sensitivity is the degree to which a system is affected when it is exposed to a threat. It describes the system's capacity to cope with the consequences without changing the function of the system (this is sometimes referred to as engineering resilience, see Section 3.1.4). Low sensitivity can also mean that it is easier to restore the system after a disturbance. Characteristics that reduce sensitivity include redundancy, flexibility and stocks that provide a buffer.

Capacity to adapt is the capacity to change the exposure and sensitivity of the system in response to, or in anticipation of, a threat. Such transformation requires reorganisation of the system which can extend over a long time, unlike flexibility, which reduces sensitivity to short-term disturbances. The capacity to adapt is mainly concerned with providing sufficient room for manoeuvre to avoid lock-in.

5.2.2.3 Consequences

The third step is to estimate the consequences when a certain threat affects the energy system under study. This is referred to in Paper I as consequences for society. However, a different level of analysis can be used to estimate the consequences to a certain actor or region, etc.

Consequences can also be seen as risks, since the outcome at this stage is related to something that humans value.[18] A wide range of consequences may result, and there is no single topology that can classify all of them.[19] Some consequences can be quantified, e.g. loss of (electricity) load, and a subset of these may even be monetized, e.g. the value of the lost load. Other consequences may be difficult or impossible to quantify. For example, in Paper III it was found that volatile prices and physical disruptions had been claimed to trigger social and political instability.

5.2.2.4 Valuation

If security is regarded as subjective, a fourth step should be included in the assessment that involves the valuation of security. It was found in Paper I that when complex indicators (indexes) were used, one set of criteria was used to compare and rank energy security.[20] However, preferences may change over time

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[18] Aven (2012) showed that risk includes uncertain consequences related to something humans value. From this it follows that the properties of the energy system should be included, not excluded, when risk is analysed, as these properties affect the consequences if something happens. In other words, vulnerability depends on the source of risk.

[19] Augutis et al. (2012) provided examples of consequences such as: loss of human lives, damage to infrastructure, economic losses and socio-political disturbances. Carlsnaes (1988) focused on dependencies on imports and related the consequences to impacts on foreign policy autonomy.

[20] A review of such indexes was published after Paper I, by Ang et al. (2015).

and may differ between actors.[21] Actors may also have different views on the desirability of different strategies, and different levels of risk aversion. As a result of this, some may find that adapting to change is undesirable and instead promote strategies to reduce exposure, while others find the opposite more appealing.

A difficulty here is that it is not possible to know beforehand how preferences will develop. Drawing on insights from the scenario planning literature, it was suggested in Paper V that valuation could be performed by inviting different groups of stakeholders to participate in the valuation, and identifying plurality of values and the underlying cause of the values, rather than using a consensus view. An alternative approach, adopted in the same paper, was to identify which values and opinions different groups of actors have expressed in the past, and to use these in the valuation. This facilitates the identification of conflicts of interest between stakeholders.

5.2.3 Security of: supply, practices and services

Three different referent objects can be found in energy security assessments: energy supply, end use practices and energy services (see Table 3). These originate from different mind sets of what is valuable, and they offer complementary insights. In Paper I it was proposed that it is more useful to analyse security of energy services than security of supply when the energy system is changing.

Table 3.
Overview of different referent objects, i.e. What is to be secured.

Referent object	Energy supply	End use practices	Energy services
Mind set	Stability/status quo	Technological transition	Societal transformation
Vulnerability and capability dimensions	Exposure to threat	Exposure to threat Sensetivity to disturbance	Adaptive capacity
Strategies (examples)	Protect supply chains against threats. Procure from reliable suppliers.	Replace depletable (fossil) energy resources. Improve efficiency.	Diverisfy the provision of energy services. Develop enabling infrastructure.

Security of energy supply emphasise the supply side of the energy system, stability, and measures to protect the energy supply chain. The demand for certain energy resources is taken for granted and energy security is seen as making sure that the supply meets the demand at all times. Adopting this security perspective

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[21] Studies have shown that actors can have different perceptions and valuations of energy security (Blumer et al., 2015; Butler et al., 2015). See also Markandya and Pemberton (2010), who showed that risk aversion affects which energy security strategy is deemed preferable.

can make it difficult to achieve coherence between energy security and climate policies.

Security of end use practices value continuity of structure. Thus, current practices are a product of path dependency that is to be protected. Adopting this perspective will result in solutions that focus on reducing exposure and sensitivity. Technological progress and uptake is both the solution and the factor that limits the potential to achieve coherence between energy security and climate mitigation policies. This perspective was used in Paper II to analyse how replacing fossil fuels with renewable energy and improving energy efficiency affect security when road transport continues to be the norm.

Security of energy services assumes that the final energy service is valuable, allowing the service to be provided in many different ways. Actors have different perceptions of the importance of a particular energy service. A strategy perceived undesirable to some may be preferable to others, as found in Paper V. Adopting this security perspective enable a high level of coherence between energy security and climate change mitigation, since both technology and (unsustainable) practices can change. A prerequisite for greater coherency is, off-course, values and practices developing towards greater sustainability. Researchers can here be interested in studying the valuation of different energy services (e.g. “needs” versus “wants”) and conflicts of interest between different stakeholders.

5.2.4 Assessing how energy causes insecurity

Paper III presents a framework for analysing the connection between energy systems and conflicts. The framework categorises three broad groups of energy conflicts: i) when the energy system is an objective in a conflict, ii) when the energy system is a means in a conflict and, iii) when the energy system is the cause of a conflict. These can be further divided into eight subgroups, see Figure 7.

The energy system is an objective in a conflict if the actors taking part in the conflict have incompatible aims regarding who should control the supply chain or have access to the resource. The likelihood of such conflicts increases if the energy system or resources are geographically concentrated.

Societies can be sensitive to disruptions in the energy supply. This enables hostile actors to exploit this vulnerability to achieve aims that are unrelated to energy issues. For example, a country can cut off supplies, or threaten to do so, to try to influence policy decisions in the targeted country. Hostile countries and terrorists can also attack energy infrastructure, physically or virtually, with the aim of causing disruptions.

Energy systems can cause conflicts due to the excessive rents that finance conflict participants (one aspect of the “resource curse”), environmental degradation that results in a local scarcity of renewable resources, reduced security of supply resulting in economic recession and interactions with food prices that trigger food riots. It should be noted that energy should not be seen as a single cause of conflicts. In the literature it is therefore sometimes described as a “threat multiplier” or “conflict catalysts”. This is thus a situation involving multiple causality of issues that together result in the outbreak of a conflict.

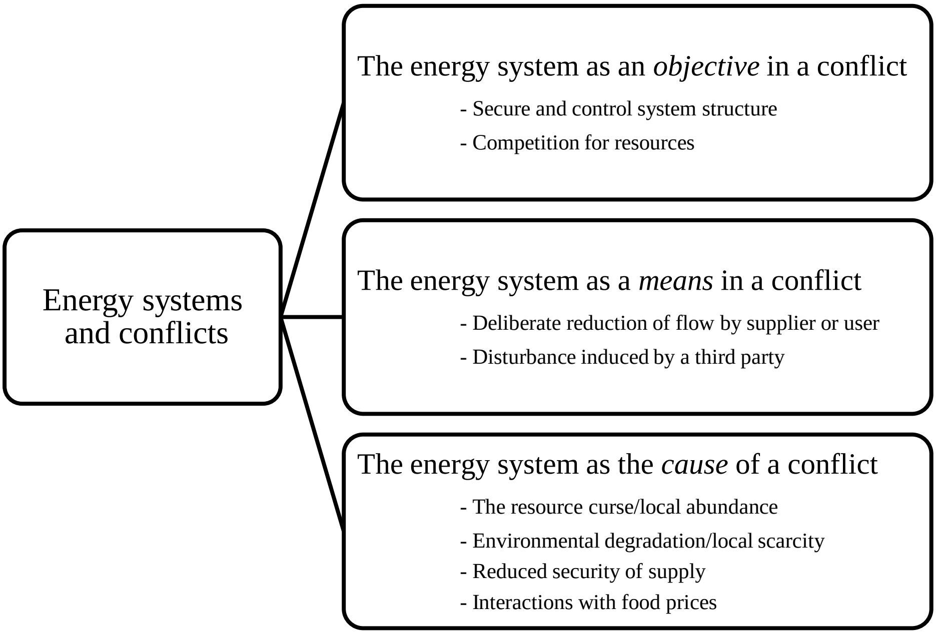

Figure 7.
Typology of links between energy systems and conflicts (from Paper III).

5.3 Security of transport services and fossil fuel independence

Several strategies can be implemented to reduce the use of fossil fuels, five of which were analysed in this work. These are: i) development of urban areas to reduce the demand for transport, ii) investing in infrastructure and modal shifts, iii) improving fuel efficiency, and replacing fossil energy carriers with iv) biofuels or v) electricity (see Table 4).

In Paper V it was found that the impact on energy security is, to some extent, affected by the way in which external factors develop. For example, importing energy is generally not a problem if there is a free international market where energy is traded as a commodity. Imports can increase (complex) interdependency as a result of integration of the importer and exporter with the world economy. Access to the international market can also be used to balance fluctuations on the domestic market. However, imports can be a security issue in situations where bilateral relationships dictate the terms of trade, and the importer's sovereignty is reduced as a result of this. This can be the case if the power shifts in favour of a few exporters. Other factors that are uncertain and were found to affect energy security in Sweden are: the development and cohesion of the EU, the rate of technological development and access to new technology, and the level of global demand for biofuels.

Table 4.

Overview of the strategies analysed to reduce the use of fossil fuels (strategies was adopted from SOU (2013)).

Strategy	Content
Development of urban areas to reduce demand for transport	Functional integration of spatial planning, increasing the use of public transport[a], raplacing commuting with working from home and virtual meetings.
Investing in infrastructure and modal shifts	Increasing the share of rail transport for goods and passengers.
Improving fuel efficiency	Improving combustion technology and using lighter vehicles.
Increasing the share of biofuels	Increasing the share of second generation biofuels, i.e. feedstock not intended for human consumption.
Increasing the share of electricity	Increasing the share of battery-powered electric vehicles and electrifying major roads

[a] The categorisation used here is the same as in the original source. Public transport can also be categorised as modal shift.

5.3.1 Security implications of the different strategies

The various strategies for the reduction of the use of fossil fuels have different impacts on energy security in different scenarios. Spatial planning to reduce the demand for transport performs well in most future scenarios analysed in Paper V. However, it requires behavioural changes that are not appealing to some actors. This illustrates how preferences and values determine whether a strategy is considered to be preferable or not.

The second strategy, investing in infrastructure and modal shift, reduces exposure to international energy markets, since the use of liquid fuels is reduced. The disadvantages of this strategy are the increase in infrastructural lock-in resulting from the high capital cost, and the low flexibility. In other words, the strategy reduces exposure to some threats (e.g. higher fuel prices) but increases the sensitivity to physical disturbances and reduces the capacity to adapt to some threats.

The third strategy, improving fuel efficiency, was found to be the most robust strategy as it performs fairly well in all scenarios. This is a ‘no-regret’ strategy. The reason that this strategy performs fairly well is that it reduces exposure and sensitivity to higher and volatile prices, and the cost of stockholding (or increases the number of days a specific stock will last). Also, no stakeholder deems the strategy undesirable.

The two strategies that focus on new energy carriers, biofuels and electrification, are both strongly affected by the development of external factors, but the way in which they are affected differs. Biofuels perform poorly if too many other countries also increase their use of bio-resources, since this increases the competition for a limited biomass resource. Electrification performs poorly if an insufficient number of countries increase their use of electric vehicles. This is because electrification benefits from increased demand as a result of economies of scale in production, learning effects, more research and development, the development of international standards, and network externalities. Electrification will also make the road transport sector dependent on the electricity system. This make the transport system exposed to technical failures, antagonistic attacks and weather events that affect the electricity grid.

It should be noted that there are differences between the biofuel supply chains that exist today, and it is unclear how these will develop. Most of the biofuel currently used in Sweden is imported. The imports consist of both energy carriers and feedstock that is converted into fuel in Sweden. In Paper II it was found that this has shifted the direct exposure from the oil market to the agricultural market. The oil and agricultural markets interact. The agricultural market is smaller than the oil market, and is subject to seasonal variations.

It was also found in Paper II that it is important to analyse relationships that result in dependencies between supply chains. Increased variety of energy carriers will not provide effective insurance to hedge disturbances if disparity of the fuels does not increase, since disturbances will spread across and between the supply chains.[22] Many current biofuel supply chains are dependent on the supply chain used to distribute fossil fuels. Therefore, it is questionable to what extent current imports of biofuels or feedstock can improve energy security or hedge against threats that affect the supply of oil. However, it was found that it is possible to develop biofuel supply chains so that they increase energy security, for example, by increasing the use of domestic resources, using residues of limited economic value to other sectors, and decentralising production.

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[22] Diversity has three properties: variety (number of categories), balance (balance between the categories) and disparity (difference between the categories), see (Stirling, 1998).

It was also found that energy security would benefit from better integration of climate, energy security and transport policies. The increase in the use of biofuels and increased efficiency over the past ten year has changed the composition of the European and Swedish vehicle fleet such that the demand for diesel has increased. This has resulted in an imbalance between petrol and diesel on the European market, which is managed through increased trade with oil products. In an emergency situation there would be a lack of diesel. This imbalance can be reduced in a number of ways, such as shifting the transport of heavy goods from road to rail, and increasing the supply and use of biodiesel.

5.3.2 Combinations of strategies: synergies and complementariness

The aim of the five strategies described is to reduce the use of fossil fuels in different sectors, regions (urban and rural) and for different purposes (personal mobility, transport of goods). It is therefore possible to combine them to achieve significant reductions in the use of fossil fuel. It was argued in Paper V that such combinations can hedge uncertainty and provide security benefits, since the strategies have complementary or synergistic characteristics.

Combining biofuels and energy efficiency provides synergy, since increased efficiency reduces exposure to higher prices (lower affordability), while the use of domestic biofuels increases the capacity to adapt to physical shortages and strains on international markets. Improved efficiency would also make it possible for domestic resources to meet a larger share of the demand. This is beneficial if access to foreign supply is restricted, or there is increased competition for the resource as a result of the increased use of biofuels in other countries.

An example of complementary strategies is biofuels and electrification. Combining these strategies hedge against uncertainty regarding the extent to which other countries will invest in, and increase their use of, renewable energy. Another example is the combination of modal shift, which provides stability, with electric hybrids or biofuels, which utilise the flexible road network.

5.4 Relations between renewable energy and conflicts

It was concluded in Paper IV that renewable energy systems have a low likelihood of being a conflict objective. The main reason for this is that renewable energy resources are more evenly distributed than fossil resources, and production covers larger areas, as the energy density is lower. In general, this makes it difficult to secure and exert control over resources, and results in renewable resources having a lower strategic and economic value than fossil resources.

Renewable energy systems have similarities to fossil energy systems regarding them being used as a means in a conflict. This is because, similar to non-renewable energy systems, renewable electricity systems can be sensitive to disturbances and be exposed to hostile attacks. Historically, attacks on electricity grids have been uncommon during peacetime. The development of “smart grids” has been suggested as a technology that will enable the balancing of electrical systems that utilise a large share of renewable electricity. This technology can increase the exposure of electricity systems to virtual (“cyber”) attacks and provides opportunities for states to target the electricity infrastructure in hybrid warfare during peace-time, since virtual attacks afford the attacker plausible deniability.

In Paper IV it was found that renewable electricity systems provide incentives for international collaboration, since expanding the grid reduces the cost of balancing variable renewable production. Constructing such interlinkages can provide interdependencies that prevent conflicts and enable (positive) security. However, if a conflict were to break out, the dependency could then be exploited. Due to this dual relationship, it is uncertain what the net effect on conflicts would be.

Abundant renewable energy production typically has lower windfall profit than is the case for the extraction of fossil resources. This is a result of the lower production volume at each site, and the higher production cost (an exception is large scale hydropower). Therefore, the likelihood of renewable energy resources causing conflicts due to local abundance is low compared to fossil resources.

Renewable energy, primarily bioenergy, increases the likelihood of local conflicts resulting from resource scarcity and environmental degradation. This is a result of increased competition for land and water. This competition can increase land rents, food prices and force people to relocate. The likelihood of such conflicts can be reduced by implementing technologies that make it possible to simultaneously satisfy several demands for biomass, and not utilising the full technical potential of biomass.

6. Discussion

6.1 Energy security is a multidisciplinary research field

Researchers and policy makers alike seem to have taken an increased interest in energy security during the past decade. This thesis has contributed to the research field by elucidating the heterogeneity and similarities in previous research by developing frameworks that show how different approaches and theories complement each other.

In Paper I it was found that the methodologies used to date to assess energy security have been adopted from a large number of disciplines. This is no surprise, since energy security interacts with so many different issues; technical, social, economic, etc., and thus several disciplines can provide valuable and complementary insights. In the present work, particularly Papers I and III, the theoretical perspectives used and the possibility of combining and integrating them were analysed. It was found that the methodology adopted affects the strategies that are promoted to enhance security. Some methods will result in suggesting diversification to improve security, while others suggest redundancy. This ambiguity can be managed by communicating which aspect of security is improved if a certain strategy is implemented, and the possible disadvantages it may have, rather than referring to energy security in general.

A shortcoming of some previous studies is the apparent lack of justification and validation of assumptions, for example, concerning actor rationale and the construction of indexes. Attempts were made in the studies presented in this thesis to improve this issue by being transparent regarding the theoretical underpinnings that were used when presenting certain conclusions. A conscious effort was also made to use coherent terminology when referring to: threats, vulnerability and capability, etc. Using one set of definitions will, hopefully, contribute to better communication between researchers and the integration of different disciplines so that the research field matures.

In Paper V, a subjective approach to security was adopted. This was adapted from security studies, and has not been used previously to assess energy security in future energy systems. The approach enabled a closer integration of energy security with the field of future and scenario studies. It also provided new insights as it showed that values determine whether a certain outcome is perceived as desirable or not. However, one limitation of this approach is the lack of knowledge on how values will develop in the future. This is discussed in more detail in Section 6.2.6.

6.2 Security implications of low-carbon transitions

6.2.1 Security threats

Increasing the share of renewable energy influences the threats to which the energy system is exposed and, thus, which is the most relevant threat to analyse. It is difficult to generalise the development of the total threat exposure due to different characteristics of different renewable technologies, differences in the threats (duration, likelihood, etc.), and in the level of uncertainty of different threats. However, it is still possible to draw some general conclusions on the character of some threats, as discussed below.

Renewable energy resources have lower geographic concentration than fossil resources. Also, the ability for producers to make excessive profits is generally lower. Threats that arise as a result of resource concentration are therefore less pronounced in renewable energy systems. Among them are competition for scarce resources and political instability in remote producer countries.

Non-renewable resources are subject to depletion. Potential resources for renewable energy can be restricted as a result of unsustainable utilisation, e.g. deforestation, and environmental degradation. Resources can also be restricted as a result of competition from other sectors and countries, as noted in Paper V. Therefore, resource availability is a factor that should be considered in assessments of security in renewable energy systems.

Many previous analyses and assessments of energy security have overlooked the interactions between fossil and renewable energy systems. These relationships can result in dependencies and disturbances that propagate between the systems. One example can be found in Paper V, in which it was concluded that situations in which access to oil is restricted, e.g. blockade or war, are also likely to restrict access to imported bioenergy and feedstock. This restricts the possibility to hedge disturbances in the oil supply by importing renewable energy. This should be considered in security assessments of renewable energy, otherwise the threats to which renewable energy systems are exposed to will be underestimated.

Interactions between fossil energy systems and renewable energy systems can have implications for the likelihood of conflicts in systems that utilise both fossil and renewable energy. It was concluded in Paper IV that the likelihood that actors will engage in conflicts to control and secure access to renewable energy resources is lower than for fossil energy. However, increasing the use of renewable energy will not necessarily reduce oil-related conflicts. This is because increasing the share of renewable energy does not reduce economies sensitivity to disruptions or alter the fact that there is only a handful of countries that hold spare production capacity and have capacity to export large quantities of liquid fuel (oil or biofuels). In other words, the number of energy producers can increase but the centrality of the major fossil exporters for countries depending on imports and economies in general will not necessarily reduce as a result of this unless the transport sectors liquid fuel lock-in is broken.

6.2.2 System sensitivity

Flexibility, spare production capacity and redundancy reduce sensitivity to short-term disturbances. These factors are typically improved by having excess capacity and emergency stocks. However, it is questionable whether renewable energy production facilities will be able to match the level of spare production capacity that currently exists for the production of oil, due to the relatively high capital intensity of renewable energy. This indicates that market prices are likely to become more volatile unless flexibility and demand response improve compared with today’s level.

Meeting the increased need for stockholding is more challenging when the number of energy carriers increases. Furthermore, some biofuels have lower storage stability than fossil oil, which makes it more difficult to keep emergency reserves, as noted in Paper V. The shorter shelf life can be compensated for by more frequent rotation of the stock. One option is to integrate the stock with the supply chain. This is not always done today, and can be difficult at remote and decentralised storage sites that are used on rare occasions, such as in the case of fuel disruptions or blackouts.

The dependence on natural flows, instead of extracting finite stocks, makes it relevant to analyse fluctuations in those flows. These can be of short term, such as variations in daily solar insolation, seasonal variations, such as intra annual crop yield and variations in solar intensity throughout the year. From a systems perspective, aggregated variations in renewable flows should be analysed in conjunction with the flexibility of distribution systems and end-user demand. In Paper II it was proposed that characteristics such as the capability to switch fuel and feedstock could be used to assess supply chain flexibility.

Electricity is likely to increase its share as an energy carrier, since it enables integration of renewable energy resources such as solar and wind, and often increased efficiency. This will make it even more relevant to analyse the (technical) reliability and sensitivity of electricity systems in future renewable energy systems.

6.2.3 Capacity to adapt to threats

The capacity to adapt is especially valuable in uncertain times, when drivers of threats are difficult to identify and control. Improved energy efficiency has many benefits as it increases the capacity to adapt to higher energy prices and the share of energy demand that can be supplied from a certain amount of energy. The general impact of the increased use of renewable energy is unclear, and depends on which technology is implemented and how external factors develop.

In Paper II, a number of factors were identified that indicate improvements in the adaptive capacity of the emerging biofuel supply chain in Sweden, e.g. increased diversity of primary resources, flexibility in the use of different feedstocks, decentralisation and increased diversity of actors. Several of these characteristics can also be found in other renewable energy supply chains. These changes indicate increased capacity to manage long-term physical disturbances of renewable energy systems.

In Paper V it was found that reduced use of fossil fuels through investing in infrastructure and modal shift can break the current lock-in to fossil fuels, but may instead introduce new path dependencies that restrict the possibility to adapt to long-term stress. In other words, reduced use of fossil fuel can increase the capacity to adapt to some threats, while simultaneously reducing the capacity to adapt to others. It is not possible to know beforehand which these threats may be. One threat identified in Paper V is climate change, and increased infrastructural lock-in may make it more difficult to adapt to this.

6.2.4 Conflicts involving non-state actors

Renewable energy can be related to conflicts. However, the introduction of renewable energy affects the type of conflicts that are most likely to occur, the actors who will participate in the conflicts, and the level at which the conflict takes place. This has implications on the way in which energy conflicts are analysed.

Renewable energy is generally used closer to where it is produced, as a result of its abundance, low geographic concentration and higher transportation cost compared to fossil energy. In Paper IV it was found that this contributes to a low incentive for global renewable resource conflicts between states. Intraregional trade can still be important, especially electricity trading that enables sharing of back-up power and a lower cost of balancing the grid. Such trade provides incentives for international cooperation, but it can also be used for extortion, i.e. the energy weapon. In other words, a transition to renewable energy systems makes global energy security issues less pronounced, but increases the relevance of analysing the regional level, e.g. regional security complexes.

It was concluded in Paper IV that renewable energy conflicts are likely to involve non-state actors. This differs from many fossil energy conflicts, in which the analysis of states has been most relevant. This is a result of greater competition for land and the negative effects on food security that follow from this. National self-sufficiency is also expected to increase in many countries as a result of domestically available renewable resources and improved energy efficiency.

Changes from the global to the regional, and from the national to local levels have implications for energy security research. Energy security should be approached with a deeper perspective of security, otherwise the outlook regarding the security benefits associated with a transition to renewable energy will be too optimistic.

6.2.5 Technology as an enabler or a cause of insecurity

Increasing the use of renewable energy will not necessarily increase the general level of security, but is likely to replace some risks with others, as noted in the discussion above. Introducing novel energy production technologies and control systems, such as smart grids, makes systems more complex and difficult to manage. This may lead to systemic risks and unclear relationships between the cause of the disturbance and its effect. In other words, ontological uncertainty is replaced by epistemological uncertainty, which is assumed to be managed by experts who are striving to refine their models, assessments and predictions. This is in line with the hypothesis of a risk society, i.e. responding by fixing symptoms (greenhouse gas emissions), which creates new risks that have to be managed by experts, rather than remedying unsustainable practices.

It was found in Paper V that energy conservation, i.e. reducing the use of energy, can alleviate unsustainable practices. These strategies are uncomplicated with regard to uncertainty, since they do not depend on the development of new technology, and the result of these strategies is relatively easy to understand. However, some actors find these strategies undesirable because they compromise practices that they value.

6.2.6 Uncertain external factors

Some factors are external to policy makers, but affect the threats that may emerge in the future, and the characteristics of the energy system that strengthen energy security. This is particularly the case for small countries with open economies. One example is Sweden, which depends on imports and technological development in other countries. Vulnerability is dependent on the kind of threat, i.e. a characteristic that makes the system more vulnerable to one threat may make it less vulnerable to another. Identifying strategies that provide acceptable outcomes in different situations requires low vulnerability to many threats, or the capacity to adapt the strategy as time passes and new information emerges. This aspect has not been thoroughly analysed in previous energy security studies.

The use of scenarios to analyse the sensitivity to uncertain external factors was proposed in Paper I. This method was used in Paper V and enabled the identification of improved energy efficiency as the most robust strategy. Increased use of renewable energy was found to be less robust but it can increase the adaptive capacity.

6.2.7 Subjective energy security

Values can change over time, and differ between different actors. It is therefore impossible to know how a certain outcome will be valued in the future. This is a challenge that is seldom addressed in energy security studies. In Paper V, energy security was approach as a subjective concept, and stakeholder statements were analysed. This epistemology has not been used previously to assess energy security in future-oriented analysis. It provided a new dimension of energy security, since it enabled the identification of incompatible stakeholder preferences regarding what is considered desirable. Conflicting values and perspectives of security mean that a low-carbon energy system is not a universal solution from a security perspective. Researchers should bear this in mind, and be transparent regarding whose security is affected by a certain policy, and how. One way forward is to strive towards more stakeholder participation in the analysis of energy security and to conduct longitudinal analysis of how the valuation of energy security has changed in the past. This would enable assessments that are more in line with the preferences of the public.

It should also be noted that security is only one part of energy policy, and that decision makers have many other goals in the development of society. Referring to the term “security” creates a sense of urgency, and that the issue is important. Studies in which a discursive approach to security was adopted have shown that this is sometimes used by actors to legitimize and prioritize a certain strategy that benefits their own interests. A subjective security approach provides opportunities for multiple interpretations of what energy security is and why it is perceived as a matter of security. This can, hopefully, improve energy security discussions as it forces the participants to be explicit regarding what they mean by security.

7. Conclusions

The overarching question addressed in this thesis was - *How will the introduction of low-carbon energy systems affect security?* To answer this question, frameworks were developed in which different theoretical perspectives were integrated, and then used to analyse efficient renewable energy systems. The frameworks developed also contributed to the understanding of how energy security is related to the broader field of security, for example, by connecting approaches used to study energy security with the epistemologies found in security studies.

Concerning approaches, most previous research tends to define and approach energy security as a negative concept, i.e. security in the face of a threat, rather than as a positive concept in terms of security “to do something”. Also, security is generally seen as objective, meaning that it can be understood and characterised based on only material factors.

It was proposed in this thesis that it is useful to consider both negative and positive security when analysing evolving energy systems, since they provide complementary insights. The former is useful in identifying threats, while the latter can be used to identify the capability to adapt to the threat. It has also been proposed that security can be approached using the epistemology of subjective security. This enables the consideration of diverging preferences and the identification of strategies that can be accepted by actors with different sets of preferences. This is especially useful if the dominant set of preferences is assumed to change over the period analysed. Furthermore, strategies to substantially reduce the use of energy extends beyond energy policy and involve, for example, spatial planning. The analysis of energy security in evolving energy systems should, therefore, focus on the security of energy services, and how different services are valued by different actors, since not all energy services are valued as equally important or necessary by all actors as they may have a different set of preferences.

There are dependencies between fossil supply chains and some renewable supply chains, for example, oil and biofuel. As a result of this, disturbances can spread and propagate. This restricts the possibility of hedging disturbances in oil supplies by the increased use of those biofuels. Renewable energy is variable over both short and long periods of time, making it necessary to increase the flexibility of the supply chain, for example, by increasing the diversity of resources, storage or demand response.

The work presented in this thesis has shown that external factors affect how strategies intended to reduce emissions from the transport sector affect energy security. It was found that strategies that increase the share of renewable energy are more sensitive to external factors than strategies to improve efficiency. Reduced use of energy enables improvement in adaptive capacity, since the room for manoeuvre increases as the available resources can then meet a larger share of the total demand. Examples of strategies that are sensitive to external factors are the electrification of road transport and the increased use of biofuels. Electrification improves security most provided a sufficient number of other countries also implement stringent emission reductions, while the opposite is the case for biofuels. Decision makers can take this into consideration and combine strategies that provide complementary characteristics. Such decisions require the consideration of threats in different futures, the capabilities that need to be developed, the perceived level of knowledge and risk aversion.

It was also shown that that renewable energy is less likely to trigger international geopolitical conflicts, but can be more likely to trigger local and sub-national conflicts, compared to fossil energy. This is a result of its lower energy density, the larger land area require and interactions with food production. Apart from the implications regarding conflicts, this highlights the need to analyse renewable energy conflicts from a deeper perspective of security, otherwise, the analysis will provide too optimistic an outlook on the likelihood of conflicts resulting from the introduction of renewable energy.

8. Suggestions for future research

A number of research gaps were identified which were not addressed in the present studies.

- Most of the energy technologies considered in this thesis are on-shore renewable technologies and improved energy efficiency. It would be interesting to study other technologies that can also for part of a low-carbon energy mix. These include offshore renewable electricity production, such as wave power and wind power, CCS and a nuclear renaissance with small-scale reactors or fourth generation reactors. These technologies may interact with transboundary waters/sovereignty, technological lock-in and political economy, and nuclear proliferation.
- It was found in this work that the assumptions and hypotheses used to construct complex indicators (energy security indexes) are seldom tested and validated. This could be done by analysing historical experiences of energy insecurity. Conducting such valuations would strengthen the scientific contribution of these methods. This also applies to actor's rationale, such as the motives behind deliberately restricting energy flows (the "energy weapon") or targeting energy systems in a terrorist or military attack. Further research should be carried out to assess the rationality of past behaviour, whether the loss of the exporter and the loss of the importer are valued equally (e.g. economic loss, geopolitical considerations, etc.) and the antagonist's security doctrine.
- Previous energy transitions have been additive, i.e. new energy resources have been added to the energy mix without removing existing ones. A low-carbon energy system is principally different, as it requires reducing the absolute volumes of fossil resources extracted and leaving resources in the ground that could be of value on (illegal) markets. These "not to be extracted resources" can be of concern for security as well as the behaviour of actors who currently benefit from the demand for fossil fuels. Further research is needed to explore these issues.
- Researchers from the field of political science tend to focus mainly on energy security in relation to foreign politics and international relations when interactions with climate change mitigation is analysed, but more analysis of the sub-state level would be useful. Ensuring energy security lies in the interest of sovereign states, and is sometimes regarded as a part

of national security. Recent decade have seen the deregulation of national energy markets in many European countries, together with the implementation of policies steering development towards lower emissions. It is unclear who is responsible for security in these (partly) deregulated markets with some state intervention, agency of subnational actors and what effects the privatization will have for different actors.

- Threats to energy security can change over time. Renewable forms of energy are dependent on natural flows, either directly in the case of solar radiation, or indirectly for example biomass, wind and hydropower. Climate change will affect these flows. Further research into how climate change and other environmental problems can affect various sources of renewable energy in the future would be useful.
- Most previous studies adopt a negative definition of energy security, i.e. freedom from threat, instead of “freedom to do”. This is particularly the case when the energy system is seen as a security subject affecting conflicts. Virtually all of these studies approach the energy system as something that generates conflicts. More research is needed to understand the conditions under which energy systems can enable security, such as international collaborations.
- Finally, there is a lack of longitudinal studies in which the co-evolution of energy systems and different actors’ valuation of energy security is analysed.

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