ENERGY SECURITY AND CLIMATE CHANGE MITIGATION AS COMBINED AREAS OF ANALYSIS IN CONTEMPORARY RESEARCH

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ABSTRACT

Climate change mitigation and energy security are partly interacting areas that both present future challenges. The extensive research underway within these areas is mainly conducted in separate research communities, although there are some integrative efforts. This paper examines the breadth and heterogeneity involved in treating energy security and climate change mitigation as a combined research area. The outcome is a comprehensive analytical framework which considers energy security aspects, climate change mitigation strategies, temporal scope and future perspective, analytical focus, approaches and methodologies, geographical scope, and scientific traditions and perspectives.

Keywords
energy security, climate change mitigation, energy, climate change, interdisciplinary

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1. Introduction: Literature selection and analytical framework

Well-functioning energy systems are essential for society, but the energy systems in use today are also the main contributors to one of the major threats of our time, climate change. Climate change mitigation will require significant changes in the energy system, with energy efficiency improvements, deployment of renewable energy, nuclear and carbon capture and storage as proposed main options (e.g. International Energy Agency (IEA), 2011; Intergovernmental Panel on Climate Change (IPCC), 2007; Greenpeace and European Renewable Energy Council (EREC), 2010). Different factors are stressed to various degrees by different actors depending on e.g. evaluation of the economic feasibility and sustainability of the suggested mitigation options. However, it seems quite clear that the enormous changes proposed will alter the current relationship between energy and security.

There is a vast body of research literature on climate change mitigation and the necessary transformation of the energy system, and also on energy security. However, the research is mainly conducted in separate research communities with little integration. Although energy security is sometimes noted in the mitigation literature and *vice versa*, thorough analyses of the interactions lacking and need to be further explored.

This paper presents a state-of-the-art review of research published to date dealing with climate change mitigation and energy security in a more or less integrated way. The main aim of the review is to demonstrate the breadth and heterogeneity when energy security and climate change mitigation are treated as a combined research area. Another aim is to identify methodologies, perspectives, aspects and themes, and combinations of these, not yet subjected to exhaustive research. The paper thus forms a good starting point for work to develop integrated research approaches on the issues of climate change mitigation and security aspects of the energy system.

The paper starts with a short introduction to the methodology and a description of the main dimensions of the analytical framework proposed. This is followed by an analysis of the literature using the framework and a discussion of the main strengths and weaknesses in current approaches. The paper ends by listing some areas where further research is especially relevant, based on the results of the framework analysis.

To locate relevant published literature, we searched for academic papers relating to *both* energy security and climate change in databases for scientific papers during 2011. A number of significant non peer-reviewed reports from reputable organisations (e.g. International Energy Agency) were also included when they provided other perspectives than the academic papers. These non peer-reviewed reports and other significant 'gray' literature included in the review are referred to as *reports*, while peer-reviewed articles are referred to as *papers*. All the reviewed papers (29 in number) and reports (16 in number) fulfilled the search criteria and examined one of the following questions in some way:

- How do climate change mitigation and energy security interact?
- How do climate change mitigation strategies and policies affect energy security?

- How do energy security strategies and policies affect the possibilities to mitigate climate change?

In their analysis and conclusions, a number of the papers in the first category, on the interaction between climate change mitigation and energy security, give rather equal weight to climate change and energy security (e.g. Bang, 2010; May, 2010; Rogers-Hayden et al., 2011; Turton and Barreto, 2006). However, some of the papers, although using an integrative approach, lean more towards analysing energy security aspects of climate strategies (e.g. Bauen, 2006; Bollen et al., 2010; Huntington and Brown, 2004; Persson et al., 2007), while others take energy security as their point of departure (e.g. Chalvatzis and Hooper, 2009; Garg and Shukla, 2009).

The papers analysing how climate strategies affect energy security differ in approach. In some papers, climate policy is the obvious point of departure, while energy security is one of many effect areas discussed as externalities (e.g. Blesl et al., 2010; Southworth, 2009). Other papers investigate how climate strategies affect energy security explicitly, either in terms of climate strategies being used as a lever for increased energy security (e.g. Henriques and Sadorsky, 2010; Mignone, 2007; Nuttall and Manz, 2008), or in a more neutral fashion by analysing energy security effects resulting from energy mix changes (typically, an increased share of low-carbon energy sources) (e.g. Grubb et al., 2006; Hedenus et al., 2010; Jun et al., 2009; Lilliestam and Ellenbeck, 2011). In other papers energy security is both the point of departure and the subject of conclusions, but changes resulting from climate change mitigation are used as external inputs, for example increased energy efficiency, or energy mix changes due to CO_2 emission targets (e.g. Helm, 2002; Kruyt et al., 2009; Mallah, 2011).

Our review method involved mapping, sorting and labelling the characteristics of the papers and reports reviewed, using the following starting points for our analytical framework:

- Energy security perspectives and aspects included or analysed
- Climate change mitigation strategies included or analysed
- Temporal scope and future perspective used
- Analytical focus: policy and actors, or system and technology
- Approaches and methodologies used
- Geographical scope
- Scientific traditions and perspectives forming the basis of the publications

The analytical framework was then filled with content found through the review (see Appendix 1). The framework is thus based on the findings from the review, but also supplemented with some elements which we believe to be relevant when aiming to obtain a comprehensive perspective on energy security and climate change mitigation. Moreover, themes which could be considered suitable for future research, or further elaboration, are highlighted.

2. Energy security perspectives and aspects

There is a great wealth of definitions of the 'energy security' concept in policy contexts and in academic works. It was not our ambition to bring order to the terminology, but when it comes to meta-level perspectives some aspects require mention. First, energy security can be interpreted as either (Johansson, 2013):

- Energy systems being *exposed to security threats* (e.g. security of supply or demand, resource availability, infrastructure protection, market share protection), or
- Energy systems *generating or enhancing insecurity* (political risk factors such as exercise of power through dependencies or struggle for scarce resources, technological risk factors such as nuclear safety, and environmental risk factors).

The former perspective is the most common among the papers and reports reviewed. Some publications use the second perspective, but generally with the focus only on political risk factors.

A second meta-level way for structuring energy security analyses is to separate:

- *Root causes of system insecurity* (e.g. extreme events such as weather events or accidents, inadequate market structures, production capacity or infrastructures, and unhealthy market concentrations), from
- System, or societal, *resilience*, i.e. the ability to cope with events or aspects of insecurity, regardless of root cause.

The overwhelming majority of the papers and reports reviewed use the former perspective.

Some of the academic papers reviewed approach the energy security concept in general terms, not analysing the ingoing elements of energy security in detail (Bauen, 2006; May, 2010; Rogers-Hayden et al., 2011; Southworth, 2009). In a great majority of the reviewed papers, however, long-term security of supply is either the specific energy security aspect analysed, or at least should be seen as the main, or one of the main, components of energy security (e.g. Bang, 2010; Brown and Huntington, 2008; Helm, 2002; Turton and Barreto, 2006).

Building on the notion that the end-consumer is not interested in energy *per se* but in energy services (e.g. Jonsson et al., 2011), the Energy Research Centre of the Netherlands (ECN, 2006) covers not only supply security but also supply chain security, using the Supply/Demand index. On analysing five scenarios with different amounts of renewables and penetration of energy efficiency measures, ECN concludes that climate mitigation policies increase the level of energy security. The largest improvements were observed when policies for both renewables and energy efficiency were combined. On the other hand, only increasing a single policy goal (e.g. through higher targets for renewable energy) displayed a diminishing marginal utility for the increase in energy security.

A common view is that there is enough primary energy available to satisfy the demand and the focus is instead on whether the infrastructure is adequate to satisfy the demand. For example, the UK Department of Energy and Climate Change (DECC, 2011) simulated producer investment in new capacity in the UK electricity sector under current and alternative legislative frameworks. According to the simulations, the UK's current climate mitigation policies will not lead to a desired outcome for consumers, since they do not offer enough incentives for producers to install back-up capacity. Thus the policies need to be constructed to optimally spread the risk among the stakeholders (government, producer and consumer) to ensure that enough back-up capacity is put on the grid. Implementing specific energy security policies would lead to fewer blackouts and to less volatile prices in the electricity sector.

Climate strategy impacts in terms of short-term effects such as disruptions, shocks (regarding price or indirect effects of disruptions) and physical stability (of infrastructure) are highlighted in some papers. Hedenus et al. (2010) analyse the cost of oil supply disruption as a key energy security aspect. Jun et al. (2009) also highlight disruptions, but distinguish between direct factors in the form of physical disruptions and economic disruptions, and indirect factors associated with social and environmental disruptions which indirectly influence energy security. Helm (2002) also elaborates on disruptions, shocks and physical stability, understood as aspects of network security (other energy security dimensions discussed by Helm are supply security and contracting, diversity and the environmental constraint). In addition, a number of papers elaborate on price security and/or economic risks, but do not analyse disruptions explicitly (e.g. Bang, 2010; Brown and Huntington, 2008; Henriques and Sadorsky, 2010; Huntington and Brown, 2004).

Some of the papers reviewed claim to use a geopolitical perspective on energy security. However, they seldom elaborate on what should be considered 'geopolitical' and what are examples of import dependency and diversity issues, aspects closely related to price security and/or economic risks. For example, the cost-benefit assessment model proposed by Bollen et al. (2010) handles various dimensions of diversification and also distinguishes between high-risk and low-risk suppliers. The comprehensive indicator approaches presented by von Hippel et al. (2011) and Kruyt et al. (2009) also cover geopolitical aspects and price security/economic risks. Kruyt et al. take their starting point in four main dimensions of energy security: availability (elements related to geological existence), accessibility (geopolitical elements), affordability (economic elements) and acceptability (environmental and social elements). They go on to map 17 types of existing indicators and five aggregated indices to their four main dimensions of energy security, which shows a centre of gravity on accessibility and affordability. The indicators are orientated towards e.g. diversity, supply market concentration, import dependence, political stability, oil price and market liquidity (Kruyt et al., 2009).

A common view is to focus on import dependency and diversity issues (e.g. Blesl et al., 2010; Chalvatzis and Hooper, 2009; Garg and Shukla, 2009). The main point of departure for Garg and Shukla (2009), for example, is that domestic coal use in India (in combination with Carbon Capture and Storage (CCS) mitigates national energy security risks. Another Indian case study (Pode, 2010) addresses a similar delimitation of energy security, i.e. geopolitical aspects in terms of diversity and import dependency, in exploring the effects of a renewable energy mix.

Import dependency is also one of the most commonly analysed issues in the reports reviewed (e.g. APERC (Asia Pacific Energy Research Centre), 2010; ECN, 2005; EPA (Environmental Protection Agency of the US), 2011). Extensive reliance on a few foreign regimes is usually perceived as a situation that a state should seek to avoid through diversification of suppliers, decreased level of imports or a combination of these. Using a Herfindahl-Hirschman index, IEA (2007) constructs several indicators for analysing the concentration on the market. Thus, the market concentration serves as a proxy for risk exposure to threats from outside a state's boundaries. In the case of oil imports, EPA (2011) analyses how increased fuel efficiency standards for medium and heavy duty vehicles in the US would affect energy security and emissions from the vehicle fleet. In the study, the US is assumed to be a monopsony power on the global oil market. Therefore, substantial decreases in domestic oil consumption will not just lower US demand for oil but also the global demand, which might lead to a reduced world market price for all buyers.

The aspect of generating security through mutual dependency, or interdependency, is not commonly analysed. An exception is Lilliestam and Ellenbeck (2011), who argue that a diversity index penalises energy imports even if it is not established that domestic energy is always more secure than imported energy. Such indices only measure the supplier diversity, not whether a certain system is more secure than another.

Security of demand – i.e. securing revenue by way of delivering energy to global energy markets or specific customers – is rarely analysed in an exhaustive manner. One exception, on the effects of climate mitigation strategies on security of demand, is the study by Persson et al. (2007). The study concludes that major oil exporters, such as the OPEC (Organization of Petroleum Exporting Countries), may profit rather than lose in a carbon-constrained world (using the notion "security of revenue"). However, very stringent climate targets would make OPEC lose. The size of the future conventional oil reserve is also a subject of uncertainty affecting price and thus revenue (van Vuuren et al., 2003).

Besides the aspects described so far, energy security, or "energy and security", is also associated with aspects of security policy, foreign policy, and international relations, i.e. considered as an issue of national security, sometimes with military implications. Other frequently used notions in this context are e.g. political stability, political situation, political risks, political pressure, political demands, the energy weapon and resource curse. A broader interpretation of geopolitics than previously discussed is sometimes present. Rather than just supply diversity and import dependency, geopolitics refers to aspects such as power relations and the political, social and historical dimensions of geography, as well as territorial issues.

Only a handful of the academic papers reviewed deal with these broader security aspects in an obvious manner. 'National security' generally refers to US security policy (e.g. Bang, 2010; Mignone, 2007). 'Political stability' generally refers to the conditions, or political situation, in an oil or gas exporting country in terms of form of government, corruption, social tensions, poverty etc., sometimes manifested through the United Nations' Human Development Index (HDI) (Kruyt et al., 2009), or the Global Peace Index (GPI) (Jun et al., 2009). Political stability can also refer to the alignment of political orientation between supplier and consumer (Kruyt et al., 2009). On the one hand, political stability can be valued in a somewhat cynical way: for example, the lack of democracy does not matter as long as energy is continuously delivered. On the other hand, the fact that energy imports might support repressive regimes can be regarded and valued in terms of human rights, or human security, which is a dimension present in e.g. von Hippel et al. (2011). In the energy security conceptual framework presented by von Hippel et al., hard military-security issues are included (e.g. naval power protection of sea lanes and shipping, and international management of plutonium), as well as social-cultural energy security policy issues (e.g. institutional capacities and corruption). The broad framework is built up with six main dimensions of energy security; energy supply, economic, technological, environmental, social & cultural, and military/security. Attached to each main dimension are various measures and attributes, mostly quantitative, although there are a number of qualitative indicators.

Lee (2009) also uses a broad security perspective and emphasises resource challenges rather than just energy, making a distinction between supply- and demand-induced scarcities as causes of conflict, highlighting structural scarcity, i.e. when groups have systematically unequal access to resources.

The notion of the energy weapon concerns the willingness to use extortion, in terms of political pressure and demands, and the exposed actor's vulnerability to extortion. Based on the DESERTEC scenario (North African Concentrated Solar Power (CSP) exported to Europe) (DESERTEC Foundation and The Club of Rome, 2009; DLR (Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt, i.e. German Aerospace Center), 2006), Lilliestam and Ellenbeck (2011) investigate the threat of North African countries using the energy weapon against Europe by way of assessing the interdependence, in terms of bargaining power symmetry, of a disruption in future electricity trade. Lilliestam and Ellenbeck conclude that Europe is susceptible to political extortion only if all North African exporting countries unite in using the energy weapon.

Some of the reports reviewed take this broader view on security and sometimes also look upon energy as a resource that needs to be secured from threats. The report by the US Center for Naval Analyses (CNA, 2009) for example, explores the US military's energy security and points out several situations where climate mitigation policies might provide a tactical and/or strategic advantage. Combining energy efficiency with renewable distributed generation at military bases and on the battleground would reduce the exposure of both the supply chain and the grid to terrorist attacks, hence offering tactical advantages. If climate mitigation policies were to be adopted at large scale in the US, national security might benefit, since the US would then become less dependent on foreign countries and the need for military intervention to protect energy infrastructure might decrease.

Finally, geological, social, environmental and technical security aspects are included as energy security aspects in some analyses (e.g. Nuttall and Manz, 2008; Turton and Barreto, 2006).

3. CLIMATE CHANGE MITIGATION STRATEGIES

A great majority of the papers claiming to analyse both energy security and climate mitigation strategies often only discuss the latter issue in a general manner. When strategies are more nuanced, three main ways to mitigate climate change can be identified: energy mix changes, energy efficiency measures, and the implementation of CCS.

A handful of papers have an isolated focus on the energy mix issue, typically more renewables (Chalvatzis and Hooper, 2009; Grubb et al., 2006; Huntington and Brown, 2004; Lilliestam and Ellenbeck, 2011) or nuclear power. Mallah (2011) argues more or less one-sidedly on the opportunities of nuclear power, while Jun et al. (2009) highlight nuclear power in comparison with coal, oil and Liquefied Natural Gas (LNG).

Some papers suggest combinations of strategies aiming for energy efficiency and energy mix changes (Hedenus et al., 2010; Henriques and Sadorsky, 2010). The broadest approach is that adopted by Blesl et al. (2010), also including CCS together with energy mix changes and energy efficiency (other papers analysing or discussing CCS in relation to energy security are Bauen, 2006; Drake, 2009; Garg and Shukla, 2009).

The coverage of climate mitigation strategies in the reports reviewed is largely similar to that in the papers. The single most common mitigation strategy is energy efficiency. This is commonly a policy area where win-win situations between energy security and climate mitigation can be observed. In some studies, energy efficiency is considered in a general manner, e.g. the efficiency scenarios in ECN (2006) have an overall decreased energy demand. Other reports have a narrower scope and evaluate increased energy efficiency in a certain sector (e.g. EPA, 2011).

4. Temporal scope and future perspective

Energy security and climate change mitigation can be analysed with a historical perspective, a focus on present times or a future perspective. Helm (2002) uses the historical perspective when distinguishing the main components of contemporary energy policy as security of supply, sustainability and competition. Nuttall and Manz (2008) also use the historical perspective as their point of departure when devising a new energy security paradigm for the twenty-first century. Some papers could be considered short-term historical, as they collect empirical data for further analyses rather than performing historical studies. For example, Chalvatzis and Hooper (2009) examine the development of the electricity sector in four European countries during 2000-2005 in order to better understand trade-offs and synergies considering policies for climate change mitigation and electricity supply security (other studies with similar empirical approaches are e.g. Bang, 2010; Southworth, 2009).

Some papers principally deal with present times combined with a short-term future outlook, or where exactness considering the temporal dimension is not a key feature (Bradshaw, 2010; Hedenus et al., 2010; Henriques and Sadorsky, 2010; Jun et al., 2009). A typical example is that by Jun et al. (2009), which analyses the energy security cost of disruption periods from six months up to 2 years for different energy sources, including climate change mitigation effects.

In the lower mid-term segment with a 2020-2030 perspective (Bauen, 2006; Garg and Shukla, 2009; Pode, 2010), Bauen (2006) for example, presents cost projections of different renewable energy sources until 2020. In the upper mid-term segment with a 2030-2050 perspective (Grubb et al., 2010; Blesl et al., 2010; Kruyt et al., 2009; Lilliestam and Ellenbeck, 2011; Mallah, 2011), Grubb et al. (2006) for example, analyse the influence of low-carbon objectives for the diversity and security of UK electricity generation. A set of fuel source scenarios in combination with different levels of CO_2 reduction until 2050 are analysed, with the result that low-carbon scenarios are associated with greater strategic security of supply.

Papers applying a long-term perspective, i.e. papers extending the analysis up to 2100, generally use specific models, such as MERGE (Model for Evaluating Regional and Global Effects) (Bollen et al., 2010; Mignone, 2007), GET (Global Energy in Transition) (Persson et al., 2007) or ERIS (Energy Research and Investment Strategies) (Turton and Barreto, 2006).

The majority of the reports reviewed focus on the period from 2020 to 2030 (e.g. DECC, 2011; Ecofys, 2009; WRI (World Resources Institute), 2007). The CSIS (Center for Strategic and International Studies (US)) and WRI report (2009) assesses how the energy security situation develops under eight different climate mitigation scenarios in the year 2035. According to the authors, a shorter timeframe will not be enough to allow more significant technological improvements, while a more distant future will compromise the ability of the analysis to capture important near-term dynamics.

Only a few reports analyse more distant futures, up to 2050 (DECC, 2009; UKERC (UK Energy Research Centre), 2011). On the other hand, the present situation is the subject of some qualitative reports analysing policy integration (ECN, 2005; SIEPS (Swedish Institute for European Policy Studies), 2009).

5. ANALYTICAL FOCUS: POLICY AND ACTORS, OR SYSTEM AND TECHNOLOGY

One way to structure the analytical focus is to address the different aspects of change. As noted in the previous section, most of the papers reviewed deal with the future in some way. Future development can be regarded as a process of change with objects of change (energy systems, technology, the climate system, policies, states, institutions etc.), means of change (policies, strategies, means of control, innovations and technological improvements, etc.), and agents of change (politicians, states, international organisations, industry, researchers, engineers, energy providers etc.) (Jonsson, 2006).

Among the papers reviewed, the analytical focus varies. In some papers, policy is considered the principal means of change. Papers with a strong orientation towards policy are generally of a qualitative nature, and in these papers the agents of change can be more easily identified (Bang, 2010; Drake, 2009; Helm, 2002; Lee, 2009; May, 2010; Rogers-Hayden et al., 2011; Southworth, 2009). Southworth (2009) for example, investigates the effects of corporate voluntary measures, in the absence of uniform regulations and controls, and concludes that voluntary measures are useful but insufficient solutions for climate change and (corporate) energy security.

Some papers study policies in a scenario context (Bollen et al., 2010; Henriques and Sadorsky, 2010; Mignone, 2007; Nuttall and Manz, 2008), sometimes manifested through the use of various 'policy scenarios'. In Bollen et al. (2010) for example, the policy scenarios cover combinations of policies to manage local air pollution, global climate change and security of supply, as well as a business-as-usual scenario, resulting in eight different policy scenarios.

Papers involving an analytical focus on system and technology are sometimes case studies, sometimes generalised, but always with an in-depth view of the objects of change (Chalvatzis and Hooper, 2009; Garg and Shukla, 2009; Grubb et al., 2006; Jun et al., 2009; Mallah, 2011; Pode, 2010). The objects of change can either be the energy system as a whole, various subsystems with the focus on different kinds of energy sources or energy carriers, or separate components and technologies. Pode (2010), for example, suggests considerable technological and system changes for Indian energy supply in order to simultaneously enhance energy security, mitigate climate change and improve quality of life.

Of course, many of the papers cover both policy/actors and system/technology (Turton and Barreto, 2006; Huntington and Brown, 2004; Blesl et al., 2010; Hedenus et al., 2010; Lilliestam and Ellenbeck, 2011). Lilliestam and Ellenbeck set out from a vision of a changed European electricity system but end up in the actor perspective by way of challenging the importer-exporter power balance with future supply, and thus revenue, disruptions. Huntington and Brown (2004) also combine policy and system analyses, where a distinct feature is 'policy interactions' in combination with energy system changes. Huntington and Brown simulate the combined effects of policies for reducing import dependency and for reducing CO_2 emissions, and conclude that the integrated approach can reduce the cost of meeting carbon constraints in industrialised countries. However this could impose higher aggregated costs, in a global perspective, since the most carbon-intensive fuels will not be taxed most heavily.

In a similar way to the academic papers, some reports focus exclusively on policy, while others view technology as the object of change. The latter approach proceeds in roughly two different ways, either by evaluating technology-orientated scenarios in a general manner (CSIS and WRI, 2009), or by comparing different technology options (AEA (privatised offshoot of the Atomic Energy Authority (UK)), 2010; Bradshaw, 2010). However, many reports tend to combine policy/actors and system/technology by way of analysing how the energy system, and hence energy security, will evolve when different policies are implemented (e.g. Ecofys, 2009; EPA, 2011). Another approach is to use a three-step method to select policies. In the first two steps, mitigation and security policies are evaluated separately. In the third step, the policies that individually give the most desired outcomes are combined to assess their combined performance (DECC, 2011; NEPI (National Energy Policy Institute (US)) and RFF (Resources for the Future), 2010).

6. Approaches and Methodologies

The majority of the papers reviewed at least partly adopt a quantitative approach but also usually include elements that could be labelled qualitative. Some papers use a mainly qualitative approach, sometimes in combination with quantitative elements. A typical approach is to set up the object of analysis in the form of the energy system (present or future) in some way and then make a valuation of energy security, environmental pros and cons, etc. in terms of e.g. emissions, costs, risks or combined effect variables.

Many papers use (quantitative) mathematical models to generate the object of analysis. The approach can be simulation (Bauen, 2006; Bollen et al., 2010;

Henriques and Sadorsky, 2010; Kruyt et al., 2009; von Hippel et al., 2011) or system optimisation (Blesl et al., 2010; Brown and Huntington, 2008; Turton and Barreto, 2006). Simulations and optimisations are also commonly used techniques in the reports reviewed, which generally simulate or optimise the economic choice of an agent, sometimes in combination with indicators (e.g. CSIS and WRI, 2009; DECC, 2011).

In contrast to mathematical modelling, the object of analysis can be qualitatively selected in terms of e.g. the present system, available scenarios or forecasts and trends (indeed with quantitative content) (Bauen, 2006; Chalvatzis and Hooper, 2009; Lilliestam and Ellenbeck, 2011; Pode, 2010). Many papers and reports use various scenario approaches, which could be considered a specific type of methodology. We opted to distinguish between predictive, explorative and normative scenarios as defined by Börjeson et al. (2006). Predictive scenarios, e.g. forecasts and projections, try to answer the question *What will happen?* Explorative scenarios, e.g. external and strategic scenarios, answer the question *What can happen?* Normative scenarios, e.g. visions and backcasting images of the future, answer the question *How can a specific target be reached?* Among the papers and reports reviewed, the predictive and explorative approaches are most commonly used, for example as forecasts or combinations of alternative policy and technology development scenarios. The normative dimension is also present, however, for example in terms of certain CO_2 emissions targets.

Forecasts can be used either as support for claims in semi-qualitative studies (e.g. DECC, 2009), or as a business-as-usual scenario that is quantitatively compared with alternative climate mitigation scenarios using indicators (e.g. APERC, 2010; Ecofys, 2009; IEA, 2007). For example, Garg and Shukla (2009) use projections of energy resource availability and end-use demand in India until 2030 as input to a bottom-up energy-environment optimisation model, with the aim of evaluating how CCS can mitigate both climate change and energy security risks.

The valuation step and how the results are presented can also be quantitative, qualitative or combined. An obvious combined valuation approach is the use of both qualitative and quantitative indicators (Kruyt et al., 2009; von Hippel et al., 2011). For example, Kruyt et al. (2009) provide an overview of available indicators for long-term security of supply and advocate the use of multiple indicators in order to increase understanding. Kruyt et al. incorporate these indicators into a model-based scenario analysis and conclude that oil production will become increasingly geographically concentrated up to 2030, after which the supply will be more diversified. However, stringent climate policies might hamper the diversification process due to reduced demand for oil.

Many papers are entirely based on qualitative methods (Bang, 2010; Drake, 2009; Helm, 2002; Lee, 2009; May, 2010; Nuttall and Manz, 2008; Rogers-Hayden et al., 2011; Southworth, 2009). For example, the explorative analysis in Bang (2010), with the focus on contemporary US Congress energy policy, is based on empirical data from e.g. government documents, statements by politicians and personal observations. In Rogers-Hayden et al. (2011), critical discourse analysis is used in combination with semi-structured interviews with UK stakeholders (similar to Drake, 2009). Notably, most of the entirely qualitative papers are also case studies (however not Lee, 2009; May, 2010).

In the reports where qualitative methods are used, some of the most common techniques encountered for information gathering are interviews and workshops with experts and/or stakeholders (AEA, 2010; CNA, 2009; CSIS and WRI, 2009; DECC, 2009; DECC, 2011). In reports that assess policy integration, the main source of information is instead policy documents (e.g. ECN, 2005; SIEPS, 2009). Reports from think-tanks generally tend to use qualitative or semi-qualitative methodology.

Regardless of the method used, most reports (and papers) start by identifying root causes of insecurity and then develop measures to quantify these causes (e.g. AEA, 2010; IEA, 2007). The Ecofys report (2009) for example, identifies three broad groups of root causes: extreme events (e.g. weather events, terrorism or accidents), inadequate market structures (e.g. insufficient investment in new capacity or regulatory failures) and market concentration (e.g. a small number of producers controlling the market). According to IEA (2007), the greatest interactions between energy security and climate change mitigation policies can be found in the last group, i.e. market concentration. Therefore, measures are only developed to evaluate these aspects. The Ecofys report, written on behalf of the European Commission, has a wider scope and analyses interactions with all of the previously mentioned root causes. After evaluating case studies on EU-27 countries, they conclude that climate mitigation policies tend to shift problems away from those related to primary fuel supply to vulnerabilities related to the electricity system. This is caused by an increased amount of intermittent energy production.

Identifying and evaluating root causes of insecurity is a proactive technique that proposes taking preventive measures, i.e. policies that will prevent a situation with an inadequate amount of energy from occurring. The opposite, i.e. a reactive analysis, has been thoroughly used by UKERC (2011) to study the resilience of the UK's gas system. This approach – which is rather unusual, even among academic papers – allows the authors to disregard what caused the disruption (e.g. strike, weather event or political blockade). Instead, the key issue is the energy system's ability to manage the disruption. UKERC complements the resilience analysis with an insurance analogy, i.e. after weak spots have been identified and possible improvements have been put forward, they assess the frequency of disruption at which the policy begins to be economically beneficial.

In some reports, expert judgement is used to simultaneously assess and score qualitative and quantitative data (AEA, 2010; ECN, 2006; RIVM, 2004; WRI, 2007). For example, AEA (2010) uses multi-criteria analysis, a methodical approach for decision analysis. Options are compared against each other on several different aspects and assigned a value that enables benchmarking at a later stage. This approach has the advantage of allowing intangible aspects of energy security, which can be difficult to evaluate with quantitative methods, to be scored. This makes it possible to compare and evaluate different policy options on both objective factors (e.g. the potential decrease in CO_2) and subjective factors (e.g. exposure to politically instable countries). In some reports, all energy security aspects are represented in one single digit that is graphically plotted against the ability to decrease CO_2 emissions (ECN, 2006; WRI, 2007). Thus, communication of the result is facilitated at the expense of accuracy.

Finally, a number of the academic papers and reports included in this review use a case study approach. Case study as a method, or research strategy, is generally associated with social science research on contemporary phenomena when "how" or "why" questions are posed (Yin, 2003). In the present context, however, we took a rather liberal view on what could be considered a case study (see the following section).

7. GEOGRAPHICAL SCOPE

In the academic papers, the EU, or a group of EU countries, is the most common geographical scope (e.g. Blesl et al., 2010; Chalvatzis and Hooper, 2009; Hedenus et al., 2010; Lilliestam and Ellenbeck, 2011). In Chalvatzis and Hooper (2009) for example, multiple case studies of selected EU countries are performed, among others the UK, which is the most common country case (Drake, 2009; Grubb et al., 2006; Helm, 2002; Rogers-Hayden et al., 2011). Some case study papers also focus on the US (Bang, 2010; Southworth, 2009), and on India (Garg and Shukla, 2009; Mallah, 2011; Pode, 2010).

A number of regions and states are potential case study objects for future research, e.g. Africa and energy exporting states, although Persson et al. (2007) focus on major oil exporting countries. One paper at least partly including the exporting side as well as Africa is that by Lilliestam and Ellenbeck (2009). Although the vulnerability of the EU is the main focus for Lilliestam and Ellenbeck, they could also be considered to have accounted for the energy exporting perspective, since their assessment is based on the balance between exporter and importer.

All reports reviewed are case studies on one or a group of countries. The geographical coverage is similar to that found in the academic papers, i.e. most of the reports focus on the developed economies (it should be noted however, that due to linguistic limitations, we were only able to review reports in English). The EU 2020 targets are a recurring theme in case studies (ECN, 2006; Ecofys, 2009; SIEPS, 2009). Some reports specifically analyse the situation in the UK (DECC, 2011; UKERC, 2011). Together, these reports cover a broad range of energy security aspects and methodological approaches. On the other hand, reports on US energy security are generally from think-tanks and tend to be qualitative or semi-qualitative (e.g. CNA, 2009; CSIS and WRI, 2009). There are some quantitative reports that address the US specifically (e.g. EPA, 2011; NEPI and RFF, 2010). However, in comparison with reports addressing the EU, these reports have a greater bias towards oil-related security aspects.

8. SCIENTIFIC TRADITIONS AND PERSPECTIVES

Scientific research and knowledge building on the interactions between energy security and climate change mitigation can gain from interdisciplinary efforts. The reports reviewed are generally more interdisciplinary than the academic papers, perhaps due to the nature of the peer-review journal system as primarily discipline- and theme-orientated but of course also due to the fact that we selected reports providing other perspectives than the academic papers. For example, the CSIS and WRI report (2009) proposes that energy security be evaluated on eleven different factors (including geopolitics, price volatility, energy intensity, affordability and the risk of nuclear proliferation). Hence, perspectives from economics, technology and political science are all integrated in the analysis. However, interdisciplinarity is not evident in *all* reports (e.g. ECN, 2005; SIEPS, 2009).

Some of the academic papers express an explicit interdisciplinary ambition (e.g. Kruyt et al., 2009; von Hippel et al., 2011), but the majority are – at least partly – based on an economics perspective. Awerbuch (2006), for example, applies the perspective of economics using mean variance portfolio theory to optimise the overall production cost and risk of energy systems. Most of the economically orientated papers emphasise a cost perspective, i.e. the analyses are based on real costs or on other non-monetary efforts, effects or aspects operationalised as costs. In Bollen et al. (2010), cost-benefit modelling is used to perform an integrated assessment of climate change, air pollution and energy security for eight different policy scenarios. A main finding of that study is that energy security policy alone does not decrease the use of oil. Only integrated policy for the three policy areas can make the world's oil reserves last to the twenty-second century, and also limit the global mean temperature increase to 3 degrees Celsius compared with pre-industrial levels. Other papers emphasise cost-effectiveness or cost-minimisation (e.g. Hedenus et al., 2010), or cost-projections (e.g. Bauen, 2006; Jun et al., 2009), while some apply a price perspective. For example, by way of modelling the relationship between environmental sustainability, energy prices and stock prices, Henriques and Sadorsky (2010) show that a company's energy price exposure can be reduced through sustainability measures. Theirs is an example of a paper with a business economics perspective, which is also the case for Southworth (2009). However, most economically orientated papers in this review are based on a national perspective, i.e. "economics", or even aggregated global economics, e.g. in terms of world-cost minimisation (Huntington and Brown, 2004). Persson et al. (2007) address revenues, but with a national, rather than corporate, perspective.

The economic perspective is often combined with a technological or technological change perspective (Blesl et al., 2010; Garg and Shukla, 2009; Grubb et al., 2006; Turton and Barreto, 2006). Blesl et al. (2010), for example, evaluate economic optimal energy supply structures of the European energy system in 2020 and beyond, given a certain energy service demand and a certain CO_2 emissions reduction by 2050.

Political science is another main category when it comes to scientific perspectives and traditions (Bang, 2010; Helm, 2002; Rogers-Hayden et al., 2011; von Hippel et al., 2011). Bang (2010) explores whether putting energy security and climate change on the decision making agenda simultaneously is a trigger for general energy policy change in the US. Rogers-Hayden et al. (2011) analyse how climate change and energy security are perceived as motivators for change in UK energy policy.

Notably, a political science perspective is seldom combined with either economics or technological change. There are some exceptions, for example in Nuttall and Manz (2008), where the prerequisites for a new energy security paradigm are elaborated. Based on the assumption of an extensive transition towards clean energy technology due to the impacts of climate change becoming apparent earlier than expected, Nuttall and Manz discuss changes in international relations where foreign and trade policies and military policies are concerned.

Lilliestam and Ellenbeck (2011) combine the economics perspectives with a geopolitical perspective in a novel way. This is one of a few examples of a paper dealing with the security dimension of political science in a quantitative manner and the only example of a paper quantitatively addressing future political security of renewable electricity supply.

As regards the reports reviewed, those by ECN (2005) and SIEPS (2009) both have a political science perspective and qualitatively compare policy integration in the US and the EU, respectively. ECN concludes that current US policy is focused on 'enhancing future oil and gas imports' as well as 'political ties' to key fossil fuel producers. If policies for decreased import dependence were to be encouraged, then most measures would be synergetic in nature with climate change mitigation. SIEPS compares four different legislative areas in the EU (the effort sharing, the Emissions Trading System, the Renewable and CCS directives). Several synergies are highlighted, e.g. measures that simultaneously reduce fossil fuel consumption and import, but also trade-offs, e.g. Clean Development Mechanism (CDM) credits, from the Kyoto Protocol, that may benefit climate mitigation but without enhancing the EU member country's energy. SIEPS (2009) concludes that the different policy areas are path-dependent considering timeframe, geographical scope and internalisation of costs and that this may lead to different outcomes.

A number of the academic papers are at least partly grounded in environmental science and/or resource theory (Bauen, 2006; Chalvatzis and Hooper, 2009; Hedenus et al., 2010; Kruyt et al., 2009; Persson et al., 2007; Pode, 2010; Turton and Barreto, 2006). For example, Hedenus et al. (2010) analyse the expected cost of oil supply disruptions given different energy and climate policies in the EU-25 and conclude, among other things, that imported sugar cane ethanol is more cost-effective than domestically produced wheat ethanol.

Finally, the geographical science perspective is present, although represented in only a few papers (Bradshaw, 2010; Drake, 2009; Turton and Barreto, 2006). Based on the economic geography of globalisation, Bradshaw (2010) demonstrates how a geographical perspective is useful for the analysis of energy security and climate change. Bradshaw addresses different energy dilemmas for different regions and countries based on characteristics such as energy use, energy resources, economic situation and carbon intensity. A more specific geographical perspective is used in other papers and reports labelled as case studies. An example of a case study also actually resting on a geographical science perspective is that by Drake (2009), which examines regional energy policy and the rehabilitation of coal, in combination with CCS, in response to climate change. The conclusion is that the region as a territorial structure could be a useful device in promoting national priorities.

9. DISCUSSION AND SYNTHESIS: TOWARDS AN ANALYTICAL FRAMEWORK ON ENERGY SECURITY AND CLIMATE CHANGE MITIGATION

This review included papers and reports from various fields of science, as well as various approaches to energy security and climate change mitigation. Starting with scientific perspectives, traditions and analytical focus, somewhat of a dividing line was identifiable, at least among the academic papers. Papers emphasising the economic and technological perspectives are seldom combined with analyses of policy and actors, and *vice versa* for political science papers. The dividing line is also apparent when methodologies, approaches and future perspectives used are considered.

The policy- and actor-orientated papers tend to be qualitative and contemporary (or unspecific about temporal scopes), while the system- and technology-orientated papers generally use specific quantitative methodologies with clear timeframes. There is a lack of papers using a comprehensive socio-technical perspective in which actors and policies, as well as technology, are equally represented. However, the integrated socio-technical perspective is much more common among the reports reviewed.

The fact that different academic disciplines study different aspects of energy security and climate change in different ways is of course not a problem *per se*. The problem is the distance, and the lack of interaction, between these two knowledge production streams when the overall development of this line of combined research is considered. On a generalised level, the differences can be described by trying to interpret the underlying purpose of the papers/reports. One possible purpose-based categorisation could thus be:

- To orientate, inform, describe, elaborate, discuss, generalise or nuance – in order to create a better understanding and to contribute to policy debate and the academic discourse.
- To calculate, compare, optimise, simulate, analyse and assess – in order to refine methodologies, to generate policy inputs, or to evaluate policies.

The former knowledge production stream is important in order to understand what is relevant to analyse in the latter, and the results from the latter should of course be continuously integrated into the former. Among the papers reviewed here (and to some extent the reports as well), there is a clear lack of such cross-reference. One problem seems to be the pronounced willingness (or unwillingness) to quantify. In the disciplines where quantification is considered a main feature, it sometimes appears as though the possibility to quantify rather than the research question dictates the choice of methodology and scope. Moreover, aspects of an obvious qualitative nature associated with structural uncertainty are sometimes quantified in order to fit into a certain model or to contribute to an absolute quantitative result. Due to uncertainties or excessive locking of variables, some problems cannot be solved in a relevant and meaningful way through optimisation or simulation, and are thus consciously avoided. Methods other than the common dissolve mode to handle uncertainties might be fruitful in this context (which will be elaborated later in this section).

On the other hand, the qualitative studies sometimes show an unwillingness to separate important aspects from others and tend to be deliberately vague considering definitions, for example when discussing the energy security concept, despite the fact that a broad array of indicators, developed within the quantitative production stream, is available. Moreover, the qualitative papers sometimes tend to avoid thoroughly accounting for delimitations and the methods used, seemingly to increase the scope for discussion later in the text (however this is only our opinion, not a supported conclusion).

The lack of knowledge stream integration is not as obvious in the non-academic reports, which are generally of an interdisciplinary nature. The will to quantify is still great in the reports, but also the will to simplify, perhaps in order to deliver the desired clear policy inputs.

To conclude, there are known problems associated with integrating different scientific traditions. However, the analytical framework developed here, which captures the perspectives and aspects associated with contemporary research (see Appendix 1), at least reveals the gap between the two knowledge production streams and might also contribute to decreasing the gap in the future.

Generally, the academic papers reviewed that treat a number of energy security aspects thoroughly only leave room for a general view on climate strategies, and *vice versa*. However, some of the reports reviewed have a fairly broad scope on both energy security and climate strategies, notably quantitative reports with the emphasis on valuation and impact assessment (IEA, 2007; UKERC, 2011).

As shown in this review, energy security aspects have generally been more thoroughly researched than climate change mitigation aspects. The vast majority of the papers only discuss the climate issue in a general manner. There is also a lack of nuance regarding the three main mitigation strategies (efficiency, energy mix changes, and CCS). For example, efficiency could involve both end-use efficiency and conversion and distribution. Moreover, indirect means of control (e.g. taxes, spatial planning, CO_2 trade etc.) could be an area for more extensive research. However, it should be stated that indirect means of control are indirectly implied, although not explicitly analysed, in, for example, policy scenarios and assumptions on future emission levels. In the table in Appendix 1 we employ the categorisation of climate mitigation strategies used by IEA (2011) (and highlight areas which could be suitable for inclusion in future integrative research).

Another observation is that the consumer perspective is generally limited to prices and costs, which might be considered too narrow a view – not least when trade-offs between climate mitigation and energy security are considered. Energy is used by people/households in order to maintain everyday life and to fulfil basic needs, which cannot be simplified to an isolated cost issue. Other social sciences (apart from those encountered in the literature) such as behavioural science could perhaps make important contributions to this combined research area.

In the literature, security aspects beyond security of supply and dependency and diversity issues are often lumped together, e.g. as security politics or geopolitics, involving military aspects, international relations aspects, political stability and resource curse in exporting countries, poverty and human rights issues etc. There are several reasons why a more nuanced approach would be beneficial. For example, narrow military perspectives and national security considerations are generally more geographically specific than a broad security policy aiming for stable international relations in a globalised world, including notions such as fair trade and non-nation specific power games in international forums such as the UN (e.g. the developing countries' common standpoint in the climate negotiations). Indirect security political effects such as hampered foreign relations and unholy alliances, due to dependencies, also risk being omitted from the analysis when the notion of security policy is unspecific or insufficiently nuanced. One solution could be to try to separate traditional (realist/mainstream) state-orientated security political aspects from perspectives often included in the security discourse nowadays, for example (denoted 'post-modern security political aspects' in our analytical framework (Appendix 1);

- *human security* (in contrast to national security, see e.g. Alkire, 2003),
- *securitization* (when energy transforms from a political to a security issue, and civil politics becomes geopolitics with military involvement, see e.g. Buzan et al., 1998),
- *interdependency* (as a security building aspect, in contrast to always seeing dependency as a problem, see e.g. Russet et al., 1995; Keohane and Nye, 1997), and
- *international flow security* (to enable the intricate system of inter-woven, international interdependencies associated with continued globalization, see e.g. Ries, 2010).

When it comes to temporal scope, few existing studies adopt a long-term perspective, so the timeframe generally evaluated is too short to allow for substantial infrastructure changes or commercialisation of novel technologies to take place. Therefore, the energy systems analysed commonly have an energy mix that is similar to the current mix, which limits the results in terms of effects from climate mitigation strategies and improved energy security.

The long-term perspective is obviously associated with great uncertainty and (at least quantitative) analyses might be considered not meaningful. A step in the right direction might be to abandon the will to *dissolve* uncertainty, and instead *structure* uncertainty using external explorative scenarios. Uncertainty structured as scenarios could also form the basis for a qualitative sensitivity analysis on the results. An area for future research is thus the development of methods for qualitative impact assessments and valuation of results (rather than just 'discussions'). When scenario approaches are considered, normative goals for energy and climate are generally present as the basis for analyses, e.g. in optimisation models. However, no paper or report makes the normative approach its main feature, for example in terms of backcasting specific future energy security and climate targets and analysing how e.g. society, human behaviour and values, consumption, industry and trade, settlement patterns and travel must change, or could be arranged, in order to fulfil the targets.

The EU and the UK in particular seem to be well-researched cases. However, very few EU case studies deal with security policy and there seems to be a lack of quantitative US case studies, at least where academic papers are concerned. Unstudied places are developing countries in general, Africa (except partly in Lilliestam and Ellenbeck, 2011), South America and most parts of Asia. The somewhat biased Western World perspective associated with energy imports and security of supply also dominates issues concerning mainly energy exporting countries and regions, e.g. security of demand and revenues, as well as societal risks related to global climate policy and the future development of oil and gas exports. Consequently, the possibility to generate security through mutual dependencies, i.e. interdependency, is an energy security aspect generally missing in the analyses.

10. CONCLUSIONS

This review demonstrated the breadth and heterogeneity of approaches, perspectives, methodologies and aspects included in studies aiming to analyse energy security and climate change mitigation in a more or less integrative manner (see Appendix 1). It should be noted that our way of highlighting certain aspects is by no means a valuation or conclusion on what is most important when approaching energy security and climate change mitigation. We simply identified opportunities for future research. Our hope is that this will inspire disciplinary researchers to analyse certain themes associated with their particular line of science. For interdisciplinary research, as well as the work of policy-orientated institutions and think-tanks, the framework could serve as a checklist so that no relevant perspective or aspect is overlooked. This checklist could of course be expanded and complemented as future research efforts continue.

A great challenge is how to move from an analytical framework, which aims to identify, visualise and inspire, to a methodological framework generating policy inputs and new research themes; a refined, developed and aspect-rich framework with the purpose of valuing how energy security is affected by individual climate change mitigation strategies and by comprehensive climate policies. Based on current CO_2 emission trends, it can be assumed that not only climate *mitigation* strategies but also climate *adaptation* strategies will be relevant in this context.

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Appendix 1. Analytical framework on combined energy security and climate change mitigation research. The table reflects issues covered in the publications reviewed. **Bold type** indicates opportunities for further future research, e.g. common, but not thoroughly elaborated themes in the publications (e.g. geopolitical energy security aspects) or missing themes (e.g. South America as a geographical area). Themes which could benefit from more nuanced analyses are also highlighted (e.g. conversion, distribution and end-use efficiency as climate mitigation strategies instead of just 'efficiency').

ENERGY SECURITY ASPECTS	CLIMATE MITIGATION STRATEGIES	TEMPORAL SCOPE AND FUTURE PERSPECTIVE	ANALYTICAL FOCUS	APPROACHES AND METHODOLOGIES	GEOGRAPHICAL SCOPE	SCIENTIFIC TRADITIONS AND PERSPECTIVES
Energy system exposed to security threats vs. **generating or enhancing insecurity** Root causes vs. **Resilience** Long-term security of supply / **security of demand** / **security of revenue** Supply chain security / Disruptions and shocks / Physical stability and infrastructural aspects Price security / Economic risks **Geopolitical aspects** / Import dependency / Market concentration / High risk suppliers / Diversity issues **State-orientated security political aspects** (e.g. national security, military aspects, indirect effects of e.g. foreign policy) **Post-modern security political aspects** (e.g. risks from securitization of energy, human security, flow security and international interdependencies)	**End-use efficiency** **Conversion and distribution efficiency** **Renewables** **Biofuels** Nuclear CCS (Carbon Capture and Storage) **Indirect means of control**	Historical Contemporary Short-term future Mid-term future **Long-term future**	System and/or technology Actor and/or policy **Socio-technical integrated**	Qualitative methodology Case studies Scenario approaches (predictive, **explorative, normative**) Simulation Optimisation Valuation / Impact assessment (quantitative and **qualitative**)	Europe UK **Africa** US **South America** **Asia** **China** India **Developing countries in general** **Energy exporting countries in general**	Resource theory / Environmental science Technology / Technological change Economics Political science **Geographical and geopolitical science** (political, sociological, historical dimensions of geography) **Other social sciences**