A dissertation submitted to the department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Doctor of Philosophy

Energy security and renewable electricity imports: the case of a Supergrid connecting Europe, North Africa and the Middle East

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Author's declaration

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Furthermore, this dissertation contains no materials previously written and/or published by another person, except where appropriate acknowledgment is made in the form of bibliographical reference, etc.

Johan LILLIESTAM

The work with this dissertation has led to a number of journal publications, some of which have been published at the time of finishing the dissertation and some of which are still in review or in preparation but may be published after the dissertation is finished. In particular, this refers to the articles Lilliestam and Ellenbeck (2011), Lilliestam *et al.* (in preparation) and Lilliestam (in review). As these articles are based on the work for this dissertation, parts of the text of this dissertation have been or will be published in these articles. In all cases, the text here and the corresponding articles are original work carried out and written by me.

THE CENTRAL EUROPEAN UNIVERSITY

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for the degree of Doctor of Philosophy and entitled: Energy security and renewable electricity imports: the case of a Supergrid connecting Europe, North Africa and the Middle East.

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To mitigate climate change, European countries need to decarbonise the electricity sector by 2050. Decarbonisation options include importing solar electricity from the Middle East and North Africa through a long-distance transmission system, a Supergrid. Such imports raise questions about energy security: will Europe become vulnerable to coercion and embargoes, or to terrorist attacks and extreme natural events?

In this dissertation, I assess the impacts of a Supergrid scenario (Desertec) on European energy security in comparison with the present situation, a business-as-usual and a decarbonisation scenario from the Global Energy Assessment.

First, I define energy security as ‘low vulnerability of vital energy systems’. I contextualise this generic definition by identifying which vital energy systems and vulnerabilities are priorities in the European context, based on an analysis of empirically observed policy measures. European energy security policy focuses on mitigating physical supply disruptions and excessive price volatility, caused by a small number of threats to national and regional electricity and gas systems. I could not identify any environmental or social aspects of energy security.

Second, I develop and apply new methods for assessing the vulnerability to energy coercion, infrastructure failures and terrorism in scenarios. I base these methods on the ideas of power balances, chokepoint failures, action attractiveness to hostile states and non-state actors, and energy system resilience.

I show that all scenarios and the present system are well-diversified and sufficiently resilient, which makes them not vulnerable to coercion or chokepoint failures.

No single country has power to coerce Europe, as single-country export cuts inflict high and sustained costs on the exporters themselves, but not on Europe. Single-country interruptions cause costly but short-lived end-use outages in Desertec, but not in the present system or in the other scenarios. However, if embargoes are coordinated among the majority of electricity or gas exporters, the costs for Europe may be both sustained and higher than for the exporters in Desertec, the other scenarios and the present system.

Similarly, 3-5 failures of energy import chokepoints would cause short end-use outages in Desertec but not in the present system or the other scenarios. Large and lasting outages only follow 10 or more simultaneously disabled chokepoints. However, disabling a large number of chokepoints and causing lasting end-use outages is difficult, making energy infrastructure an unattractive terrorist target. Likewise, simultaneous failures of multiple chokepoints are very unlikely outcomes of natural or technical events.

Thus, I show that the Desertec scenario does not cause significant worsening of European energy security, related to the two assessed threats, compared to today or to the other scenarios. I obtain these results by novel, context- and threat-specific methods, and the results are in partial contrast to assessments using the widely used but generic diversity indices also carried out here. Further research may build on this dissertation with a more detailed representation of (a) energy security policy concerns (beyond reflection on policy measures), (b) coercion events (taking into account ‘political’ costs and actors’ willingness to accept damage), and (c) alternative terrorist motivations (beyond causing outages).

Keywords: energy security, renewable electricity, Supergrid, power balance, critical infrastructure vulnerability.

To Elis.

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Abbreviations

CCS	Carbon capture and storage
CI	Critical (energy) infrastructure
CSP	Concentrated (thermal) solar power
ENTSO-E	European network of transmission system operators for electricity
ENTSO-G	European network of transmission system operators for gas
ETS	European emissions trading scheme
EU	European Union
FSU	Former Soviet Union
GDP	Gross domestic product
GEA	Global energy assessment
HDI	Human development index
HHI	Herfindahl-Hirschmann index
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IEA	International energy agency
ICRG	International country risk guide
LNG	Liquefied natural gas
MENA	Middle East and North Africa
MVP	Mean variance portfolio
NATO	North Atlantic treaty organisation
OECD	Organisation for economic co-operation and development
OPEC	Organisation of the petroleum exporting countries
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SWI	Shannon-Wiener index
VOLL	Value of lost load
WTO	World trade organisation

1 Introduction

1.1 Background

The European electricity system stands before dramatic changes. A dominant driver for these changes is the increasing knowledge and concerns about the impacts of climate change: the Intergovernmental Panel on Climate Change (IPCC) recommends that the global greenhouse gas emissions are reduced by 50-80% by 2050 compared to 1990, should the world stand a fair chance of avoiding dangerous climate change (Metz *et al.* 2007). To achieve this, a rapid and radical phase-out of carbon-emitting energy sources is required, in Europe[1] and in the rest of the world, through a rapid and radical transformation of the energy system. Building the future, climate-friendly energy system has been described as nothing less than "*a historic challenge for humankind*" (Edenhofer *et al.* 2010:11).

There is a strong consensus that this emission reduction requirement first of all applies to industrialised countries, which are responsible for the lion's share of the historical emissions, later to be followed by climate protection efforts in developing countries coherent with the concept of "*common but differentiated responsibilities*" (UNFCCC 1992:Art. 3). Adhering to this principle, the European Union (EU) has adopted a medium-term climate target of 20% decarbonisation by 2020, whereas its longer-term target is still being negotiated (EC 2010a). Climate and renewables targets of similar level of ambition are in place, or in negotiation, in the non-EU member countries of the European Energy community (Energy community 2012;

[1] I define 'Europe' as the European continent, except the post-Soviet countries but including the Baltic countries, as well as Turkey. Hence, Europe consists of all members of the European Union-27, Norway, Switzerland, Croatia, Serbia, Bosnia-Hercegovina, Macedonia, Montenegro, Albania and Turkey. I do not consider Iceland. All countries referred to as Europe, except Switzerland, are members or observers of the Energy community. In the scenarios, there are minor deviations from this, see section 7.4.

Energy community treaty 2005). An unofficial target of 80-95% emissions reduction by 2050, an ambition level roughly consistent with the recommendations of the IPCC, has been ratified by the European Council at numerous occasions and the contemporary European energy policy is directed towards this objective (EC 2011d, f). For the European electricity sector, in which ample decarbonisation possibilities exist, the long-term society-wide decarbonisation target means a stricter decarbonisation than for society as a whole – some even argue that a complete or almost complete decarbonisation by the middle of this century is necessary – in order to compensate for shortcomings and difficulties to decarbonise other sectors (EC 2011d; ECF 2010; MacKay 2009).

At the same time, other energy policy objectives than decarbonisation must be fulfilled. Over the last years, the issue of energy security has re-emerged as an important policy issue. These concerns and the consequent reactions were triggered by various events, and are sometimes reinforced by ongoing, longer-term processes such as the depletion of the fossil fuel resources in the North Sea, and the rapidly increasing energy demand in the emerging economies. Among the more recent events, the Russian-Ukrainian gas conflicts are perhaps the most prominent, spawning fears that Europe may have problems to access reliable fossil fuel supplies in the future. These fears, in turn, have led to a desire to diversify the European energy supply away from overly high reliance on single fossil fuels and suppliers, and to limit the increasing energy imports (e.g. EC 2011d). The Arab Spring, which started in 2011 in a number of Middle Eastern and North African (MENA[2]) countries, has increased European concerns about the short-term reliability of oil and gas suppliers in the case of revolutions and

[2] I define MENA as Morocco, Algeria, Tunisia, Libya, Egypt (which together form 'North Africa'), Jordan, Lebanon, Syria, Iraq, Iran, Kuwait and the countries on the Arab Peninsula (see section 7.4).

unrest. It has also caused worries about the long-term ability of the countries in the MENA to produce and export fossil fuels, as the uprisings have greatly increased uncertainty and deterred urgently needed energy sector investments (Darbouche and Fattouh 2011; Nicolini and Porcheri 2012). Similarly, following a number of large blackouts in different parts of Europe in the last decade, voices are heard that new, European governance systems are needed to maintain electricity system reliability, both with and without decarbonisation policies (Silvast and Kaplinsky 2007; van der Vleuten and Lagendijk 2010a, b). Even events far away from Europe have triggered energy security concerns and action: the Tohoku earthquake and Fukushima nuclear disaster in 2011 forced Japan to temporarily stop its nuclear reactors, causing significant capacity shortages (Vivoda 2012). In Europe, this event had repercussions as well, as Germany rapidly and permanently shut down half of its nuclear capacity, triggering fears of capacity shortages in the winters to come (Tagesschau 2011). Increased energy security concerns following spectacular triggering events are not new: the 1973 oil crisis is the most prominent example, but there have been numerous other events, such as the British coal miners' strike in 1973-74, which caused 3 months of electricity rationing, and a subsequent policy redirection away from coal towards gas and nuclear power (National archives 2011; Yergin 2011).

This duet of climate and energy security objectives has strong impacts on the European electricity options for the future. On the demand side, some climate and security objectives may be seen as synergistic. Increasing energy efficiency and reducing demand in the gas sector, for example, would have benefits for both targets by simultaneously reducing the European import dependence and its greenhouse gas emissions (EC 2011c). On the supply side, the targets are sometimes conflicting: for example, turning to conventional coal power – the only large European domestic fossil energy resource – is incompatible with the European emission reduction targets (e.g. Turton and Barreto 2006). Instead, the low-carbon electricity options fall into three broad categories:

- Expanding generation from nuclear fission power stations
- Continuing to rely on fossil primary energy for electricity generation, but capturing the CO_2 and storing it away before it is vented into the atmosphere, using Carbon Capture and Storage (CCS) technologies
- Replacing fossil-fuelled electricity generation with electricity from renewable sources

Any climate-friendly future electricity mix will consist of these three categories, in some constellation and with some demand-size (Bruckner *et al.* 2010; Solomon *et al.* 2007). The manoeuvring space in these dimensions however seems limited: common features of essentially all decarbonisation scenarios are their much reduced energy intensity, and their strong reliance on renewables – some decarbonisation scenarios foresee a strong increase of renewables in the electricity sector, and some foresee a *very* strong increase (Edenhofer *et al.* 2011).

One group of scenarios with a renewables-dominated electricity supply is the *Supergrid* scenarios. These scenarios differ in the details, but share one common feature: they rely on the backbone of highly efficient high-voltage direct current (HVDC) transmission lines, which span all of Europe and reach into the MENA region in a vast power system – an intercontinental Supergrid. This Supergrid system supports the integration of renewables so that this scenario group foresees the very far-reaching, or total, decarbonisation of the European electricity sector with renewable electricity by 2050, of which a considerable share is imports of solar and wind power from the MENA. Supergrid solutions to the climate problem in the electricity sector have been proposed by researchers (e.g. Battaglini *et al.* 2009; Czisch 2005; Düren 2011), green advocacy groups (e.g. ECF 2010), industrial advocacy groups (e.g. Dii 2013; Zickfeld *et al.* 2012), and governmental advisory boards (e.g. EEAC 2009; EASAC 2009 (European level); SRU 2010 (Germany)). The publication and promotion of the *Desertec* scenario (Club of Rome 2008; Desertec 2009), foreseeing 80% decarbonisation of the European power system with renewables by 2050, of which 17% are imported, as dispatchable solar power from the MENA, has put this idea on the European energy policy agenda.

The main reason for such Supergrid proposals is that the solar and wind power potentials in the deserts of the MENA are very large. In the much more densely populated Europe, the land availability may limit the possibilities to decarbonise the European power system with domestic renewables. Accessing the prime production sites in MENA could therefore allow for very large-scale production of renewable electricity for both Europe and MENA itself, and significantly decrease the total costs of the decarbonisation compared to an approach in which countries expand only their own renewables (Czisch 2005; Zickfeld *et al.* 2012).

In addition, three effects affecting grid integration of renewables come to bear in Supergrid systems. First, the deserts offer potentials for a dispatchable source of electricity, concentrating solar power (CSP). This technology, which has a very limited potential in Europe, could play an important role to balance the European domestic renewable electricity generation, mainly intermittent photovoltaic and wind power. Second, the large Europe-MENA Supergrid system would span an area larger than most weather systems, so that there is always wind or solar power generation available somewhere in the system. Via the HVDC grid, the areas with excess generation can supply areas experiencing generation shortages at any given time. The cumulated feed-in of intermittent renewable generation would thus be stochastically smoothed and overall generation fluctuations greatly reduced. This effect is caused by the negatively or un-correlated generation patterns of wind and, to a lesser extent, solar power stations separated by very large (>800-1000 km) distances. Third, extending the electricity system beyond the European climate zone enables significant seasonal smoothing of feed-in, as North Africa has strong winds in summer whereas Europe has strong winds in winter. In addition, the seasonal fluctuation of solar radiation is much lower in the MENA deserts than in Europe (Czisch 2005, 2006; DLR 2006; Katzenstein *et al.* 2010; Kempton *et al.* 2010; MacKay 2009; Patt *et al.* 2011).

In early 2009, the non-profit Desertec Foundation was established, consisting of a number of engaged individuals and surrounded by a growing number of mainly German scientists, politicians and industry representatives, with the aim to promote the Desertec vision (Desertec 2012). The Desertec Industrial Initiative (Dii), an industrial consortium dedicated to investigate and lobby for a policy and economic environment suitable for desert electricity for export to Europe, was formed in July 2009. The Dii consisted of a number of large, mainly German, companies, including Munich Re, Siemens, Eon, RWE, Abengoa Solar, and Deutsche Bank, and until today, the Dii has grown to include 21 shareholder companies and 35 associated partners from Europe and MENA (Dii 2009, 2012b). At the time of writing, the construction of the first Desertec "*reference project*", a CSP station of 400 MW in Ouazarzate, Morocco, is about to begin (Dii 2012a).

Although Supergrid scenarios are an increasingly frequent research area, many questions remain unanswered both regarding how such intercontinental plans can be implemented and regarding whether a Supergrid future is at all desirable. One such critical question concerns the issue of European energy security: if a Supergrid is not secure enough, Europe would be well advised not to pursue such projects and instead focus on other electricity pathways.

A Supergrid proposal such as Desertec raises a number of justified questions in an energy security context. For example, the solar electricity produced in and transmitted through the harsh desert climate could be interrupted by sudden and violent sandstorms, which are "*one of the most challenging technical factors for building solar power plants in the desert*" (Beckman 2011:1). Similarly, one may fear that Europe would pay "*a hell of a lot of money*" (EURELECTRIC President Lars Josefsson, in: Lubbadeh 2009) for a Supergrid, just to manoeuvre itself into a another dependency on energy deliveries from 'unreliable' foreign states. One might perceive that "*the stage is set to recreate an uncomfortable parallel with western dependency on oil from Saudi Arabia, Iran and Iraq*", thus voicing fears of energy coercion and a new 'oil crisis' – this time with electricity – and ask "*why create a new hostage to fortune?*" (Pearce 2009:42). These fears are exacerbated by the Arab Spring (Stonington 2012). Similarly, as the electricity system is the engine of modern societies, a relevant question is whether "*we want to be dependent on North Africa for our electricity supply when anyone with a shoulder-launched missile can take out the electricity supply for Europe*" (Michael Liebreich, CEO of Bloomberg New Energy Finance, in: Morales 2010).

Others, such as the Desertec Foundation, dismiss such statements as fear mongering and note that there is no record of electricity blackouts in Europe due to politically motivated embargoes or terrorist attacks. Instead of bringing risks, they claim, Desertec will bring Europe and North Africa closer together culturally, economically, socially and politically. This will bring advantages for all and therefore reduce or eliminate political risks and tensions. Further, they claim that Desertec will "*contribute to stability*" in the wake of unrest and war during the Arab Spring (van Son, in: Kirschbaum 2011), so that the social benefits of Desertec makes it "*an ideal anti-terror program*" (Desertec 2010:1).

Energy security statements such as these are heard both from Supergrid proponents and from opponents, respectively, but they appear speculative and not supported by scientific analysis. Thus, in the present dissertation, I will provide a solid scientific analysis to answer the justified questions about the European energy security in a Supergrid scenario.

1.2 Research questions

My overarching objective is to find out how a Supergrid future with significant renewable electricity imports from MENA would affect European energy security. For this, I must first know what energy security is, in the European context I am interested in, and then find methods suitable to assess energy security in scenarios. In this dissertation, therefore, I develop and apply new methods based on theories and concepts from within and outside the energy security research field. Hence, my focus is to find answers to the overarching research objective, but it is also methodological and epistemological as I will develop new methods to define energy security in a context-sensitive manner and to assess energy security in scenarios.

To make the overall research objective operational, I break it down the work down into three connected but distinct research questions. The first research question, which I handle in part 1 of the dissertation, refers to the definition of energy security:

1. **What is energy security in a European perspective?**

In this dissertation, I investigate how European energy security would be affected in a Supergrid future. This means that I need to know what energy security is in the European context. In the first part of the dissertation, therefore, I explore and define the concept of energy security – the low vulnerability of vital energy systems – in a European perspective. Concretely, I analyse the European energy security policy in order to identify which *vital energy systems* it is concerned with, as well as with which *threats* – events that may materialise and detrimentally affect energy security – and with which *disruptions* – the potential impacts of the threats, should they materialise. I analyse observed policy measures, which may be different from the policy rhetoric, in order to identify actual European policy priorities. Based on the identified measures and their aims, I induce a context-specific and operational policy-based definition. By doing this, I identify which threats to which systems are in focus of European energy security policy and which types of disruptions it aims to avoid, and whether energy security in this perspective includes environmental, social and other aspects sometimes included in definitions in the literature. The main purpose of the definition part of the dissertation, however, is to provide the conceptual frame for the second part of the thesis, in which I assess the European vulnerability in scenarios.

Three important notions underlie the work with the second part – the energy security assessments – of the dissertation. First, if one scenario is seen as too insecure and is thus ruled out, another scenario future will take its place. Doing nothing is not an option, as even the present will develop into a business-as-usual future, also if no further policy action is taken. As all energy scenarios hold specific sets of vulnerabilities, the relevant question is not whether a Supergrid scenario is vulnerable, but whether the vulnerabilities of a Supergrid are higher or lower than that of alternative futures. Second, not all energy security threats can be meaningfully assessed in scenarios. This is especially the case for threats that are not possible to assess for the future. It also applies to threats that affect all scenarios in the same way, as an assessment of such threats would not contribute to informing the strategic choice between scenarios. Here, I analyse the two threats in focus of European energy security policy that can be meaningfully assessed for scenarios: critical infrastructure failures, including terrorist attacks, as well as dependence and the possibility that the exporting countries use the energy trade as a tool for political coercion. Third, not enough detail and data is present to assess all aspects of energy security in scenarios. Instead, it is more interesting to assess whether the parts that distinguish the assessed scenario from other scenarios or a benchmark hold different, inherent vulnerabilities.

In the second part of this dissertation, I assess the European energy security in a Supergrid scenario. Concretely, applying the three notions described above, this means that I in the assessment part investigate the European vulnerabilities to coercion and infrastructure failure introduced by a Supergrid and whether these are higher or lower than the vulnerabilities of today’s system, of a non-decarbonisation baseline and of an alternative decarbonisation scenario.

I thus assess two distinct threats in this part, each of which is related to a separate research question. The work with these questions also has a methodological and epistemological focus, as I develop and apply new methods alongside with applying existing methods to answer these two research questions.

In the work with the second research question, I focus on the threats related to European dependence and the threat of coercion by exporting countries:

2. **How serious is the European vulnerability to energy coercion by the exporters in a Supergrid future compared to other scenarios?**

The geopolitical threat that the energy exporters may wield the *energy weapon* against Europe is prominent both in the Supergrid and in the general energy security debates. The term 'energy weapon' refers to events in which an exporter use the cancellation of energy exports (or the threat of doing this) as a political tool to coerce the importer into accepting political or economic demands. Despite the prominence of this threat in the energy security debate, most existing methodologies focus on the construction of de-contextualised indicators, like import dependency or diversity, but do not look at what happens during the event as such. Here, I adopt theories and concepts from within and outside the traditional energy security field and develop and apply a new methodology, explicitly tailored to assess what happens during a coercion event. I base this methodology on the notions of power balances, dependence and interdependence, and draw especially upon theories from international relations research. At the core, the question of vulnerability to coercion is a question of power: can the exporter, by cancelling the energy deliveries, cause enough damage to coerce the importer into accepting demands? And will the exporter suffer damages, e.g. from lost income, so high that the credibility of the threat is diminished?

For the third research question, I focus on the threat of failing infrastructure:

3. **How serious is the European vulnerability to critical infrastructure failures, caused by terrorists, natural events, or technical failures, in a Supergrid future compared to other scenarios?**

The threat of end-use outages following infrastructure failures, caused by terrorists, natural extreme events or technical failures, is prominent in the Supergrid discourse as well as in the wider energy security discussions. Modern societies are highly dependent on a continuous energy and, especially, electricity supply: outages rapidly lead to high economic costs, and long outages may even be a threat to social stability. If such dramatic, spectacular effects are attainable to terrorists, critical infrastructure could be an attractive attack target and a serious vulnerability for society. Equally, if natural events or technical failures can cause serious outages in a system, that system is vulnerable. Therefore, understanding vulnerability to critical infrastructure failure is a matter of understanding how threats to infrastructure unfold and how resilient the system is to infrastructure failure. In the critical infrastructure literature, methods are available for assessing vulnerabilities in existing, well-defined energy systems. For only broadly defined systems, like scenarios for the remote future, such methods are not applicable, as the necessary system topology data is not available. Here, I therefore develop and apply new assessment methods drawing both on critical infrastructure theories and external ones to assess the vulnerability of the infrastructure to both malevolent attacks and random natural or technical failures based on the notions of infrastructure chokepoints and target attractiveness.

Hence, I have two sets of foci in this dissertation. The first set refers directly to the answers to the three research questions. This focus is reflected in the two-part structure of the dissertation and concerns the split of first defining energy security in the European context and then assessing the European vulnerability in scenarios. The second set is methodological and epistemological in nature: to find answers to the research questions, I will here develop new context-specific methodologies to analyse and understand the energy security in as great detail and as close to reality as possible.

1.3 Structure

I follow an intuitive and systematic sequence of stages in this dissertation (see Cherp and Jewell 2013), by first defining energy security in a specific context and the by assessing it. This sequence is reflected by the overall structure of the dissertation in two distinct but related parts, in which the results from the definition part flow into and provide the conceptual frame for the assessment part, see Figure 1. Each of the parts has its own literature review, theories and methods, results and discussion chapters.

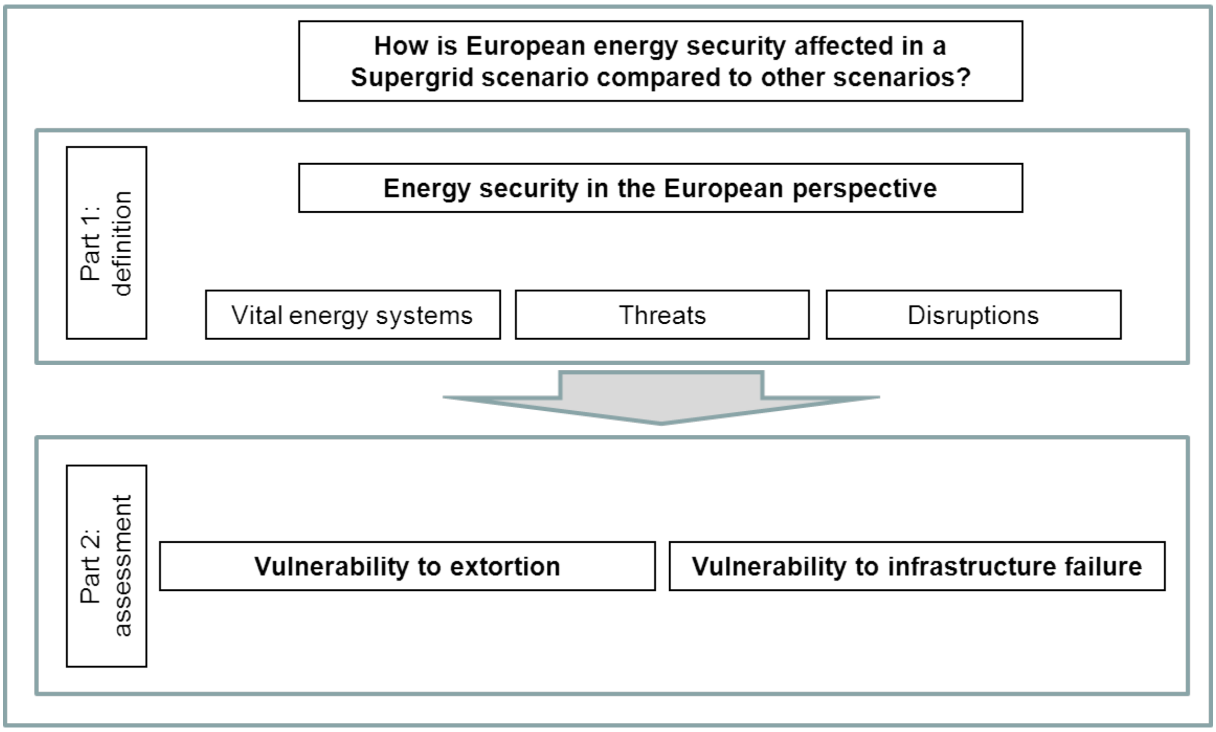

Figure 1: Overall structure of the dissertation.

There are two separate but interconnected parts: the results of the definition part provide the frame for the assessments in the second part.

In the first part, consisting of chapters 2-5, I define energy security in the European context, in two steps. First, following a review of energy security definitions in the literature (chapter 2), I develop a method of defining energy security for a specific context, based on observed energy security policy concerns (chapter 3). Second, using this method, I delineate the vital energy systems in focus of European energy security policy along their sectoral and geographical boundaries and identify the perceived threats to these vital energy systems and the types of disruptions European energy security policy aims to avoid (chapter 4). I discuss and interpret these results in chapter 5, including a discussion of the implications of this policy-based definition for the assessments in the second part of the dissertation (section 5.3).

The second part, which consists of chapters 6-10, is framed and guided by the definition results of the first part. In the assessment part of the dissertation, I assess the vulnerabilities of the identified systems to the identified threats, as long as these can be meaningfully assessed for scenarios. After the review of how energy security is assessed in the dedicated literature (chapter 6), I build the second part around a two-step sequence. First, I investigate how the identified threats may develop and cause disruptions in the vital energy systems. Based on this knowledge about how each threat unfolds and how systems react to disturbances, I develop threat-specific new methodologies and metrics to assess the vulnerability of vital energy systems, including both threat exposure and system resilience (chapter 7). Second, I quantify the vulnerability metrics for the selected scenarios (chapters 8 and 9) and interpret and discuss the assessment results and methodologies (chapter 10).

The final chapter of this dissertation, chapter 11, holds the conclusions of the definition and assessment parts, as well as the answers to each of the three research questions.

Part 1: Energy security definition in the European perspective

In this part of the dissertation, I develop and apply a new methodology for defining energy security in a bottom-up, context-sensitive way, based on empirically observed policy measures and aims. I apply this methodology to the energy security policies of three European case studies and analyse these to identify the vital energy systems policy seeks to protect, the perceived key vulnerabilities, and the response mechanisms policy deems necessary, effective and feasible. By doing this, I induce an energy security definition for the European context, which I will use as the conceptual base for the energy security assessments in the second part of the dissertation.

2 Literature review: what is energy security?

Energy security is an important aspect of energy policy both in Europe and around the world, and there is a large and growing body of literature dedicated to studying it. At a first glance, the term ‘energy security’ seems intuitively clear: it has something to do with the absence of vulnerability in energy systems. However, as I will show in this chapter, the interpretations of what energy security is vary in the literature, so that “*the concept of energy security is widely used, yet there is no consensus on its precise interpretation*” (Kruyt *et al.* 2009:2166). The result is that ”*the concept of ‘security of energy supply’, or in short form ‘energy security’, seems to be rather blurred*”[3] (Löschel *et al.* 2010:1665, see also Bigano and Sferra 2008, Winzer 2012).

A key reason for this diversity of definitions is the context-dependent nature of energy security. Chester (2010:892) finds that energy security “*takes on different specificities depending on the country (or continent), timeframe or energy source to which it is applied*”. Hence, energy security may mean something different in Europe than in China or Brazil, and it may have meant something different 20 years ago than it does today. As different studies focus on different systems, threats, times and regions, they also use different definitions. However, the underlying assumptions for the energy security definition are not always made explicit, thus hiding the polysemic, context-dependent nature of the concept behind an identical vocabulary of ‘energy security’, making it “*slippery*” (Chester 2010:892, also

[3] The focus on the supply-side of energy is emphasised by the observation that many authors use ‘security of supply’ as a synonym to ’energy security’ (e.g. Winzer 2012, see also many of the citations in this chapter). There is a debate, although not a widely pursued one, about whether these terms are synonyms (see Jansen and Seebregts 2010), and as shown here there is indeed more to energy security than only energy supply security. Nevertheless, due to the way the terms are used in the literature, I treat the two terms as synonyms.

Winzer 2012). Adding to this problem is the political nature of energy security: to a large extent, energy security first of all a political concept and only thereafter a scientific one (Goldthau and Sovacool 2012; Helm 2002). In the words of Joskow (2009:11): "*if you cannot think of a reasoned rationale for some policy based on standard economic reasoning then argue that the policy is necessary to promote 'energy security'*". Consequentially, the boundaries of the concept of energy security depend not only on the context but also on political considerations.

My aim in this part of the dissertation is to find out what energy security means in Europe, and for this, I need to identify where the boundaries of the concept in this particular context are, which components or dimensions are included, etc. In the following sections, I review the range of energy security definitions from the literature and their underlying differences, structured around the main lines of discussion concerning what energy security is.

These division lines mainly concern the sectoral and geographical boundaries of the systems to assess (section 2.1), what constitutes a threat to energy security and whether this includes both shocks and stresses (section 2.2), as well as the distinction between physical and economical aspects of energy security (section 2.3). A fourth line of division concerns whether to put the security of the utility the energy systems provide to its customers, including their resilience, in focus, as opposed to the security of the systems themselves (section 2.4). A fifth, rather recent research stream adopting the view that energy security in the modern day is broader and more complex than it used to be, triggering a need for new and more holistic definitions of energy security along the lines of 'new dimensions', is reviewed in section 2.5. These review sections are followed by a summary, including a critical appraisal of the literature (section 2.6).

2.1 Sectoral and geographical system boundaries

The first line of division concerns the scope of the conceptualisation, and defines the sectoral and/or the geographical scope. These boundaries to some extent depend on each other: some countries/regions rely more on particular energy sectors, whereas other do not even have all energy sectors. Examples of this is the strong reliance on coal in Poland, which is quite different than in France, which uses almost no coal; the French nuclear power dependence, however, stands in contrast to the absence of nuclear power in most countries in the world. Similarly, on the end-use side, practically all countries have a transportation sector relying on oil and most countries import the bulk of their oil needs, but only a few countries have large oil export sectors. At the same time, the energy sectors partially determine the geographical scope: oil is traded globally, whereas gas is traded regionally (although increasingly globally) and lignite is not traded internationally at all. Electricity systems are generally national (or sometimes sub-national), but are, especially in Europe, increasingly integrated to regional systems. Therefore, the national focus is often a natural boundary choice, but studies involving energies traded internationally may have an international aspect as well (see below).

Generally, the choice of the scope follows from the research question, which is influenced by the policy context, priorities and concerns. As not all authors are concerned with the same sectors in the same region, a wide diversity of sector/geography combinations exists in the literature. There are studies concerned with the supply of *oil* (e.g. Fattouh (2007), who focuses on the reliability of Middle Eastern oil exports) or *gas* (e.g. Le Coq and Paltseva (2009), who focus on the transit risks of gas imports). Others focus on *electricity* (e.g. Bennett (2011), who focuses on underinvestment and the reliability of electricity grids), including the *primary fuels* going into this sector (e.g. Damigos *et al.* (2009), who focus on the willingness to pay for increased gas supply security for electricity generation).

Yet other studies focus on *energy* in a general sense, mainly from the supply perspective (e.g. Löschel *et al.* (2010), who focus on the supply of oil, gas, coal and nuclear fuel). Cases exist in which authors define, in the beginning of their article, that they are concerned with 'energy', but later on focus primarily on one sector. An example of this is Yergin, who claims to discuss energy, but focuses almost all of his argumentation on oil and oil products (see Yergin 1988, 2006, also e.g. Bielecki 2002). In some studies, the supply-side focus is complemented by adding a demand-side or energy services view, thereby emphasising the utility provided by the energy system needs to be protected, and not only the system as such (e.g. Cherp *et al.* (2012), who place vital energy systems in focus; see below and section 2.3, also Scheepers *et al.* (2007)). Only a smaller number of studies highlight energy exports as an important end-use sector, emphasising the importance of security of demand for exporting countries (e.g. Bhattacharyya and Blake (2010), who analyse the oil export dependence of 7 MENA countries).

Definitions and studies also differ with respect to their geographical (or political) boundaries. As many energy systems have distinct national boundaries and are still governed by national policy, choosing *national borders* as geographical assessment boundaries is often a natural choice (e.g. Grubb *et al.* 2006, who assess the security of the electricity system of the United Kingdom (UK) under decarbonisation policies). Sometimes *a number of single countries* are assessed, still using the national borders as system boundaries (e.g. Cabalu (2010), who looks at the gas security of 7 separate Asian countries; or Cohen *et al.* (2011), who focus on 26 single OECD countries). Other studies focus on *an entire region*, thus integrating countries into one single system (e.g. Engerer *et al.* (2010), who assess European gas security by looking both at the vulnerability of the EU as a whole and of the most vulnerable states). Less frequent are studies focusing on *subnational* regions (e.g. Hughes (2007), who focuses on the Nova Scotia region in Canada). Global system boundaries is seldom, but exists especially in studies focused on oil (e.g. Bielecki 2002), and it is particularly frequent in the peak oil discourse, which is concerned with the global availability and production capacity of oil (e.g. Aleklett *et al.* 2010).

A distinct approach towards defining the system boundaries is the concept of vital energy systems defined by Cherp and Jewell and used in the Global Energy Assessment (GEA). Vital energy systems are defined first of all as systems – a set of components (physical or otherwise) that are connected to each other stronger than to the surrounding world, so that failed parts of a system cannot easily be substituted with parts from another system. These systems provide vital energy services, namely "*those that are necessary for the stable functioning of modern societies*". If a vital energy system breaks down, strongly detrimental, or even destabilising, effects for the economy and society may be the effect (Cherp *et al.* 2012:331; Cherp and Jewell 2011b, this is further explained in section 3.1). This focus on the critical function energy provides for society places energy security in the domain of national security and goes beyond the mere protection of energy supplies and physical assets (Cornell 2009). Importantly, this also explicitly introduces the energy export sector as a vital energy system: just as the loss of energy supply can destabilise an importing country's economy, the loss of energy export revenues can destabilise an exporting country (Cherp *et al.* 2012, also Bhattacharyya and Blake 2010). Vital energy systems can therefore exist on all levels, from the global to the local, and they can be defined along boundaries of primary fuels, energy carriers or end-uses (including exports), thus including all steps along the energy value chain, from the oil well via the needed infrastructure to markets and final consumers. Exactly where the system boundaries are is context-dependent and differs from one country, region or time to another. I adopt and apply the concept of vital energy systems in this dissertation (see chapter 3).

2.2 Cause and nature of energy security threats

A further line of distinction among energy security conceptualisations is the cause and nature, also including the time-perspective, of the threats in focus. I here define a 'threat' as a possible, detrimental energy security event (see section 3). Myriads of different threats may affect energy security and "*it is not very hard to conceive of the kind of event that could trigger a crisis*" (Yergin 1988:111).

There are different categorisations of energy security threats. Yergin, for example, states that threats may be of a "*political, military or technological*" nature (Yergin 1988:111), thus implicitly excluding natural events as an energy security threat. Winzer (2012:39), in contrast, perceives that energy security events are either "*technical, natural* [or] *human*". In this latter categorisation, the technical threats include mechanical or functional failure causing components to break down, natural threats means resource intermittency, depletion as well as natural events and disasters, and human threats include coercion, terrorism, geopolitical competition, war and political instability (Winzer 2012). Cherp and Jewell (2011b) explain the breadth of energy security definitions by identifying three distinct perspectives on energy security, each of which developed in response to distinct policy agendas, so that each perspective has a different intellectual history and disciplinary root:

- The *sovereignty* perspective, with roots in war-time supplies and the oil crises, focuses on intentional actions of potentially hostile actors (in particular geopolitical threats, such as the 'energy weapon') and is mainly based in international relations, political science and security studies.
- The *robustness* perspective focuses on roughly predictable failures, caused by roughly predictable natural and technical events (e.g. storms, fossil fuel depletion, component breakdown), and is mainly rooted in the engineering and natural sciences.
- The *resilience* perspective, which focuses on no specific type of threat, but rather on the ability of systems to withstand interruptions without breaking down and recover quickly regardless of the cause of the interruption. This perspective, which includes unpredictable threats like terrorist attacks, has its roots in economics and complex systems and networks analysis.

Two of these perspectives are thus similar, although not identical, to Winzer's human risks ('sovereignty' in Cherp and Jewell), and technical and natural threats ('robustness'). The resilience perspective cuts across and goes beyond Winzer's threat categories, by focusing on a system's survivability as a source of security rather than its threat exposure as a source of insecurity. I will build my assessment metrics around this idea (see chapter 3). Further, the critical infrastructure literature (see section 6.2) introduces a classification which distinguishes between random events, originating in natural and technical threats, and intentional events caused by humans with the aim of causing maximum damage (e.g. Brown *et al.* 2006). Thus, overall, the prevailing view in the literature is that the threats to energy security are either political, including all human-made threats, natural or technical.

Closely related to the cause of energy security events is their nature, in particular how often and how fast they happen, and how long they last. The principle division line is between what Stirling refers to as *shocks* and *stresses,* or between short-term sudden events and gradually emerging pressures (Stirling forthcoming, also Boston 2013). This distinction is important, both due to the different impacts and to the different causes of such events. Further division lines are sometimes introduced, especially regarding the duration of events. This is included in Stirling's characterisation of shocks and stresses, with shocks as "*short-term transitory perturbations*" and stresses as changing (permanently) conditions, or an "*enduring pressure*" to a system (Stirling forthcoming:10), whereas Winzer (2012) sees duration as a factor of its own, as also shocks (e.g. the 1973 oil crisis) can last long.

Shocks are singular, but sometimes recurring, events, such as "*technical failure, weather* […] *strikes, terrorist attacks* […] *wars and civil strife, regime change* […] *and a deliberate restriction of exports*" (Fattouh 2007:7). Such events are typically mainly physical events – an interruption of supply somewhere along an energy chain – but the effects can be either only sudden outages (such as during the 2006 Western European blackout) or price spikes, or both (such as the 1973 oil crisis). Both types of shocks can have strongly disruptive impacts on the final consumer, and most studies and energy security conceptualisations thus address shocks (Costantini et al. 2007; Helm 2002; Winzer 2012; Yergin 1988).

The effects of stresses are important, but not always clear-cut: for example, it is not easy to know how the reliability of a power station changes with age. Stirling defines stress as changes in a system's overall surrounding conditions and mention examples as diverse as climate change, demographic shifts, or long-term trends in global markets (Stirling forthcoming). Stresses are threats that do not trigger an energy crisis as such, but rather work by increasing the probability and impact of shocks happening by changing the system conditions (Scheepers *et al.* 2006; Kruyt *et al.* 2009). Some authors highlight underinvestment, caused by for example sustained periods of volatile prices or inadequate market functioning, as the principal stress to energy systems, or indeed even one of the largest threat to energy security (e.g. Goldthau 2008). The rationale behind this is that insufficient investments may lead to aging (and consequently more frequently failing) components and "*slowly emerging capacity gaps*" as "*new supplies may not be brought on stream on time to meet growing demand*" and to replace old assets that are retired over time (Correljé and van der Linde 2006:538; Bielecki 2002:237; Yu and Pollitt 2009).

2.3 Physical and economic disruptions

The absence of energy disruptions stands in the centre of most energy security definitions. In this dissertation, I define 'disruption' as a disturbance in the primary function of an energy system (see section 3), but still the exact meaning of this is not obvious. In the literature, there is a principal division line between physical and economic disruptions. Probably the most mainstream "*definition of energy security is simply the availability of sufficient supplies at affordable prices*" (Yergin 2006:70f), because certain prices or sudden price movements can be as disruptive to society as physical outages. However, this is, as are many other definitions, built around ambiguous terms, like 'sufficient' and 'affordable', which need to be interpreted and operationalised to be useful. In addition, a closer look in the literature reveals that an economic component is not always present, that some authors propose more components beyond these two, and that there are numerous subtle, but important, differences among the definitions of what constitutes a disruption.

At the core of most energy security definitions stand the adequacy, or availability of sufficient amounts, of energy and the reliability of energy distribution. A secure system has enough energy, which can be supplied to customers when and where they need it. In a metastudy of 91 peer-reviewed energy security studies, Sovacool and Brown (2010) found that over 80% referred to the physical supply as a component of energy security. Sometimes, especially among the studies focusing on electricity, the physical component is the only, or at least principal, component of the energy security conceptualisation. In such definitions, energy security may be "*the likelihood that energy will be supplied without* [physical supply] *disruptions*" (Ocaña and Hariton 2002:9), or, more generally, "*more secure systems are those with lower risk of system interruption*" (Lieb-Dóczy *et al.* 2003:11).

Many authors state that energy security has not only a physical, but also an economic component: over 50% of the 91 reviewed articles in Sovacool and Brown (2010) have a physical and an economic component in their definitions. Some see these components as interconnected, as "*low reliability usually contributes to high and volatile prices*" (Ocaña and Hariton 2002:9), and hence energy security refers to "*a partial or complete disruption of energy supplies*" which may "*induc*[e] *price increases*" (Scheepers *et al.* 2006:13). For the final consumers, it matters little what the exact reason for a disruption is, or whether they have no energy supply or if they cannot afford to buy the amounts they need – the effect for them is the same: they have no or too little energy (see Scheepers *et al.* 2007). Consequently, as mentioned initially, the bulk of definitions in the literature refer to both economic and physical parameters, viewing a secure energy system as one with an "*adequate, affordable and reliable*" energy supply (Ölz *et al.* 2007:13). The meaning of some terms, like 'adequate' and ‘reliable’ may be clear (at least in specific contexts[4]), but other terms – like ‘affordable’ or ‘reasonable’ – are fuzzier. Such terms are, for example, used in the International energy agency’s (IEA) definition that energy security means “*adequate supply of energy at a reasonable cost*”[5] (IEA 1985:29). Hence, energy security can have an economic component prescribing that prices (or costs) are affordable or reasonable, but this “*begs a fundamental question* […]: *affordable to whom and in the context of which expenditure basket?*” (Mabro 2008:3). Determining what such terms mean is “*clearly a subjective matter*” (Cornell 2009:3). The discussion concerning this is furthermore to some extent rooted in the shock/stress distinction, circling around the question whether the stress of high and/or slowly rising prices qualify as a ‘disruption’, or if a sudden price shock is the only economically disruptive impact on prices to be take into account.

High or rising prices may thus be seen as a “*crucial SOS* [Security of supply] *indicator*”, as it could indicate an emerging mismatch between supply and demand (Kruyt *et al.* 2009:2169). Others adopt the view that the thing to protect is the economy (or society) that relies on the energy system, so that high prices are not only an indicator on energy insecurity, they indeed constitute the insecurity itself (Scheepers *et al.* 2007). This leads to an intuitive interpretation of ‘affordable’: high prices can be equally disturbing, and thus equally unacceptable, as direct energy outages and may indeed cause *de facto* outages for poor customers.

The view that high prices are an energy security problem is however contested, for example by Keppler: “*High energy prices are frequently confused with energy supply risks. This is*

[4] ENTSO-E (2010:13), for example, define generation adequacy as “*the ability of the generation on the power system to match the consumption on the same power system*”, whereas power system reliability is defined as the continuity of supply (CEER 2008).

[5] It seems that the IEA conflates price and cost, and largely uses the term ‘cost’ in the meaning of ‘buyer cost’, or ‘price’.

wrong [as] *high prices are not the problem (in the long run, economies can adapt with relative ease) but the speed and the magnitude of sudden price changes leading to economic disruption are*" (Keppler 2007b:23, also Keppler 2007a; Winzer 2012). The argument that "*higher prices are not an energy security problem but a solution*" exists in the literature, as demand will be reduced and supply increased by the higher prices until a new equilibrium is found (Noël 2008). Others perceive that energy insecurity "*refers to the loss of economic welfare that may occur as a result of a change in the price or availability of energy*" (Bohi and Toman 1996:1). Consequentially, 'affordability', 'reasonable price' and similar terms in this perspective mean "*that prices are cost-based and determined by the market based on supply/demand balances*" (Bielecki 2002:237). Threats to energy security are consequently "*constituted by unforeseeable events threatening the physical integrity of energy supplies or leading to sudden and discontinuous energy price rises independent of economic fundamentals*" (Keppler 2007b:22, also Mabro 2008). In this view, therefore, the economic component of energy security "*is not really an issue of high prices but of volatile prices*" (Markandya and Pemberton 2010:1611).

2.4 Resilience of systems

Some authors divert their definitions away from the perfect reliability of the system itself and the acceptability or affordability of prices, towards the utility provided by the energy system to end-users. In doing so, the focus is shifted towards the ability of a system to withstand threats without being seriously disrupted – towards its resilience. Definitions explicitly targeting resilience adopt a customer- or service-based definition and view the utility the customers draw from consuming energy, and not the energy system as such, as the thing to protect.

This can take the form of accepting a pre-defined level of unreliability for some customers in order to protect the bulk of consumers. EURELECTRIC, for example, defines electricity security as "*the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality* […] *relating to the existing standards and contractual agreements at the points of delivery*" (EURELECTRIC 2006:6). Other conceptualisations put the substitutability of fuels in a key position. For example, Findlater and Noël explicitly target the resilience of the whole energy system – including demand reductions and fuel switches – to a shock in a single fuel system. They define security of gas supply as "*the ability of a country's energy supply system to meet final contracted energy demand in the event of a gas supply disruption* [so that it] *may enjoy a high level of gas supply security even if it is unable to replace all disrupted gas supply by alternative gas*" (Findlater and Noël 2010:2). In this resilience perspective, failed gas supply must not be substituted with other gas, as long as it is possible to maintain the customers' energy service, without utility losses, with other fuels.

Jansen adopts that view that the term energy security should be rephrased into "*energy services security*", thus going beyond both the energy supply system and the end-users as such by also focusing on the end-uses of energy and on the utility the customers experience from using energy (Jansen 2009:7). This view is reflected in the GEA, which defines energy security as the "*uninterrupted provision of vital energy services*" needed for the stable and proper functioning of society (Cherp *et al.* 2012:37). This is an extension into the end-user domain from the national security view that a secure energy supply is one that does "*not jeopardize major national values and objectives*" (Yergin 1988:111). In such an end-use-perspective, the key to energy security is "*system-wide resiliency – that is, improving the ability to continue service delivery despite limited infrastructure failures or external supply disruptions*" (Cornell 2009:3).

2.5 The 'new dimensions' of energy security

In a distinct, and rather new, direction in energy security research, authors perceive that "*it is no longer possible to view energy security as merely direct national control over energy fuels*" (Sovacool and Rafey 2011:93). Instead, the traditional definitions must be expanded by adding concepts like "*price stability, diversification of energy sources, energy storage, economic investments, infrastructure protection, political and military power balance, geopolitics, homeland security, energy efficiency, energy markets, sustainability, etc.*" (Yusta *et al.* 2011:6101). Sovacool and Brown (2010) note that 1/3 of the studies assessed in their metastudy refer to increased energy end-use efficiency and 1/4 to environmental aspects as integral components of energy security. This extension of energy security beyond the physical and economic components is done with fervour, viewing the new concept of energy security as "*the challenge of equitably providing affordable, reliable, efficient, environmentally benign, properly governed and socially acceptable energy services*" (Sovacool and Rafey 2011:93). Interestingly, the 'new dimensions' include threats (e.g. natural disasters), the potential impacts of threats on the energy system (e.g. supply and economic disruptions) and problems that may be caused by the energy sector in systems outside the energy sector (e.g. environmental damages, low social acceptance, etc.) into new, very broad definitions of energy security (e.g. Sovacool 2011a).

In recent years, a group of authors have risen to the challenge of defining a "*new concept of energy security*" as "*the last decade has seen an extraordinary shift in energy security challenges that challenge existing policy orthodoxies*" (Vivoda 2010:5258f). Therefore, "*old energy security rationales are less salient*" today than they were in the past (von Hippel et al. 2011:6719) and researchers must find "*a more comprehensive operating definition of 'energy security'*" (Vivoda 2010:5258). Two things are particularly worth noticing about this stream of research: first, it to the largest extent consists of studies that aim to define energy security, as opposed to most of the abovementioned studies that primarily aim to assess it. One could thus expect these definitions to be more precise and better justified than the definitions reviewed before. Second, they seek not only to identify the concerns of the 'new' energy security concept, but also to identify quantifiable indicators directly tied to each identified concern.

The first two papers in this stream (Vivoda (2010), who builds on von Hippel *et al.* (2011)[6]) take a very broad approach on defining energy security, essentially looking for all things that could potentially be an energy vulnerability. They identify a wide range of concerns, based on which they then deduce the "*dimensions*" (Sovacool 2011b) of energy security. The result is von Hippel *et al.*'s 6-dimensional definition of energy security[7], consisting of 29 distinct "*policy issues*" to be measured by 24 indicators (of which 8 are assigned to the environmental dimension). von Hippel *et al.* (2011:6725) themselves claim that this definition is "*by no means complete*", and Vivoda, following an epistemologically similar approach of deducing dimensions from general, abstract considerations, adds another 5 dimensions[8], arriving at 44 policy issues (or "*attributes*", of which 13 applies to the "*policy*" dimension) which can be directly quantified (Vivoda 2010:5261). Sovacool and colleagues state that also Vivoda's list of attributes is "*incomplete and at times conflate*[s] *actual metrics and indicators with dimensions and components*" (Sovacool 2011a:7472). Based on 68 semi-structured interviews

[6] von Hippel *et al.* was published after Vivoda, but was available as an 'in press' article already in 2009.

[7] The dimensions are Energy supply, Economic, Technological, Environmental, Socio-cultural, and Military-security.

[8] Vivoda's dimensions are the same as in von Hippel *et al.*, plus Demand management, Efficiency, Human security, International, and Policy.

geared towards identifying all threats and other aspects of energy security, and towards developing corresponding metrics, they arrive at a 20-dimensional energy security definition[9], to be directly assessed by the use of an array of up to 372 indicators[10] (Sovacool 2011a; Sovacool and Mukherjee 2011).

Such broad definitions can also be found in official policy documents. The rhetoric of the European Commission, for example, defines energy security as a strategy that is "*geared to ensuring, for the wellbeing of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development*" (EC 2000:2, see also section 5.1). Speculatively, given the timing of publication, the 'new' broad academic definitions draw on such similarly broad policy definitions, rather than the other way around (see also the quote by Joskow in section 2).

von Hippel *et al.* (2011:6722) note a convergence in both in scientific conceptualisation and energy security policies across the world, towards the wide range of concerns they identify as energy security issues. They see this as an "*encouraging sign with regard to minimizing the potential conflict that may come from differences in energy security concepts, as reflected in the different energy security policies that countries adopt*". Littlefield (2013:779), in contrast,

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[9] Sovacool's dimensions are Availability, Dependency, Diversification, Decentralisation, Innovation, Investment, Trade, Production, Price stability, Affordability, Governance, Access, Reliability, Energy literacy, Resilience, Land use, Water, Pollution, Efficiency, Greenhouse gas emissions.

[10] Although both Sovacool (2011a) and Sovacool and Mukherjee (2011) apparently refer to the same study and the same interviews, they describe their methodologies differently. Importantly, Sovacool's interview questions refer to energy security in Asia, whereas Sovacool and Mukherjee ask about energy security without a specific geographical context. Also, the 'dimensions' in Sovacool (2011) are renamed 'components' and, somewhat confusingly, grouped into 5 dimensions in Sovacool and Mukherjee (2011).

perceives the increasingly broad definitions both in academia and in policy rhetoric as a sign of a deliberate and "*systematic dilution of meaning*" of the term energy security in order to push and support certain political and economic interests using the terminology of security. This, he argues, threatens to render any energy security debate useless. Further, Ciuta views that "*energy is a special thing: a prime mover, a complex category, a total field. Nothing exists that is not energy, or not affected by energy. Energy security is therefore a homologous field, which means that security ceases to be a bounded domain of meaning and practice*", so that the boundaries of energy security become, almost by definition, blurred and all-inclusive (Ciuta 2010:124).

Cherp (2012), on the other hand, views the very broad 'new dimensions' definitions of Sovacool (2011a) and, by extension, Sovacool and Mukherjee (2011) as the result of weak methods. This weakness lies in particular in the interview design, which, in Cherp's view, leads to a non-discriminatory inclusion of all possible problems instead of offering a means to emphasise prioritisation among energy security issues: "*such a setup was very likely to encourage an excessively broad definition*" (Cherp 2012:841). Similarly, Cherp and Jewell (2011a:344) also observe a convergence towards a number of energy security "*storylines*" and a scientific assessment paradigm of "*finding the 'right' indicator rather than* […] *stimulating a process through which energy security concerns relevant to specific contexts can be identified, quantified and dealt with*". They find this "*worrying*" rather than encouraging. To them, many energy security concepts (and metrics) in the literature suggest, often implicitly but sometimes explicitly, that the definitions and related indicators are objective and universal, and thus directly applicable to all contexts. Instead of presenting and quantifying local concerns and discourses as "*universal and objective*" indicators and concepts, they propose an approach starting with the global knowledge about possible energy security concerns and contextualising, or adopting, them to the local situation for the case to be discussed or assessed (Cherp and Jewell 2011a:344). I develop this idea further in this dissertation (see chapters 3 (definition) and 7 (assessments)).

2.6 Summary and critical appraisal

As shown above, there is an ongoing discussion about the scale on which to view energy security (e.g. local, national, global), and about the relative weight of different perspectives on energy security (e.g. natural, technological and geopolitical threats, or the sovereignty, robustness and resilience perspectives, etc.). To a large extent, the choices concerning these issues depend on the research aim of each study. It is not critical whether a study looks at short-term or long-term threats to gas, oil or electricity (or all of them) in a national or regional perspective: all can be justified, but on many occasions, this justification is hidden behind a universal language of 'energy security'.

Currently, a main area of true disagreement concerns the 'dimensions' of energy security, or which types of threats and disruptions should be included in the concept. Most scholars agree that the adequacy and continuity of physical energy supply to consumers are components of the concept, but there is disagreement concerning the inclusion of other concerns, prominently economic issues. The discord about economic disruptions focuses both on whether these are a part of the concept and on whether this is related to the absolute price of energy or rather to price stability, or to both. Some authors include environmental and social issues in their energy security definition. The discussion on what energy security is has so far primarily taken the form of a stream of new suggestions on what the concept should contain – its scope, the threats and disruptions in focus, and the 'dimensions' of energy security – but there has been little emphasis on a theoretical and/or systematic methodological discussion on how to define it. A discussion has been emerging, but there is still a need for a more systematic understanding of what energy security is.

In some cases, in particular in the ‘new dimensions’ literature, I and others have observed a claim to universality of definitions, in the form of a discussion of what energy security is in general and generic terms. This claim is often implicit, by the omission of a discussion of the specific geographical, political or sectoral context in the definition, as well as a tendency to discuss ‘energy security’ while actually only assessing or deliberating on a small number of threats to single energy systems. The ‘new dimensions’ literature, which aims to define (and assess) energy security in its entirety – thus explicitly aiming for universality – considers all energy systems, all possible threats and all potential disruptions. Therefore, these explicitly universal and all-hazards definitions have no clear boundaries and become very broad or even all-inclusive, making them void in all their richness.

However, energy security is not a universal concept but rather a context-dependent one, and the meaning of energy security varies between cases, geographies and times. This mismatch between the general, universal language of definitions and the context-dependent nature of the concept is an important reason for the ‘blurry’ landscape of definitions. The variety of definitions are mainly caused by different contexts of different studies with different research questions from different disciplines, and not necessarily because the energy security concept is particularly intricate or ‘blurry’. Consequentially, the search for ‘the definition’ of energy security will fail, as there is no universally valid definition of a context-dependent concept.

This has some consequences for me and this dissertation, in which I assess the European energy security implications of scenarios. For this, I need to know what energy security is in the particular European context and base my assessment on this definition. The literature, while holding many useful thoughts about what energy security is, is of little help in this, not because it is necessarily wrong but because it offers no way of knowing which issues are important and which are not in the particular European context I am interested in.

The criticism found in the literature, in particular as reviewed in section 2.5, holds a number of useful points showing the way towards a methodology able to produce context-specific and operational definitions in a systematic manner, useful for the objective in this thesis. Such a definition approach could be based on observed energy security policy concerns, related to specific perceived threats to specific vital energy systems in the particular geographical or political context. Building a definition around observed concerns related to specific vital energy systems could offer a way to contextualise the definition, thereby introducing natural boundaries and making it both policy-relevant and operational. It could also offer a tool to prioritise and separate core energy security concerns from secondary and indirect ones. In the following chapter, I develop a method to define energy security in a specific political or geographical context.

3 Theory and methods: energy security definition in the European perspective

In this chapter, I develop a methodology for a contextualised energy security definition in the European perspective, including a description of the theoretical background and the case studies of this analysis.

I base the work to define the concept of energy security in an operational and contextualised way for Europe on two theoretical notions. First, energy security is a generalisable concept to the extent that all energy security considerations aim to protect vital energy systems from disruptions, either by reducing the threat exposure or by increasing the resilience of the system (Cherp *et al.* 2012; Cherp and Jewell 2011a, b). Here, therefore, I adopt a generic definition of energy security, as *low vulnerability of vital energy systems*. This generic definition is largely in agreement with other definitions in the literature (e.g. Winzer 2012, see chapter 2), but it is neither operational nor context-specific. I thus need to operationalise and contextualise this generic definition in a systematic way.

Second, the precise meaning of this generic definition depends on the specific context and is, for example, influenced by a country's history, energy system structure and economy (Chester 2010, see chapter 2). This means that the terms 'vulnerability' and 'vital energy systems' of the definition may vary between contexts and need to be defined on a case-by-case basis. Here, I do this by defining which the vital energy systems (see section 2.1) are, specifically for the assessed case (Europe), and by exploring the context-specific meaning of 'vulnerability'. In a general sense, the vulnerability describes a system's inability to withstand a detrimental event (Bhattacharyya 2009), and I thus consider vulnerability to be the negation of energy security. The term vulnerability consists of two components: the *threat* – the potential detrimental event – and *resilience* – the system's capability to maintain functionality or to regain it quickly after an interruption. If a threat materialises and overcomes the resilience capacity of a vital energy system, a *disruption* – a disturbance in the system's primary functionality – may be the consequence. A disruption can be, for example, a supply outage experienced by final consumers, but it could also take other forms (see e.g. section 2.3). This distinguishes a disruption from an 'interruption', which I define as a disturbance in energy supply somewhere along the energy chain, for example a failed transmission line, which may or may not lead to supply disruptions for final customers.

Together, these two notions show that the challenge of defining energy security is to systematically identify the specific interpretation of three terms 'vital energy systems', 'threats' and 'disruptions' on a context-specific, case-to-case basis.

I contextualise the generic definition and fill it with concrete meaning through an analysis of observed European energy security policies. In this, I identify the proposed measures and aims of the policies and based on this, in turn, I induce a case-specific energy security policy definition. The approach I develop and apply here thus follows the view that "*the starting point for defining energy security should be empirically observed policy concerns*" (Cherp and Jewell 2011b:210).

There are three main reasons for basing the definition on observed policies. First, energy security is an intrinsically political concept (see section 2; Goldthau and Sovacool 2012). As policy always takes place in a particular context, basing a definition on observed policies offers a way to contextualise it. Second, as the aim of energy security policy is to prevent or to minimise disruptions of vital energy system, regardless of which threat caused the disruption (Scheepers *et al.* 2006), energy security policy can be expected to be holistic in the sense that it acknowledges threats from all three energy security perspectives (sovereignty, robustness, resilience, see section 2.2; Cherp and Jewell 2011b). Third, energy security policy cannot be equally and simultaneously concerned with all potential threats against all energy systems, but is more likely to focus on the most pressing problems. The focus on concrete policy measures and aims, as distinct from policy rhetoric, is therefore a useful tool to identify real policy priorities and filter out concerns of secondary importance.

In sum, observed energy security policies are likely to focus on the issues that are most pressing to policy in a particular jurisdiction at a particular time. An analysis of energy security policy is therefore a tool to systematically organise the vast number of potential threats and disruptions associated with the various vital energy systems, and to focus the definition on the core concerns in a particular policy context. It is therefore a practical way to move away from universal definitions to contextualised ones. This approach however also has its limitations. Most importantly, policy is likely to take action against the most pressing problems, but there is no guarantee. It is possible that policy does not recognise a particular problem as being important, or that it ignores a problem because no practical or attractive solution is available at a given time. Similarly, policy may overemphasise a problem if its nature is spectacular and easy to understand (see Jänicke *et al.* 2002), and policy priorities may change over time. In contrast, measures addressing multiple problems, for example climate protection and energy security, are more likely to prevail in the policy process. I discuss the strengths as well as these and other limitations of the methodology developed and used here in section 5.2. In the following sections, I develop and describe the method for this analysis as well as the cases I apply it to.

3.1 *Vital energy systems, threats and disruptions*

A vital energy system is an energy system whose failure would threaten to disrupt the functioning of society, or a critical part of society (Cherp and Jewell 2011b, also section 2.1). These systems can be defined according to spatial or political boundaries (e.g. national, global), according to primary energy sources (e.g. natural gas, crude oil, hydro power), according to energy carriers (e.g. oil products, electricity), or according to energy end-uses (e.g. transport, industry, residential/commercial, energy exports). The perception of what is vital may differ between countries, regions and times, and not all energy systems exist in all countries. For example, gas for heating is a vital energy system in Germany, as disruptions in the gas system in winter could, among other things, cause severe problems in the residential sector. In Norway, however, the residential sector is primarily heated with hydro-powered electricity, making hydropower as well as Norway's substantial gas export sector – and not gas for heating – vital energy systems there. This definition of vital energy systems is similar to the definition of critical infrastructure as infrastructure that is "*essential for the maintenance of vital societal functions*" (Yusta *et al.* 2011:6101, see section 6.2), but differs in two main aspects: first, vital energy systems is a narrower concept than CI, as it focuses only on energy (excluding other CI related to, for example, water). Second, it is broader than the CI concept, as vital energy systems may include not only infrastructure but also all other parts of the energy value chain, ranging from natural resource extraction to final consumers.

As shown in the literature review (section 2.2), vital energy systems may be disrupted by a number of potential threats, which can be categorised into three 'perspectives' – sovereignty, robustness, resilience – of energy security. The threats can occur rapidly as sudden shocks or gradually as slowly emerging stresses. A threat may, should it overcome a vital energy system's resilience, cause disruptions of the physical flow of energy to customers or disruptively affect energy prices, while possibly affecting other ‘new dimensions’ of energy security as well (see sections 2.3-2.5). As mentioned above, in order to answer questions about a vital energy system’s vulnerability, I thus first need to systematically identify which the vital energy systems in focus in Europe are, including their structure and their resilience, as well as the threats and disruptions potentially affecting these systems.

3.2 Three questions to analyse energy security policy

My aim in the definition part of this dissertation is to fill the generic notion of energy security as ‘low vulnerability of vital energy systems’ with concrete and contextualised meaning by inducing a context-specific (for Europe) and operational definition of the terms ‘vital energy system’, ‘threat’ and ‘disruption’. I do this in two steps.

First, I investigate European energy security policy documents and identify what European energy security policy proposes to do (‘measures’), why the measures are proposed and what they are intended to achieve (‘aims’). Due to the expected overlaps between energy policy areas (such as competitiveness, climate protection and security, e.g. EC 2011d), I only consider measures and aims which are explicitly referred to as immediately concerning or improving energy security[11]. Conversely, if a policy measure does not refer directly and explicitly to energy security, I view this measure as belonging to a policy area other than energy security: I do not further consider such non-security measures.

[11] The terms ‘energy security’ and ‘security of supply’ are used interchangeably in the policy documents. See also footnote 3 (page 16).

Second, I analyse the collected data on energy security policy measures and aims. I frame this analysis by asking three fundamental energy security definition questions to define and gain context-specific insights about the nature of the three terms ‘vital energy system’, ‘threat’ and ‘disruption’: What to protect, from which risks, and by which means?

I ask the first question (What to protect?) in order to identify the vital energy systems in focus of energy security policy in the assessed case. This question thus defines the geographical and sectoral boundaries of the energy security concept in the particular context.

The second question (From which vulnerabilities?) aims at identifying the threats and types of disruptions in focus of energy security policy. By doing this, I identify the threats – the potential causes of disruptions – of primary importance. Consequently, the answers define the set of possible threats to understand and assess for the particular case, including information about the distinction between short-term shocks and long-term stresses. Further, the second question also helps me to define the nature of possible disruptions. This concerns the substantial division of whether disruptions are of a physical supply and/or economic nature and, if so, what this concretely means in the specific context. It also refers to whether other ‘dimensions’ of disruptions, such as social or environmental concerns, are integral parts of the energy security concept in the assessed case.

The third question (By which means?) provides further support to identify threats and disruptions and to prioritise among the identified concerns. By identifying measures to mitigate a threat, the answers also provide insights into the anatomy of the threat and the nature of a disruption, which may prove valuable for assessing the vulnerability of a vital energy system.

Based on these three definition questions, I induce a definition of what energy security is in a European policy context, thus answering the first research question (see section 1.2). This definition is in the form of concrete answers to which vital energy systems and which threats are in focus of European energy security policy, and which disruptions it aims to with avoid.

3.3 Case selection and description

The objective for the definition part of this thesis is to define energy security in a European policy context. For this, I apply the method described in the previous section to the policies of three European case studies: the European Commission, the United Kingdom (UK) and Sweden. These cases were chosen as they have very different energy systems and highly progressive energy policies, to increase the internal and external validity of the resulting energy security definition.

Case 1: The European Commission

The first case study is the energy security policies of the European Commission. As this is the policy of the European Union, this is a natural choice for a case study of energy security policy in Europe.

The EU today (December 2012) comprises 27 member states with heterogeneous energy systems partially integrated with each other. Its energy supply is based on oil (36% of gross domestic consumption), gas (24%) and coal (18%). The EU imports most of its fossil energy, and the import share is increasing, especially for coal and gas (Eurostat 2010, 2011). Although the European energy policy rhetoric frequently uses the general term ‘energy’, the majority of its policies focus on the supply and end-use of gas and electricity. The overall European energy policy objective is to achieve a competitive, climate-friendly and secure energy system (EC 1995, 2000, 2006, 2008a, b, 2010b).

The European Commission has an increasingly active energy policy, especially following the Lisbon treaty, which expanded its mandate to a range of energy policy areas, including energy security. Energy is thus more and more 'europeanised', and the European Commission is increasingly influential on perceptions of national energy and energy security policy (Nilsson *et al.* 2009; Solorio 2011; Verbong and Geels 2007, also chapter 4). Importantly, the EU-level energy policies dominate the national-level ones in all member states, as well as in the European Energy Community countries[12], by defining overarching targets, objectives and principles which the states must adopt, for example the EU renewables targets and the rules of the internal market. Thus, energy security priorities of the European Commission are likely to be priorities, or at least very important determinants, of the European national energy security policies as well.

Case 2: the United Kingdom

The energy system of the UK is based on gas (37% of gross domestic consumption), oil (36%) and coal (18%, Eurostat 2010). At present, the UK energy policy focuses mainly on its national systems for electricity and natural gas (which fuels 42% of its electricity generation). The UK has a long tradition of energy policy and related scholarly discourses. After the oil shock in the 1970s, the state strongly supported domestic coal and nuclear energy production. This strategy was reversed in the 1980s in particular in response to perceived inefficiencies and the electricity supply disruptions during the coal miners' strikes (Helm 2002; Kuzemko 2011). In the following decades, the UK introduced at home and vigorously pioneered abroad

[12] The Energy Community includes all countries defined as 'Europe' in this dissertation, except Switzerland. The Energy Community also includes Ukraine, Moldova, Georgia and Armenia, which are not a part of the geographical unit 'Europe' here, see section 7.4.

the idea that liberalised markets was the most effective way "*to ensure secure, diverse and sustainable supplies of energy at competitive prices*" (DTI 1998). However, as cheap and abundant domestic energy resources were rapidly depleted – in 2004, the UK went from being a net energy exporter to being an energy importer – and as the infrastructure showed signs of underinvestment and climate commitments appeared beyond reach, energy was "*re-politicised*" in the early 2000s (Kuzemko 2011:65). The overarching objective of UK energy policy is "*to ensure sustainable and reliable supplies of energy* [that] *benefit all UK consumers*" while simultaneously considering "*the social implications of our policy*" (DTI 2007:23).

The shift from energy exporter to importer has strongly shaped the British energy and energy security policy and has forced it to become one of the pioneers in energy security thinking with a highly influential and explicit energy security policy framework (Kuzemko 2011). Hence, I expect the UK energy security policy to cover the breadth of modern energy security concerns of a European country.

Case 3: Sweden

The Swedish energy system is characterised by a high reliance on electricity, due to a large electricity-intensive industry and the prevalence of electric heating: 35% of the final energy consumption in Sweden is electricity, compared to 21% in the EU (Eurostat 2010). This electricity is provided by mainly nuclear and hydropower (both 45% of generation) and is traded on the integrated Nordic (and, to a lesser extent, European) electricity market. The Swedish energy system is based on nuclear power (34% of gross domestic consumption), renewables (31%) and oil (28%). Natural gas does not play any significant role in the Swedish energy system, and it has no national gas system but only a small regional network along the west coast (Eurostat 2010; ND 2002).

A further characteristic of Swedish energy policy is the planned phase-out of nuclear power plants by 2010 as required by a 1980 referendum. Because of the unsuccessful phase-out – only 2 of 12 reactors were shut down – the end-date was scrapped in 1997 and the phase-out decision was revoked in 2009. A main aim of Swedish energy policy has been to close the capacity gap resulting from the planned phase-out to avoid capacity shortages and price spikes in the Nordic electricity system during winter. This capacity gap would be further aggravated by the electricity system imbalance between the north (where most hydroelectric generation is located) and the south (where the reactors stand and most electricity is consumed). Sweden has highly progressive energy policies and is in particular a pioneer in sustainability policy (e.g. Emerson *et al.* 2010). As such, Sweden is strongly committed to decarbonising its energy system: the planned phase-out of oil for transport and heating, a main focus of Swedish energy policy, is not mentioned as an energy security policy, despite the complete Swedish dependence on oil imports, but is seen exclusively as a climate protection programme (MD 2009; ND 1997, 2002, 2009).

The European Commission has very advanced energy policies and is the dominant 'thinker' in the European energy policy, whereas the UK and Sweden have highly progressive energy policies and are energy policy pioneers, especially in terms of energy security (UK) and energy sustainability policy (Sweden). By including not only the EU-level policies but also the two country cases, which represent two of the most advanced European jurisdictions in the energy field, I increase the *internal validity* of the definition. Given the progressive nature of energy policy in the three cases, I expect that the European Commission's policies and those of the country cases contain the newest and most developed facets of energy security. Hence, if there is a 'new concept of energy security' (see section 2.5), this broad view should be reflected in the policies of the three case studies. Conversely, if the policies of the most progressive jurisdictions have a very narrow view of energy security, this is a strong indication that energy security in Europe is indeed a narrow concept.

The case study choice also gives the definition *external validity*. A key hypothesis in this dissertation is that energy security is context-dependent, so that the view of energy security may be different in Europe as a whole and in the single countries, despite the dominance of European-level policy. The single country policies should be aligned with the EU's, at least in the competence areas of the Commission, but may differ in other aspects, reflecting specific differences in energy system structure, history, etc. By including not only the EU-level, but also the very different energy systems and energy policy approaches of Sweden and the UK, I expect to identify core energy security priorities that are similar across the cases, although the cases themselves are very different. The inclusion of Sweden, as a small European country that can be expected to have smaller policy capacity than large countries – and hence a more focused energy security policy – may be helpful to see which issues are really at the heart of the energy security concept in Europe. These case study choices thus increase the generalisability of the results, although one cannot be sure that the details of the results apply to all single European countries (see section 5.2 for further discussion on limitations).

3.4 Policy documents for the energy security definition

I base the analysis on data of specific energy security policy measures and aims for the period relevant for understanding the current energy security policy priorities. I gather this policy measure data from strategic energy and energy security policy documents and proposals. The focus on strategic documents is important: these describe and propose a broad range of measures covering the entire field of energy security concerns in each case, as opposed to directives and regulations, which generally focus on single issues. Further, the strategic documents place the security concerns in a wider energy policy context and give detailed descriptions of which problems the measures address, why the problems are important and of how the measures are to solve the problem. Hence, I expect to find clear answers to all three definition questions in these documents. I include the most recent as well as older energy security policy documents, to achieve a more robust base for identifying energy security priorities, both to increase the data available for analysis and to filter out the policy effects of single events, which enables me to identify the full breadth of European energy security priorities. This also decreases the time-sensitivity of the results as although policies change over time, I expect that the core logic of energy security policy does not change rapidly.

For the investigation of EU energy security policy measures and aims, I analyse the Green papers of 1995, 2000, 2006 and 2008 as well as the 2008 Second strategic energy review, the 2010 Communication Energy 2020 and the 2011 Energy roadmap (EC 1995, 2000, 2006, 2008a, b, 2010b, 2011d). For the UK, I include the White papers of 2003 and 2007, the Energy review of 2006, the 2009 Low carbon transition plan and its accompanying energy security discussion, the 2009 Wicks report (DECC 2009; DTI 2003, 2006, 2007; Wicks 2009). For the Swedish case, I investigate the policy documents accompanying the energy reforms of 1997, 2002 and 2009 (MD 2009; ND 1997, 2002, 2009).

4 Results: energy security definition in the European policy perspective

In this chapter, I present the results of the three case studies for the energy security definition in the European policy context (sections 4.1-4.3). I conclude the chapter with a synthesis section (4.4) of the case study results and give the answers to the three energy security definition questions asked in section 3.2.

4.1 The European Commission

In the energy security policy documents of the European Commission, I identified 17 distinct measures with 42 stated aims, of which many appear more than once. I classify these measures into five groups as described below. The measures are summarised in Table 1.

The measures in the first group focus on securing uninterrupted access to external energy resources. The Commission sees a common European foreign energy policy, giving Europe "*a single voice*" on the global markets (EC 2006:20), as particularly important. This would allow Europe to "*throw its combined market weight effectively in relationships with key third-country energy partners*" and "*use its political and economic influence to ensure flexible and reliable external supply conditions*", thus securing long-term access to diversified foreign resources and reducing the risk of import interruptions (EC 2010b:17; 2000:73). Often, such measures are justified by "*recent experience*" (EC 2006:8), referring to several interruptions of oil and gas imports from Russia, which have "*acted as a wake-up call* [by] *exposing Europe's vulnerability*" (EC 2010b:3; EC 2008b). This competitive view is complemented by a cooperative view, aiming to stabilise the energy imports by fostering "*good governance,* *respect for the rule of law and protection of EU and foreign investments*" throughout the energy chain (EC 2010b:18; 2000). By doing this, the European Commission aims to increase the stability of imports by building "*trust* […] *and legally binding ties between the EU and producer and transit countries*" (EC 2008b:7).

The second group contains measures to reduce external supply risks by increasing the share of domestic energy. The European Commission does not have a mandate for the energy mix or import sources and had no energy policy mandate at all before the Lisbon Treaty. Instead, it aims to increase the reliance on domestic resources through the environment mandate and proposes European targets for low-carbon energy. In addition, the European Commission proposes measures to support new technologies to access the European domestic "*secure and low-carbon energy sources*" and to diversify the fuel mix (EC 2006:9; 1995; 2000). In particular, these technologies are renewable energies – "*the most promising* [sources] *in terms of diversification of supplies*" (EC 2000:46) – carbon capture and storage (CCS), and new nuclear reactor generations (EC 2000, 2008b).

The third group of measures focuses on strengthening the response capacity should energy supply shocks occur, caused by for example "*strike, a geopolitical crisis or a natural disaster*", or by the "*terrorist threat*" (EC 2000:64; EC 2006:8). These mechanisms are focused on ensuring both effective national responses (e.g. emergency stocks) and fast reallocation of energy supplies – "*solidarity*" – between the member states in case of emergencies. The EU policy in this area encompasses both institutional and infrastructural response mechanisms which are "*essential to spread and reduce individual risk*", including measures to identify and protect European critical infrastructures against failures and attacks (EC 2008b:4; 2006, also European Council 2008). The EU therefore focuses much of its energy security efforts on removing intra-European transmission bottlenecks by strengthening the interconnectivity in the European electricity and gas systems to enable solidarity between member states during emergencies. In particular, much of the EU energy security policy focuses on the security of its most vulnerable member states in Central and Eastern Europe as well as the Baltic countries, which rely strongly on imports of Russian gas and some of them depend on Russia for their oil supplies and electricity backup capacity. System and market integration across all EU countries, but especially between Eastern and Western member states, is a dominant theme in the European energy security policies, as transmission bottlenecks and fragmentation of the European energy systems "*undermine*[s] *security of supply*" so that "*the obligation of solidarity among Member States will be null and void without a sufficient internal infrastructure and interconnectors*" (EC 2010b:4, 10).

The fourth group consists of measures to increase energy efficiency with the objective to constrain the growth of energy demand. The European Commission views improving energy efficiency as "*the most cost-effective way to* […] *improve energy security*" (EC 2010b:6). These measures include stricter standards and energy labelling of products, both within Europe and internationally, and increased CO_2 and energy consumption taxes designed "*to promote energy efficiency* [by setting incentives to] *encourage behavioural changes or to fund investments*" (EC 2008b; 2010:6). This group also contains measures for the targeted use of the cohesion funds to improve energy efficiency in Eastern European buildings, and support for modern transport solutions (EC 2010b).

The fifth group of measures aims to improve the EU natural gas and electricity markets, in order to support several energy security objectives. First, "*a functioning internal market on the basis of sufficient transmission and storage infrastructure*" is "*in itself an instrument of security of supply*", in particular because it facilitates the integration of vulnerable member states in the common European energy system (EC 2010b:13; 1995:22). A common market is even "*the best guarantee for security of supply, as energy will follow market mechanisms and flow to where it is needed*" (EC 2010b:13). Further, the Commission argues that a functioning and competitive internal market is necessary for supporting energy security by ensuring stable and competitive, or "*affordable, but cost-reflective*" prices, which send "*the right investment signals*", thus ensuring the timely replacement of ageing assets (EC 2010b:13; EC 2006:8). Unbiased prices are furthermore expected to incentivise a reduction of the overall energy demand. A functioning market also leads to competition, which in turn leads to diversification as each actor tries to spread its risks and consequently the reduction of market power of any single domestic or foreign agent (EC 2000).

Table 1: Energy security policy measures of the European Commission and their stated aims.

Measure	Stated energy security aims
I. Securing access to external energy resources	
Create single European external energy policy	Access foreign resources Add weight in negotiations with supplier & transit countries Supplier & transit route diversification Early warning and contingency preparation Stabilise imports
Improve dialogue/cooperation with suppliers & transit countries	Access foreign resources Trigger investment in upstream/transit capacities through competitive external market Stabilise imports Predictable prices, minimise price volatility on global markets Good governance and rule of law throughout the energy chain Supplier & transit route diversification
New oil and gas import infrastructure and new LNG capacities	Access foreign resources Supplier & transit route diversification Fuel diversification Stabilise imports

Measure	Stated energy security aims
II. Increasing the share of domestic energy	
Increase use of domestic (low-carbon) resources	Reduce import dependency Access domestic resources Fuel diversification
Support for development, introduction of new energy technologies	Access domestic resources Fuel diversification
Support for introduction of non-oil fuels for vehicles	Reduce consumption (oil)
III. Improving interconnectivity and supply shock response capacity	
Improve internal infrastructure and intra-European interconnection	Enable solidarity among member states, enable energy flow to adapt to new situations and crises Supplier & transit route diversification Fuel diversification
Increase storages	Improve emergency response capability, maintain supply during crises Reduce price swings during emergencies and short-term shortages
Solidarity between Member States	Improve emergency response capability, maintain supply during crises
Improve physical infrastructure protection	Increase/maintain reliability in existing assets
IV. Improving energy efficiency	
Improve efficiency/emission standards (in Europe and globally) and energy labeling	Reduce consumption (energy) Reduce consumption (fossil fuels) Reduce import dependency (fossil fuels) Decouple economic growth and energy consumption (all energy)
Improve energy and CO_2 taxes	Trigger investment in energy-efficient technologies Reduce consumption (energy)
Use of cohesion funds for efficiency in buildings in new Member States	Reduce consumption (heating, electricity)
Improve energy efficiency in the public sector	Provide energy-efficient example for rest of society, create demand for efficient products/technologies Reduce consumption (energy)
Increase use of CHP	Reduce consumption (natural gas, biomass)
Reform transport policy, multimodal transport and pan-European railways	Reduce consumption (oil)

Measure	Stated energy security aims
V. Improving the internal EU markets for gas and electricity	
Improve functioning and competition, complete internal market	Efficient allocation of energy resources, also during crises Trigger investment in production and infrastructure Reduce consumption (energy), through "true" prices Supplier diversification Fuel diversification

Sources: EC 1995, 2000, 2006, 2008a, b, 2010b.

4.2 The United Kingdom

I identified 31 separate measures of the UK energy security policy with 67 corresponding aims (of which some appear more than once). I cluster these into five groups, as described below and summarised in Table 2. The overall aim of British energy security policy is to create "*a resilient energy system, without significant weaknesses* […] *based on a mix of fuel types, a variety of supply routes, efficient international markets* […] *storage, and a robust infrastructure* […] *which recovers quickly if problems occur*" (DTI 2003:76, Wicks 2009). This concerns "*avoiding involuntary interruptions of supply*" (Wicks 2009:8), thus avoiding "*unexpectedly high or volatile prices*" (DTI 2007:106) or ensuring "*predictable prices*" (DTI 2003:76).

The first group includes measures to access foreign resources while minimising the threats associated with energy imports. To ensure sufficient and reliable energy imports the UK must "*first of all to be an attractive customer for* […] *suppliers*" (Wicks 2009:97). For this, the UK must improve its bilateral relations with supplier countries, especially Norway, Qatar and Saudi Arabia, enter into a dialogue to "*promote good governance among producer countries*" (DTI 2007:38) and throughout the energy chain, as well as support "*political and economic stability in source and transit regions*" (DTI 2006:82; Wicks 2009). Particular emphasis lies on the improvement of the European gas import infrastructure "*to bring diverse supplies on-*

stream and into the EU market" (DTI 2003:80). New and diverse supplies are important in order to minimise the threat of supply interruptions in the entire European, including the British, energy system and to ensure that the UK can "*retain independence in its foreign policy through avoiding dependence on particular nations*" (DTI 2003:80; Wicks 2009:8). In addition, targeted measures to support the deployment of renewables in developing countries are proposed to reduce the strain on the global fossil fuel markets, which in turn would reduce the British supply risks (DTI 2003, 2007).

The second group includes measures aiming to reduce import risks by substituting imports with domestic energy resources. In the short term, the maximisation of the recovery of remaining domestic fossil fuels is a "*crucial element in mitigating the risks involved in our continuing use of oil and gas*" (Wicks 2009:112). In the longer term, expansion of nuclear power and renewables are important measures, as is the development of coal with CCS in a European context. Non-financial issues, especially planning and permitting reforms and the improvement of the European Emissions Trading Scheme (ETS) are key concerns. The Wicks report also suggests to take a more strategic role in "*determining the fuel mix*", which is a step away from the liberalisation paradigm, but "*might be justified on energy security grounds*" (Wicks 2009:111f).

The third group includes measures aiming to increase the capacity to respond to supply shocks, caused by, for example, "*terrorism, accident and natural disaster* […] *international dispute*" or strike in a producing country (DTI 2007:33; DTI 2006). Domestically, these measures include promoting investments in infrastructure upgrades, and increasing the oil and gas storage capacity, both commercial (DTI 2003, 2006, 2007) and strategic (Wicks 2009). Measures to improve the physical interconnection between UK and Europe, as well as encouragement for European countries to increase the interconnections within continental

Europe are seen as crucial to enable mutual assistance between countries in case of disturbances (DTI 2007; Wicks 2009). Demand-response mechanisms to make demand more flexible using price signals are also proposed. In addition to this, the UK energy security policy aims to encourage other countries, especially other EU countries, China and India, to increase their oil and gas emergency stocks, in order to reduce price swings – which also affect the UK – on the global markets during turbulent times (DTI 2003, 2006, 2007; Wicks 2009).

The fourth group includes measures to increase the resilience of both the UK energy system and the related international markets by constraining demand. For this, "*action to improve energy efficiency should be the greatest priority both domestically and in the Government's relations with other states*" (Wicks 2009:82). Many of these measures, such as efficiency standards for appliances and transport, are advocated at the European level, given the EU internal market. Other measures, such as home insulation programmes, are carried out domestically (DECC 2009; DTI 2007). Supporting transition countries – explicitly China, India, Ukraine and Russia – to increase their energy efficiency would "*do a great deal to support EU energy security*", as it would help to reduce the strain on the international fossil fuel markets (Wicks 2009:100).

The fifth group includes measures that promote energy markets both within and outside the UK. In this, "*a market framework with the right regulatory framework* […] *incentivise*[s] *suppliers to achieve reliability*" (DTI 2003:77, 87), because it triggers adequate investments and thus increases energy security. It further helps to "*achieve diversity, as companies themselves seek diversity in order to manage risks*" (DTI 2006:19). Therefore, the UK also supports "*the completion of the EU energy market liberalisation*" (DTI 2007:108; Wicks 2009). The continued liberalisation and improvement of global oil and gas markets are equally encouraged by the UK. This international focus is important as, given the depletion of domestic UK resources, liberalisation and opening of the international energy markets addresses the many "*risks* [which] *are outside our immediate control*" (DTI 2007:108), ensures British access to global resources and allows "*us to purchase what we need at any time*" (DTI, 2003:79).

Table 2: Energy security policy measures of the United Kingdom and their stated aims.

Measure	Stated energy security aims
I. Securing access to external energy resources	
Increase import capacities (especially LNG)	Replace diminishing domestic gas production Access foreign resources Supplier & transit route diversification through flexible access to diverse gas supplies Predictable prices (gas), minimise price volatility
Bilateral relations and treaties with energy producing countries	Access foreign resources Supplier & transit route diversification (gas) Predictable prices, minimise price volatility on global markets
Improve dialogue/cooperation with producer/consumer countries	Stabilise imports Predictable prices, minimise price volatility on global markets
Support development of renewables and infrastructure in developing countries	Reduce pressure on global energy markets, by improving energy access in developing world without increasing fossil energy consumption
Development of better investment and transit regimes with potential suppliers and transit countries	Access foreign resources Trigger investment in upstream capacities by improving investment climate Stabilise imports Predictable prices, minimise price volatility on global markets Enable investments that are economically feasible by removal of bureaucratic barriers (upstream)
Promote regional stability and economic reform in producing countries	Stabilise imports Good governance throughout the energy chain

Measure	Stated energy security aims
II. Increasing the share of domestic energy	
Improve planning and permitting systems	Enable investments that are economically feasible
Improve the ETS	Trigger investments in low-carbon energy through increased certainty
Strategic approach to determining the electricity mix	Fuel diversification (avoid market-induced dash for gas)
Maximise recovery of domestic oil/gas in the North Sea	Reduce import dependency Access domestic resources
Improve support schemes to increase share of renewable energy	Access domestic resources Reduce consumption (fossil fuels) Reduce import dependency Fuel diversification
Support the development of CCS for electricity	Access domestic resources Reduce import dependency Fuel diversification
Maintain access to domestic coal mines	Access domestic resources
Nuclear power expansion	Reduce consumption (fossil fuels) Reduce import dependency (fossil fuels) Fuel diversification in electricity mix
Introduction of alternative fuels in transport sector	Reduce import dependency (oil)
III. Improving interconnectivity and supply shock response capacity	
Improve regulatory incentives for energy security in domestic infrastructure	Trigger investments in infrastructure to increase reliability Increase/maintain reliability in existing assets Supplier & transit route diversity through additional incentives
Improve intra-European interconnections	Enable solidarity among European countries, enable energy flow to adapt to new situations and crises Supplier & transit route diversification (in both UK and EU energy systems)
Support European diversification of suppliers and import routes	Access foreign resources Supplier & transit route diversification (in both UK and EU energy systems)
Increase gas storage capacity	Improve emergency response capability, maintain supply during crises Smooth fluctuations in domestic supply
Introduce strategic storage	Improve emergency response capability, maintain supply during crises (if commercial storage growth is insufficient)

Measure	Stated energy security aims
Encourage storages in non-IEA countries	Reduce price swings during emergencies, threat situations and short-term shortages
Improve demand-response capability	Reduce vulnerability to demand peaks, by shifting demand away from peak times
IV. Improving energy efficiency	
Improve efficiency/emission standards in EU	Reduce consumption (energy) in UK and EU Decouple economic growth and energy consumption
Change transport behaviour (eco-driving, public transport)	Reduce import dependency (oil)
Home insulation and other efficiency programmes	Reduce consumption (energy) Reduce import dependency
Improve energy efficiency in the public sector (esp. buildings, transport)	Provide energy-efficient example for rest of society, create demand for efficient products/technologies Reduce consumption (energy)
Support for energy efficiency in other countries (esp. fossil-fuel producing countries)	Reduce pressure on global energy markets, by reducing fossil energy consumption in exporter and developing countries
V. Improving the UK, European and global markets for gas, electricity and oil	
Improve functioning and competitiveness of domestic markets	Trigger investments in production/generation Trigger investments in flexible generation to support intermittent renewables Efficient allocation of energy resources, also during crises Supplier & transit route diversification Fuel diversification Reduce vulnerability to demand peaks, through economic incentives for demand-response
Push for liberalisation of European markets	Trigger investments by removing anti-competitive behaviour Enable solidarity, by introducing common market regulations
Encourage development of international liberalised markets	Access foreign resources Trigger investment in upstream capacities Predictable prices, minimise price volatility
Improved market data, transparency and projections, market monitoring	Trigger investments by reducing investment risks Early warning and contingency preparation

Sources: DECC 2009; DTI 2003, 2006, 2007; Wicks 2009.

4.3 Sweden

I identified 19 measures with 45 stated aims (of which many appear more than once) in the Swedish energy security policy documents. I cluster these into four groups, as described below and summarised in Table 3. The groups are similar to the European Commission and UK cases, but Sweden does not specifically address external supply risks.

The first group aims to increase the generation of heat and electricity from non-nuclear sources, especially addressing the looming capacity gap due to the nuclear phase-out. The core of these measures are incentives for renewable energy generation, including simplified grid access and planning procedures (ND 2002, 2009). They also include tax reforms to support generation investments and increased energy efficiency (see below). This approach relies on the abundance of domestic renewable energy resources, which can assure that Sweden remains "*essentially self-sufficient in electricity*"[13]. Renewables can therefore "*continuously guarantee the long-term security of supply*", while this would at the same time diversify the energy mix and "*reduce the dependence on nuclear and hydro power*" (ND 2002:18; 2009:11f). A special focus lies on stimulating investments in biomass-fuelled combined heat and power (CHP) stations and district heating (MD 2009; ND 1997, 2002, 2009). The conservative government revoked the nuclear phase-out decision in 2009 to allow for "*a gradual replacement of the existing reactors when these reach the end of their economic life*", both on grounds of climate protection and energy security (ND 2009:34). For the longer-term perspective, measures supporting the development of new energy technologies, especially biofuels and biomass CHP, are proposed in cooperation with the Baltic countries and the EU (ND 1997, 2009).

[13] All quotations in the section about Sweden are translated from Swedish by the author.

The second group contains measures to strengthen the responses to supply shocks, mainly in the electricity system. A strong focus is domestic infrastructure reinforcements, especially north-south transmission capacity, in order to remove bottlenecks and maintain electricity system balance in Southern Sweden after the decommissioning of 2 nuclear reactors there. The continued integration of the Nordic electricity grids is a second focus. The importance of the Nordic electricity system for the Swedish energy security "*cannot be overstated*" (ND 1997:12), as "*imports from abroad can contribute to smoothing fluctuations in the domestic production* […] *both during normal and strained operations*" (ND 2009:27). Other expected energy security gains from improved interconnection are less volatile prices, shared reserve capacities and reduced investment needs (ND 1997, 2002, 2009). Further, new regulations for strategic oil storage and reduced war-time storages for coal are proposed in order to make these economically more efficient (ND 1997, 2002, 2009).

The third group includes energy efficiency measures, mainly for electricity end-use and heating to maintain the electricity system balance following the nuclear phase-out. General measures, in particular increased energy and CO_2 taxes, are implemented to direct and "*support the spontaneous increase in energy efficiency that is happening in the society*" (ND 2009:39), and are flanked by direct support programmes for energy-efficient technologies (ND 2002, 2009). Other measures include information and education campaigns, as "*lack of information is one of many reasons why market actors sometimes make energy inefficient investments*" (ND 2002:108). Throughout the process, "*the public sector must provide a positive example in the energy efficiency work*" (ND 2009:84).

The fourth group aims at improving the functioning of markets, primarily the Nordic electricity market. The view is that "*the proper functioning of the energy markets is of fundamental importance for a secure energy supply*" (ND 1997:17), as these provide certainty for new investment and an efficient resource allocation, also during crises. In this, a "*prerequisite*" for a secure energy supply is "*long-term rules and stable conditions*" for energy companies, to prevent "*insecurity and failed investments*" (MD 2009:11). In particular, the policy aims to improve the competition on the Nordic market by infrastructure expansions (see above), effectively fusing the Nordic system areas together and diluting market power of potentially monopolistic actors (ND 1997, 2002, 2009).

Table 3: Energy security policy measures of Sweden and their stated aims.

Measure	Stated energy security aims
I. Increasing efficiency in using electricity and heat	
Market introduction support for energy efficient products	Decouple economic growth and energy consumption Reduce consumption (energy) Maintain electricity system balance
Energy efficiency education/info campaigns	Decouple economic growth and energy consumption Reduce consumption (energy) Maintain electricity system balance
Improve energy efficiency in the public sector	Provide energy-efficient example for rest of society, create demand for efficient products/technologies Reduce consumption (energy)
Reduce electricity use in district heating systems	Reduce consumption (electricity) Maintain electricity system balance
II. Developing domestic resources for electricity and heat generation	
Energy and CO_2 tax reforms	Trigger investments in renewables/low-carbon energy Reduce consumption (energy), through 'true' prices
Improve support schemes to increase share of renewable electricity	Maintain electricity system balance Access domestic resources Reduce import dependency Fuel diversification
Maintain number of nuclear reactors	Maintain electricity system balance, by replacing existing reactors as these reach end of economic life Fuel diversification

Measure	Stated energy security aims
Tax reform for biomass CHP	Trigger investments in biomass CHP Increase heat availability for district heating Maintain electricity system balance by maintaining economic attractiveness for existing facilities Fuel diversification
Adopt IPCC/EU accounting regulations regarding peat	Access domestic resources Trigger investments in peat-burning generation/heat Fuel diversification
Improve planning and permitting systems	Enable investments that are economically feasible
Support for technology development	Fuel diversification Access domestic resources Maintain electricity system balance
III. Improving infrastructure and supply shock response capacity	
Improve the domestic transmission grid	Increase/maintain reliability in existing assets Trigger investments through functioning electricity market Maintain electricity system balance in Southern Sweden after shutdown of nuclear power
Improve electricity interconnections	Enable solidarity among Nordic countries, enable energy flow to adapt to new situations and crises Smooth fluctuations in domestic electricity supply Improve emergency response capability, maintain supply during crises Trigger investments through functioning electricity market
Introduce common Nordic electricity capacity shortage regulations	Improve emergency response capability, maintain supply during crises
Expand demand-response capacities	Reduce vulnerability to demand peaks, by shifting demand away from peak times
Improve oil and other storage regulations	Improve emergency response capability, maintain supply during crises
Energy rationing	Ensure vital function remain operational during war or extreme crisis
Tender for back-up power	Maintain electricity system balance during cold winters
IV. Improving the Nordic electricity market	
Improve functioning and competition in domestic and Nordic markets	Trigger investments Fuel diversification Supplier diversification Efficient allocation of energy resources, also during crises

Sources: MD 2009; ND 1997, 2002, 2009.

4.4 *Synthesis*

In this section, I present the answers to the three definition questions – what to protect, from which vulnerabilities, by which means? – for the three case studies.

4.4.1 What to protect?

The energy security policies of the European Commission, the UK, and Sweden focus on the vital energy systems for the supply and demand of electricity and gas, including the provision of electricity and heating to especially the residential and commercial sectors. Hence, despite their different energy system structures, policy foci and policy capacities, they focus their energy security policy on similar vital energy systems, but the focus differs on some points (see Table 4). With respect to their geographical boundaries, four levels are addressed. Only the Swedish energy security policy explicitly addresses the sub-national level. The national level is particularly important for the UK and Sweden, but also for the supranational European Union. The European Commission focuses on increasing the security of the energy systems of its individual member states, especially the more vulnerable Central and Eastern European countries, by integrating them with each other and the rest of Europe. The regional electricity system (the European and Nordic systems) is a primary focus of all three jurisdictions, whereas the regional and, to a lesser extent, global gas system is important for the European Commission and the UK, but not for Sweden, which consumes almost no gas.

Table 4: Vital energy systems in focus of the energy security policy of the European Commission (EC), the United Kingdom (UK) and Sweden (SE).

	End-uses: electricity & heating in commercial/residential and industrial sectors	Energy carriers: electricity	Primary energy sources: natural gas
Sub-national	SE	SE	
National	EC, UK, SE	EC, UK, SE	EC, UK
Regional		EC, UK, SE	EC, UK
Global			EC, UK

These similar but distinct foci can be explained by the diverging supply and demand structures – Sweden uses almost no gas, whereas gas is increasingly important and increasingly imported in the UK and the EU as a whole – and also by recent experiences of interruptions and the fear of these repeating themselves. Oil security is not a strong focus in any of the three energy security policies, but the end-use transport sector – which depends mainly on oil products – appears as a minor issue on some occasions, in particular through increased use of non-oil fuels and efficiency measures to reduce oil demand. Perhaps remarkably, Sweden justifies its decision to phase out oil exclusively on climate rather than on energy security grounds. This can possibly be explained by the fact that Sweden imports essentially all its oil from Denmark and Norway, which are considered trusted suppliers.

4.4.2 From which vulnerabilities?

The three cases address both short-term shocks and long-term stresses. The potential shocks include gas import interruptions and energy coercion (European Commission, UK), and the threat of supply outages following infrastructure failures. The stresses emerge over long timescales, typically decades, and include underinvestment and aging of infrastructure.

Shocks and stresses are perceived as intertwined so that a stressed system (e.g. with aging infrastructure) has a higher risk of experiencing shocks (e.g. blackouts).

European energy security policies address **disruptions** of both physical (i.e. supply interruptions) and economic nature. The physical component refers to both the overall availability to sufficient amounts of gas and electricity and its reliable distribution to the final customers. The economic component refers to the stability and predictability of prices, as reflected by the aim of improving markets abroad and globally, in order to trigger sufficient and diverse investments. These measures also seek to ensure that prices are unbiased and cost-based so that no other regions/countries have the non-market advantages of accessing much cheaper energy than Europe. The price level as such is not a focus in the any of the three cases, as reflected by the presence of numerous energy security measures that indeed increase the price. Other ‘new dimensions’, like social or environmental issues, could not be identified as integral parts of energy security policy (for a discussion of both these points, see section 5.1).

The **threats** in focus in European energy security policy are not very numerous: only 7 types could be identified, and some of these are closely related. For example, the stress of aging infrastructure could decrease its reliability and increase the frequency and duration of outages. Here, I cluster these threats into three groups, based on the classification of Cherp and Jewell (2011b), see Table 5.

Table 5: Threats addressed by energy security policies of the European Commission (EC), the United Kingdom (UK) and Sweden (SE), sorted according to speed and perspective.

Speed of threat	Geopolitical threats (sovereignty perspective)	Roughly foreseeable natural and technical threats (robustness perspective)	Unpredictable events (resilience perspective)
Short-term (shocks)	Coercion and power asymmetry in energy trade (UK, EC)	Failures of infrastructure	Terrorism, strikes, unrest (EC, UK), war (SE)
Long-term (stresses)	Intentional cut-offs (UK, EC)	Depletion of domestic and global resources; growing global demand for energy (EC. UK)	
		Aging infrastructure, underinvestment	
		Nuclear phase-out (SE)	

The first group includes geopolitical threats that cannot be predicted, at least not a long time in advance, but can be handled by foreign policy and estimated on the base of prevailing interests and balances of power. These threats are related to access to foreign resources, intentional cut-offs of gas imports and, in particular, coercion by exporter or transit states. The term 'coercion' refers to the threat that exporters cut, or threaten to cut, exports in order to put Europe under pressure and force it to accept some political or economic demand (see section 7.1.1). Almost all justifications of such geopolitical energy security-enhancing policies refer to the past disturbances of Russian gas supplies to Europe and the suspicion that Russia may use its gas exports as an 'energy weapon' to coerce Europe, or that the dependence on Russia may constrain the foreign policy manoeuvring space. Import disturbances and foreign energy relations are not a priority in Sweden, which imports very little gas, and all of it from other Scandinavian countries.

The second group of energy security threats includes natural and technical threats, which can be roughly probabilistically predicted and mitigated. Three threats stand out: (a) reliability problems and capacity gaps caused by underinvestment and aging of infrastructure (exacerbated by the nuclear phase-out in Sweden), (b) extreme natural events which may cause failures in the energy infrastructure, and (c) depletion (e.g. in the UK/North Sea) and increasing geographic concentration of remaining fossil energy resources.

The third group includes diverse threats that are not necessarily linked to intentional actions but cannot be predicted with any precision. In particular, this group includes unpredictable but potentially disruptive social events, such as terrorist attacks.

Hence, European policy is holistic in the sense that it addresses threats from all three perspectives of energy security.

4.4.3 By which means?

The observed energy security measures are consistent across the three cases and fall within three categories, see Table 6. Specific threats are addressed by measures belonging to at least one of these categories, but many threats are dealt with by measures from two or all three groups in combination. These results show that the preferred way to deal with energy security threats is a combination of measures to reduce the threat exposure and to increase the systems' resilience to minimise the impacts of a threat, should it materialise.

The measures in the first category target aim to minimise the exposure to specific threats. For example, the development of domestic energy sources and establishing 'trusted' relations with external suppliers reduces the threats of coercion and other import disturbances (see groups I and II for the UK and the EU and group II for Sweden in Table 1-Table 3).

The measures in the second category aim to minimise the impacts of events by increasing the system resilience and the capacity to respond to supply shocks, should these occur. These measures include infrastructure upgrades, building up fuel storages and other emergency response mechanisms. This category also includes measures to further strengthen the integration of the European energy systems to increase the resilience of the most vulnerable regions, like the Central and Eastern European member states in the EU and Southern Sweden (see group III in Table 1-Table 3).

The measures in the third category focus on strengthening generic protection against all sorts of threats. These measures include energy efficiency, which leads to a reduction of demand, thus easing all physical security burdens and insulating the economy against price fluctuations. They also include the promotion of markets, both at home and abroad. In all three cases, policy-makers see markets as a mechanism to reallocate energy resources during disturbances, ensure competitive and stable prices and a healthy diversity of actors, energy sources and technologies, attract well-targeted investments and increase energy efficiency by sending unbiased price signals. Finally, diversification of fuels and suppliers is viewed as a tool to reduce the vulnerability to single events, regardless of the cause (see groups IV and V in Table 1 and Table 2, and I and IV in Table 3).

Table 6: Categories of energy security policy measures of the European Commission (EC), the United Kingdom (UK) and Sweden (SE)

Minimisation of import risks	Increase shock-response capacity	Generic protection mechanisms
Expand use of domestic resources	Improve infrastructure and interconnections	Improve domestic, regional and global (esp. UK) markets
Manage relationships with suppliers (UK, EC)	Increase/introduce strategic storage of natural gas (EC, UK)	Increase energy efficiency
	Emergency preparedness mechanisms	Diversification of suppliers, fuels

5 Discussion: energy security in the European policy perspective

5.1 Empirical findings

The energy security definition results show that energy security in a European policy perspective is not an all-encompassing but a well-delimited concept, consisting of a limited number of issues. European energy security policy focuses on 2 distinct vital energy supply systems (plus a cross-cutting focus on end-uses), and 7 threats potentially leading to two types of disruptions, see Table 7.

Table 7: Summary of the identified vital energy systems, threats and disruptions in focus of European energy security policy.

Vital energy systems	Threats	Disruptions
Subnational, national, European/ regional electricity systems	Coercion, embargoes and power asymmetry	Supply interruptions
National, European, international gas systems	Intentional cut-offs	Market distortions, price volatility
Electricity and heat end-uses	Infrastructure failure	
	Terrorism, etc.	
	Underinvestment, aging infrastructure	
	Resource depletion, growing global demand	
	Nuclear phase-out	

The **vital energy systems** in focus of European energy security policy are the gas and electricity supply and demand systems in the national as well as regional Nordic and European perspectives. For gas, also international level considerations are present, whereas there is a focus on subnational electricity supply in Sweden. This is different from some energy security definitions in the literature focusing on oil (e.g. Bielecki 2002; Yergin 1988, 2006). In fact, oil is not at all a focus in the current European energy security policy. The identified system boundaries are also much narrower than in 'new dimensions' literature, which focuses on all energy systems at all levels, from the individual to the global level (e.g. Sovacool and Mukherjee 2011). They are also different, as they are wider, than the boundaries of conceptualisations focusing on the national level (e.g. Yoshizawa *et al.* 2009). Although the national level is indeed a priority in Europe, the creation of the internal market and the perceived (and demonstrated) vulnerability of single Eastern European countries have regionalised European energy. The boundaries of European energy security policy have thus been extended from the national borders to the Union border and, when energy is traded internationally, also beyond.

Concerning **threats**, European energy security policy focuses on both short-term shocks and long-term stresses. Within these two categories, only a small number of threat-types could be identified as core policy concerns. These are coercion, embargoes and power asymmetries in international energy trade; gas import interruptions; emerging gaps in generation capacity (due to underinvestment, aging of components or nuclear phase-out); threatened access to global fossil resources; infrastructure failures caused by various events; and price fluctuations and market distortions. This set of threats is much more focused than suggested by especially the 'new dimensions' literature, excluding issues such as social acceptance, job creation, patents, greenhouse gas emissions and water usage (e.g. Sovacool and Mukherjee 2011; Sovacool *et al.* 2011). European energy security policy does not view such issues as sufficiently serious and immediate threats of disruption of vital energy systems to justify policy action under the label of energy security. Instead, such issues are the focus of other policy fields, such as climate and environmental protection or industrial policy, only indirectly affecting energy security policy (see also section 5.2).

The **disruptions** European energy security policy aims to avoid are also well-defined, but the findings here are not only narrower than the literature suggests, they also partially contradict it. First, European energy security policy refers to physical supply disruptions, such as blackouts. This confirms the prevailing view in the literature: energy security is first of all about accessing enough energy and reliably distributing it to the final consumer.

Second, I could also identify a distinct economic disruption component of European energy security policy, referring to unbiased and predictable energy prices. At a first glance this is similar to the academic discussion of 'affordability' (or 'reasonable', 'acceptable' prices, etc.) of energy as a component of energy security. However, a closer look shows that the interpretation of 'affordability' in energy security policies is often the opposite of 'low' prices and does not consider energy poverty. Some energy security policy measures (e.g. the introduction of new electricity generation technologies) indirectly, and perhaps involuntarily, increase prices, at least in the short-term. Other measures (e.g. increased energy taxes) indeed aim to increase energy prices. Instead, the stability of prices, rather than merely 'high', energy prices, is an energy security concern in all three cases, as reflected by the very strong focus on improving the functioning of markets and removing market power and biases. The main reason is that erratic price fluctuations can destabilise the European economy, as can prices that are substantially higher in Europe than in other regions of the world. In all three cases, policy sees competitive, well-functioning and open markets (from national to global markets) as the best way to achieve this and avoid distorted and volatile prices. In addition, unpredictable prices may lead to failed investments, which, in turn, can lead to underinvestment, aging infrastructure and various supply problems associated with that. This supports the view of Keppler, but rejects the view that high prices are an energy security problem. Energy security definitions such as "*uninterrupted physical availability of energy* *products on the market, at a price which is affordable for all customers"* (EC 2000:2) sometimes presented in the policy documents therefore turn out to be mainly rhetorical figures. The 'affordability' of energy as a component of energy security does not concern whether it is actually affordable to all, and energy poverty and similar concepts referring to the 'social dimension' of energy security are not an integral part of European energy security. Therefore, energy security and energy poverty are related issues, as they affect the same energy systems, but they are clearly distinct policy areas.

Similarly, I could not identify an 'environmental dimension' of energy security, quite in contrast to what some of the recent academic literature suggests (see section 2.3). None of the identified energy security policies aims to address environmental threats, so that energy security and environmental protection are, at least in the three cases here, clearly distinct concepts. Nevertheless, there is considerable interaction between energy security policy and environmental, especially climate, protection policies, since they affect the same energy systems. I identified two main types of such interactions. First, the planned energy system decarbonisation forms a constraint to energy security policies. This constraint, for example, prevents using domestic coal without CCS as an energy security solution. Second, some energy security and climate protection measures are identical or synergistic, such as the development of domestic renewable resources, expanding/maintaining the nuclear capacity, or increasing energy efficiency. These overlaps present opportunities for political manoeuvring, and make it politically expedient to package and justify these measures together using the rhetoric of multiple benefits of "*sustainable and secure*" energy (EC 2008b:17). This rhetorical fluidity and thematic overlap of energy security and climate protection can be observed in all three cases. For example, the energy policy in the UK shifted during the 2000s from being primarily justified as climate protection to being justified primarily on energy security grounds, although most measures remained more or less identical (see also Kuzemko 2011). Similarly, the European Commission – which before 2009 had no energy policy mandate – shaped European energy and energy security policy indirectly through its environmental mandate. The Swedish case further highlights this fluidity: measures which would in many other countries most certainly be seen as energy security policy – prominently the phase-out of oil – are here seen only as a climate protection measure, possibly for the simple reason that Swedes traditionally care about the environment but not nearly as much about energy security.

5.2 Epistemological and methodological findings and limitations

From an epistemological and methodological perspective, the approach to defining energy security I developed and applied here is different from those used in the literature, and offers three main benefits. First, structuring the analysis around vital energy systems necessary for the functioning of critical societal structures places the focus of the assessment on the entire energy chain, from production via infrastructure to final consumption. This emphasises that not the systems as such need to be protected, but rather the functions they support and indicates that the resilience of vital energy systems is a key aspect when assessing energy security. By identifying which vital energy system are in focus of policy in a particular case, boundaries (especially geographical and sectoral) are almost automatically introduced, while systems policy is not concerned about are excluded from the definition. Existing approaches in literature do not have a filter to explain which energy systems are foci of energy security in a particular context and which are not. My method, in contrast, offers a tool to identify which energy systems policy views as most important in a particular context and to define their boundaries, making the definition more manageable and policy-relevant.

Second, the new approach is based on empirically observed policy concerns. This offers a new way to narrow the energy security definition down to the core concerns, while filtering out issues of secondary importance as well as issues that are, in fact, not a part of energy security but of some other, related policy area. The focus on concrete measures, as opposed to policy rhetoric is important: talk is cheap, but the issues worthy of actual allocation of scarce funds are likely to be the most pressing ones. It also contextualises the analysis, so that the resulting definition is closer to the reality of a specific context, thus stepping away from the universalistic, open-ended language of 'new dimensions'. That approach presumes that various aspects of energy security can be objectively derived as a number of universal categories, but is unable to explain why only 10 or less concerns, out of a system of hundreds of indicators, are important in a particular country. The method I developed and used here, in contrast, does precisely this. Also in this perspective, the contextualised analysis of policy applying the lenses of vital energy systems and observed concerns makes a subsequent assessment both more relevant (to both policy and science) and more manageable by grounding it in real-world concerns and reducing the number of issues to assess.

Third, the new approach offers a way to systematically structure the observed concerns by inducing context-dependent definitions of the three terms 'vital energy system', 'threat' and 'disruption'. By doing this, the researcher is forced to remain concrete and closely tied to the policy priorities of the analysed case, thus avoiding drifting off into abstract deliberations of what energy security could be in a general sense. This makes a definition as done here precise and transparent, both as the criteria for the analysis of energy security policies are clear and, especially, as the resulting definition is concrete and does not contain terms still open to interpretation.

These three main strengths of the approach I have developed in this dissertation help to explain the differences between the empirical results here and the findings in the literature, and especially in the ‘new dimensions’ literature. Although the set of potential energy security threats is essentially unlimited, only a few of these are in fact important and immediately threaten to disrupt a given vital energy system. A possible gas import cut from Russia is one such direct and concrete concern identified as important here, as is the threat of infrastructure failure. I have identified this type of immediate threats to well-defined systems here, whereas I could not identify indirect threats, which are seen as energy security issues in the ‘new dimensions’ literature, as parts of the European energy security concept. For example, I do not identify the number of energy technology patents in a country, cadmium emission intensity and job creation (e.g. Sovacool and Mukherjee 2011) as energy security concerns in Europe. Such concerns may cause disruptions, but only in a very indirect way (e.g. high cadmium emissions cause environmental damages, and thus lead to the threat of power stations being shut down early by environmental regulation, potentially leading to capacity shortages). Other aspects are extremely indirect threats to energy security (e.g. job creation and national patent intensity, the causal link between this and energy security remains unclear). If such indirect and hypothetical threats are added to the list of energy security concerns, everything, from electricity pylon bombings to the structure of the pension system, can be an energy security issue. The definition work here, focusing on observed and concretely described energy security concerns, should thus be expected to be narrower than the open-ended lists of ‘new dimensions’ and energy security issues in the literature, simply because the number of direct threats that can disrupt vital energy systems in each particular context is in fact not very high. The narrow results are thus a reflection of a narrow energy security reality.

However, the narrow empirical results could also be the reflection of a skewed energy security debate. In particular, they may also reflect a debate held in a closed epistemic energy security community of science and policy experts. This could cause an isomorph policy landscape in the sense that policies are not adopted because they are the decided action after careful consideration of the specific, context-dependent complexities of a jurisdiction, but because others have already adopted such policies. Adopting these policies thus lends authority, legitimacy and a sense that 'it must be right'.

Further, the observed non-diversity of policy measures in the three cases, which underlies the narrow definition, could be the result of the cases analysed here. Both the UK and Sweden are EU members and, in most relevant areas, EU energy policy dominates national energy policy by determining overall aims and strategies. It is thus to be expected that the broad picture in the three cases is rather streamlined, with case-specific particulars only determining the differences in the detail. I could observe this in the case studies, for example by the frequent references to EU policy in the UK and Swedish documents. This indicates that the EU policy dominance, and not (at least not primarily) an epistemic community of experts, is a strong explaining factor for the non-diversity of policies in the analysed cases. Given the progressive nature of Swedish and UK energy policy, and the dominance of EU policies, it is unlikely that other European countries have completely diverging energy security policies, but further studies of more member states are needed to know this for sure. Similarly, more research of non-European countries and regions is needed to know whether all regions of the world show a similar convergence as the three European cases here.

The clear results presented above show that the method developed here is indeed useful, by being both manageable and capable of producing meaningful empirical results. While this capability to identify, prioritise and structure observed energy security concerns along the lines of vital energy systems are the main strengths of the approach, it also has **limitations**.

First, as I base the new approach on the issues policy-makers worry about, this methodology cannot provide a corrective view of issues that are currently – perhaps falsely – ignored by policy. Policies can be seen as the outcome of the two policy streams of problem pressure and solution availability, combined with policy capacity and coinciding (or, sometimes, creating) a window of opportunity (see Jänicke *et al.* 2002). Hence, it is conceivable that serious problems are ignored by policy, not because the problem is not pressing, but because there is no good available solution, because there are strong interests against a certain policy, or because the jurisdiction has insufficient capacity to handle the problem. For example, it is possible that the absence of a Swedish foreign energy policy can be explained not only by its small gas imports but also by the lower foreign policy capacity of small countries. Large countries, like the UK, can do their own global energy diplomacy and are thus more likely to pursue foreign energy policy because they have a higher capacity to do so. It is also possible that Sweden in part relies on EU foreign policy institutions for achieving its own foreign (energy) policy objectives. Whether such factors block certain policies is very difficult to know, and the approach I developed here cannot identify such problems. Nevertheless, policy is likely to at least acknowledge the existence of a significant energy security problem and propose some sort of action to mitigate it so that it is likely – but not certain – that an approach such as the one developed here indeed is capable of identifying all the most important threats.

Second, it is possible that policy overemphasises problems of a spectacular and easily understandable nature, in particular following actual, dramatic events such as the Russian gas crises. This would however only be a problem for the approach I developed and used here if this overemphasis blocks policy attention to other important but less spectacular problems: if this does not happen, one will still find policies addressing both spectacular and unspectacular problems in policy.

Third, a contextualised, case-by-case approach produces results that cannot be generalised to other contexts. The empirical findings thus apply for the assessed cases, but they may not apply for other countries with different energy systems or geographic, geological, economic or political structures. Some of the conceptual observations are probably generalisable: for example, any country with domestic energy supply infrastructures is likely to be concerned with its reliability. However, one would also expect that countries importing substantial shares of the energy it consumes are likely to be concerned about the geopolitical implications (e.g. energy coercion, access to foreign resources). The case of Sweden, which imports practically all its fossil fuels (Eurostat 2010) but nevertheless has no explicit foreign energy security policy, however shows that not even this energy security 'truth' is universally generalisable. Thus, some of the observations here are probably generalisable to other cases, but one cannot know for sure which ones without analysing the energy security policy of each single case. For this, the methodology developed in this dissertation is suited: although the results cannot easily be generalised, the method itself is flexible enough to be universally applicable.

Fourth, the energy security conceptualisation is not only spatially but also temporally context-dependent. The findings are thus valid for the present day and historically (10-20 years back, see section 3.4), but they are not necessarily valid for the future as policy priorities may change. History holds numerous examples of well-established truths that suddenly stopped being true. Iran, for example, was considered a reliable energy partner by the West in the 1960s and 1970s, but following the Islamic revolution the West now imposes strong sanctions against "*evil*" state of Iran (Bush 2002; EC 2012; GPO 2010; National archives 1987). However, not only the energy security analysis but also political decisions concerning future energy pathways are made 'today'. Present concerns are what drive policy and present concerns are the focus of research, not potential future concerns that are yet unknown to both scientists and policy-makers. Hence, one cannot be sure that the energy security definition results in this dissertation do not look strange and beside the point when looking back from 2050, but they are valuable contributions to the scholarly debates and policy decisions of today.

5.3 Implications for the energy security assessments

European energy security policy is concerned with 2 distinct vital energy system (plus one cross-cutting focus on end-uses), 7 specific threats potentially causing 2 types of disruptions, as summarised in Table 7 on page 73. Here, I discuss the implications of these results for the energy security assessment in part 2 of the dissertation.

Vital energy systems

The European gas and electricity supply systems, as well as the demand of these energy carriers, are the sectoral focus of the analysed jurisdictions. The geographical boundaries of these systems are first of all European, but there is also a national perspective (as demand must be met in all parts of Europe), and an international perspective when energy is imported.

In the assessment part of this dissertation, therefore, I assess energy security with respect to these systems in a European setting, acknowledging smaller geographical units when appropriate, including the vulnerabilities that may come with energy imports.

Threats

European energy security policy is concerned with 7 threats, of which 4 are shocks and 3 are stresses. The shocks are coercion, embargoes and power asymmetry; intentional import cut-offs; and infrastructure failure due to various causes, including terrorist attacks. The stresses are aging infrastructure and underinvestment; resource depletion and growing global demand; and nuclear phase-out. Whereas all these threats are important to existing systems, not all of them can be meaningfully assessed for scenarios, in particular as the assessment of some threats would not contribute to identifying differences and inform the strategic choice between scenarios.

The two shock-threat types of coercion, power and import cut-offs on the one hand, and critical infrastructure failure (regardless of the reason) are meaningful to assess in scenarios. Such events can be assessed in a what-if approach, investigating the impacts of the loss of supplies from one or more countries (coercion or cut-off) or from specific infrastructure components (component failure, natural disaster, terrorism). An analysis of the vulnerability of vital energy systems to these threats can reveal fundamental differences between scenarios, making such an assessment both possible to analyse and meaningful for informing the choice between scenarios.

The stress-threats, in contrast, are either not possible to analyse in scenarios, or the results would not lead to a meaningful scenario comparison. Underinvestment – the threat that insufficient capacities are built to support a reliable energy system – is not suitable for a scenario analysis: if insufficient investments lead to insufficient capacities, this equals the realisation of a scenario with too low capacities. Analysing this would trivially show that such an insufficient scenario, a scenario no one has suggested, is insecure. In addition, underinvestment would affect all scenarios in the same way, so that no meaningful comparison of scenarios can be done with respect to this threat. Capacity shortages following a national nuclear phase-out would practically be an underinvestment problem, as it would be the consequence of insufficient replacement investments.

The stress-threat of aging infrastructure cannot be meaningfully assessed for scenarios, as it is impossible to know how old the infrastructure is in the future. This is therefore not an issue of interest for the choice between different scenarios. In addition, it is unclear how age influences the reliability of infrastructures: one can assume that the reliability decreases, but how much depends on factors that cannot be known today, such as the system maintenance. An example highlighting this difficulty is the European domestic gas transmission pipelines: the reliability of these has *increased* dramatically with age, due to upgrades and good maintenance (see section 7.2.1).

Assessing the stress-threat of resource depletion or too high global demand in a scenario would either conclude that the scenario is feasible, as there are sufficient finite resources to realise it, or that the scenario is unfeasible, as there is not enough oil, gas, coal or uranium. Such an analysis would not say whether a scenario is secure or not.

Therefore, I will only assess the shock-threats of politically motivated import disruptions – energy coercion – as well as infrastructure failure, caused by terrorism or other events, in the next part of this dissertation. As the direct impact of import disturbances in Europe are identical regardless of whether there is a political demand attached, I assess the threat of import cut-offs not connected to political demands – for example following political instability in an exporter country – implicitly within the coercion vulnerability assessment. I do not consider the stress-threats further in the energy security assessment. This also means that, in the assessment part, I do not claim to assess energy security in its entirety, but only the vulnerability of the vital energy systems in focus of European energy security policy to the specific shock-threats that can be meaningfully assessed in scenarios.

Disruptions

The disruptions that European energy security policy aims to avoid are physical supply disruptions – i.e. blackouts, gas outages – as well as disruptive price movements. Physical supply disruptions are the immediate consequence of the two shock-threat types I assess in the next part of the dissertation.

I assess the price volatility disruption-type only in an indirect way, as the potential consequence of supply constraints (caused by infrastructure failure, coercion or import interruptions). I do not assess the vulnerability to price volatility explicitly, as the seriousness of such events depends on the market design, the actor structure and the actors' respect for the market rules, and none of these variables can be known for the future. Here, I assume (see section 7.4) that the future markets function well and are competitive, so that I exclude price manipulation of domestic actors from the assessment. Instead, I assess the risk of price volatility implicitly within the frames of the physical disruption assessment as, for the two threat-types I assess, it is the physical supply constraint (or the credible threat of such), that could cause prices to fluctuate.

I summarise the identified vital energy systems, threats and disruptions in focus of European energy security policy, as well as those I will use in the assessment part, in Table 8.

Table 8: Summary of the identified vital energy systems, threats and disruptions in focus of European energy security policy, as well as those I use in the assessment.

Vital energy systems		Threats		Disruptions	
Identified	**For assessment**	**Identified**	**For assessment**	**Identified**	**For assessment**
Subnational, national, European/ regional electricity systems	National, European/ regional electricity systems	Coercion, embargoes and power asymmetry	Coercion and power asymmetry; supply cut-offs	Supply interruptions	Supply interruptions (possibly causing price volatility)
National, European, international gas systems	National, European, international gas systems	Intentional cut-offs	(included above)	Market distortions, price volatility,	(included above)
Electricity and heat end-uses	(included above)	Infrastructure failure.	Infrastructure failure, incl. terrorism		
		Terrorism, etc.	(included above)		
		Aging infrastructure, under-investment	n/a		
		Resource depletion, growing global demand	n/a		
		Nuclear phase-out	n/a		

See also Table 7 on page 73.

Part 2: Energy security assessments

In this part of the dissertation, I develop new methodologies for assessing energy security in scenarios and apply these, as well as methodologies from the literature, to assess the energy security of a Supergrid and other scenarios. The European energy security definition results from the previous part form the conceptual frame for the assessments: I assess the vulnerability of European vital gas and electricity systems to the two shock-threats identified in part 1 of the dissertation as those that can be meaningfully assessed in scenarios – coercion and embargoes, as well as critical infrastructure failure.

6 Literature review: assessing energy security

A large body of literature is specifically dedicated to assessing energy security. In this chapter, I review the dedicated energy security assessment literature, which is split into two distinct types of approaches.

The first approach is characterised by the search for and quantification of indicators, each of which is defined as a proxy of the vulnerability to assess. In some methodologies, the interpretation of the indicator set means various forms of manipulation of the indicators, like the aggregation of indicators into an index. This first approach, centred on gathering and manipulation of indicators, is the domain of 'classic' energy security research. I review this literature in section 6.1.

The second approach is characterised by the modelling of systems and their behaviour under supply interruption scenarios. In this part of the literature, entire infrastructure systems and their reactions to disturbances, which are simulated by removing critical nodes or lines, are modelled or otherwise assessed. This research field is known as critical infrastructure (CI) research. I review this literature in section 6.2.

I conclude this chapter by summarising and discussing the literature in the light of the aim of this dissertation (section 6.3), thereby pointing out specific shortcomings for the purposes here while also highlighting certain concepts from the dedicated energy security literature on which I base the new metrics and methodologies in the subsequent chapter.

6.1 *Indicator gathering, manipulation and interpretation*

The identification and quantification of one or more indicators – i.e. quantifiable metrics referring to the state of a system variable, used as a proxy for the energy security of an entire or a part of a system – is one of the most common methods to measure energy security. Depending on the definition and the research question, such approaches may focus on single or multiple energy sectors, addressing different shocks and stresses from different perspectives, for different countries, and so on (Cherp and Jewell 2011b, see chapter 2). Thus, these approaches are similar in how they approach indicator gathering as the tool to assess energy security, but there is considerable diversity with respect to which indicators are gathered and how the quantitative indicators are interpreted to give meaningful answers.

In the following, I review the literature using single indicators (section 6.1.1) or arrays of indicators (section 6.1.2) as their frame for assessing energy security. Following this, I review the literature in which indicators are aggregated to a single value (section 6.1.3), paying particular attention to the commonly used diversity indices (section 6.1.4), before briefly looking into the mean variance portfolio analysis as a distinct indicator manipulation approach (section 6.1.5).

6.1.1 Single indicators

Sometimes, especially outside academia, authors use single indicators to show the energy security of a country or region. This is often import dependency or reserves estimates or reserves/production (R/P) ratio (e.g. Eurostat 2010; BP 2011, see Kruyt *et al.* 2009). Studies using single indicators may be explicitly focused on one aspect of energy security, for example geopolitical concerns about access to foreign resources (for which import dependency is an indicator), or about overall geological availability of fossil fuels (for with the R/P ratio is an indicator). Although these indicators cannot describe energy security in its entirety, such one-point measurements are easy to understand and are likely to resonate well with the intended policy audience (Cherp and Jewell 2011a). Nevertheless, most scientific authors recognise that "*import dependence is not a threat in itself*" – it may be a threat, but to know for sure, one needs more information (Costantini *et al.* 2007:220, also Grubb *et al.* 2006; Kruyt *et al.* 2009). For example, "*a highly import-dependent system that is well diversified need not necessarily be a risky one*" (Bhattacharyya 2009:2412[14]). Single-indicator estimates are therefore not frequently used in academic energy security research.

However, especially reserves/production or similar estimates are sometimes used as an indicator of long-term energy security. For example, Turton (2006) assesses the interplay between climate protection and energy security, using the resource/consumption ratio of oil and gas in climate protection scenarios as the sole energy security indicator for the 21st century. In the more specialised peak oil literature, conceptually similar indicators are used, but these are significantly more complex than the simple comparison of 'proven' reserves and the production of last year, taking issues like single well pressure and investment rates into account (e.g. Aleklett *et al.* 2010; Shafiee and Topal 2009).

6.1.2 Arrays of indicators

In academia, many authors use, or propose to use, arrays of indicators: although each indicator is merely a single point, studies using numerous indicators can catch all, or at least

[14] I will come back to this statement in section 10.4.

the most relevant, aspects of a more holistic energy security conceptualisation. In principle, the search for indicators is closely tied to the matter of defining energy security, with the indicator array ideally covering all aspects of the conceptualisation: the different aspects of the definition are broken down into components, each of which is assessed by an easily accessible and quantifiable indicator.

The clearest example of this define-and-quantify setting is the ‘new dimensions’ approach (the definition part of which was reviewed in section 2.5), which explicitly aims at tying the definition directly to a set of indicators holistically assessing all aspects of energy security. As shown before, the desire to include all aspects by adding more ‘dimensions’ lets the size of the indicator arrays grow. von Hippel *et al.*’s 25 indicators is made “*more robust and complete*” by Vivoda’s 44 indicators, which is viewed by Sovacool as “*an excellent starting point*”, but at the same time as “*incomplete and iterative*”, while he also criticises that the 44 indicators conflate dimensions, which are conceptual in nature, and metrics, which are empirical (von Hippel *et al.* 2011; Vivoda 2010:5260; Sovacool 2011a:7472). Sovacool in a first step expands the array to 200 indicators and then, together with Mukherjee, enlarges it to a “*useful and relevant*” set of 372 single indicators (Sovacool 2011a:7478; Sovacool and Mukherjee 2011:5353). None of these studies actually performs an energy security assessment, but only conceptualise the issue and propose indicator arrays. In subsequent articles, the ‘usefulness’ of the framework is shown in a quantitative analysis for 18 countries in the Asia-Pacific region and the EU (Sovacool 2013; Sovacool *et al.* 2011). In Sovacool *et al.* (2011), largely the same dimensions are used as proposed by Sovacool and Mukherjee (with slight changes in especially terminology). However, the 372 indicators are “*boil*[ed] *down* […] *to 20 indicators*” before being quantified so that they use the holistic indicator framework “*as an instructive guide rather than an exhaustive checklist*” (Sovacool and

Mukherjee 2011:5353). Sovacool *et al.* (2011) find that the energy security of most of the assessed countries decreased between 1990 and 2010. Sovacool (2013:156) once again presents the same results, and concludes that "*some elements of energy security, such as availability and affordability, can come only at the expense of others, such as sustainability and efficiency*", as, for example, climate protection and new technologies may increase energy prices. This competition between dimensions, he argues, is one main reason for the for the decreasing (or at least not improving) energy security of the 18 assessed countries.

There are also numerous other approaches to creating indicator arrays. Among the most rigorous ones is the energy security module of the GEA (Cherp *et al.* 2012). This study adopts a vital energy systems perspective on energy security (as do I, see section 3), linking primary fuels, conversion, transport and end-use of energy. By doing this, the GEA assumes that the aim of energy security policy is to prevent disruptions of vital energy services. It also relates the assessment to policy mind-sets and strategies, thereby making it more policy relevant than an assessment based on generic 'dimensions' of abstract threats to energy security. The GEA authors relate the energy security concerns to the three perspectives (sovereignty, robustness, resilience, see section 2.2), with the aim to "*identify globally predominant national energy security concerns rather than to compare or rank countries*" (Cherp *et al.* 2012:334). For this, they define an array of 27 indicators related to the global and national levels, as well as to all primary energy supply and distribution systems (excluding all modern renewables except hydro power), to electricity and all end-use sectors, including the energy export sector for countries where this is applicable. The GEA finds that most countries are vulnerable from at least one of the three perspectives, and that industrialised countries are mainly threatened by high import dependency and aging infrastructure (Cherp *et al.* 2012).

Similarly, the International Energy Agency (IEA) in a recent study focuses on shocks to primary energy supply systems and their related secondary fuels (e.g. oil products). This study therefore excludes "*indicators that are only relevant to the long-term perspective, such as environmental impact, rapid growth in demand and depletion*", and also "*economic issues*" (Jewell 2011:9). The study uses an array of 35 indicators related to threat exposure and resilience and quantifies them for the IEA countries. The indicators are translated into 3-5 risk classes (e.g. low, medium, high) based on their threat exposure (e.g. oil import dependency), and into up to 5 "*energy security profiles*" by adding their resilience capacity (e.g. size of available oil storage). The classes are defined partially based on expert judgement, including benchmarks for "*'safe' levels of risk and 'adequate' levels of resilience*" (Jewell 2011:12). The results show, among other things, that 2/3 of the countries have a high-to-medium risk class concerning crude oil and gas, caused by high threat exposure from high import dependency and few import points. However, almost 3/4 of the countries have a low-to-medium risk profile concerning gasoline because of their low gasoline imports, high refinery capacities and high gasoline stocks, which in part compensates the oil import risks (Jewell 2011).

Array approaches exist also for specific sectors. Chang and Lee, for example, assess the security of the electricity system, and define energy security as "*consisting of three elements: adequacy, reliability and reasonable price*" (Chang and Lee 2008:110). These elements, in turn, are defined as generation adequacy, uninterrupted supply (no/minimal blackouts), and – referring to Bielecki (2002; see section 2.3) – they define reasonable a price as "*a price that is devoid of excessive market power*", which "*assures insulation against extremely high prices in times of scarcity*" (Chang and Lee 2008:116). For the assessment, they define three system conditions – the present system, the present system during an emergency following the failure of the market's largest firm or physical unit, and a future state that can be achieved given sufficient investments. The outcome is a 3x3 matrix (see Table 9) with indicators for each of these three elements and a corresponding set of benchmarks beyond which the assessed electricity systems is considered secure. The framework is applied to the electricity markets of the UK and Singapore, and Chang and Lee (2008) conclude that both markets are secure in all three system conditions.

Table 9: Chang and Lee's classification scheme for assessment of adequacy, reliability and reasonable price in the three system conditions.

System condition	Generation adequacy	Grid reliability	Reasonable price
Present system	Reserve margin $RM = \sum_i \frac{S_i - D}{D}$ **Benchmark:** RM>20%	Interruption indices $SAIDI = T / N$ $SAIFI = n / N$ **Benchmark:** SAIDI<1.16h; SAIFI<0.92 incidents	Lerner index $L = \frac{P - MC}{P}$ **Benchmark**: L<10%
Present system (emergency)	n-1 reserve assessment $R_{n-1} = D - \sum_i S_{-i}$ **Benchmark:** Non-pivotal	Presence of interconnectors and n-1 operation rules **Benchmark:** Both present	Residual supply index $RSI = \frac{\sum_i S_{-i}}{D}$ **Benchmark:** Non-pivotal
Future system	Generation investment growth **Benchmark:** Investment level results in RM>20%	Transmission investment growth **Benchmark**: Investment growth>demand growth	Presence of financial hedge contracts and demand-side management **Benchmark:** Both present
***SAIDI=System average interruption duration index; SAIFI=System average interruption frequency index. $\sum S_i$ is the capacity of all generators *i*, $\sum S_{-i}$ is the total capacity of all generators except generator *i*, *D* is peak demand, *T* is the sum of all interruption durations, *n* is the number of interruptions, *N* is the number of customers served, *P* is the electricity price, and *MC* is the marginal cost in the system.**			

Source: Chang and Lee (2008).

6.1.3 One-point indices

One-point indices are a distinct group of assessments, characterised above all by the desire to produce results that are easy to understand and compare. This approach is similar to the array approach in the sense that the starting point is to gather indicators for various aspects of energy security. They however differ in the interpretation stage: where the array approaches define and relate results to benchmarks, temporal developments, etc., the index approach manipulates the indicators in various ways to arrive at a single number. This energy security score is a highly aggregated, ordinal-scale index value, which is easy to understand as it is only one number, although the input data can be highly complex and detailed.

Strictly speaking, all indicators are aggregates. For example, the indicator import dependency generally aggregates all imports of an energy carrier over a year, or even across different energy carriers over a year. The index approach adds another level to this indicator-level of aggregation, essentially making indices aggregates of aggregates. Such aggregation of indicators generally takes place across geographies or, most commonly, across threats. A basic assumption, although rarely explicitly written, is thus that the vulnerabilities to different threats add (or multiply) to each other: being, say, import dependent and exposed to extreme weather is worse than only being import dependent (Cherp and Jewell 2011a).

Some approaches are similar to the indicator arrays above. An example is Sovacool and Brown (2010), who conceptualise energy security as consisting of the dimensions availability (here defined as geopolitical availability), affordability (i.e. price level), efficiency (i.e. energy intensity) and environmental stewardship (i.e. emissions of pollutants). Based on this, they construct an array of 10 indicators[15]. These indicators are quantified for each OECD country, for the two years 1970 and 2007 to assess whether the energy security of the countries has increased or decreased. The country is assigned +1 point if the indicator has improved compared to the average between 1970 and 2007, and -1 if it has deteriorated. All indicators are summed up to an energy security index ranging from +10 to -10. Sovacool and Brown conclude that some countries – like Denmark and the UK (+3 and +2, respectively) – have increased their energy security, whereas most countries – like Portugal and Spain (both -6) – had a lower energy security in 2007 than in 1970 (Sovacool and Brown 2010).

In a similar array-aggregation approach, Molyneaux *et al*. (2012:189) create a "*resilience index*" for electricity generation. In their view, resilience of electricity supply – i.e. how well the system can withstand disturbances – consists of three distinct attributes: efficiency (of generation and distribution), diversity (of fuels and technologies) and redundancy (of generation). They gather an array of 7 indicators[16] related to resilience. In addition, although this is not introduced in their definition, they also add geopolitical threats (primary originating in fuel import dependency) and carbon intensity of generation (as increased CO_2 prices could increase electricity prices)[17]. They then normalise this array of "*non-subjective*" indicators and sum the scores up to an index point. Molyneaux *et al.* (2012) find that hydro power dependent countries are the most resilient, whereas countries relying on coal power are the

[15] Oil and gas import dependency, Petroleum dependence, Fuel intensity in transport, Energy intensity, Electricity intensity, Electricity and Gasoline price, as well as CO_2 and SO_2 emissions

[16] Non-renewable fuel dependence, Generation efficiency, Distribution efficiency, Carbon intensity, Fuel diversity, Spare generation capacity relative to GDP, and Import dependency.

[17] Such discrepancies between the definition and what the metrics actually assess exist also in other studies, for example Costantini *et al.* (2007). These examples suggest that authors perceive a need to define energy security, perhaps not exclusively because they need it for their work but also because of a tradition of how to begin an energy security article.

most vulnerable, as they depend both on fossil and CO_2-intensive fuels. However, as CO_2-intensive fuels are always fossil and as efficiency is negatively correlated with CO_2 emissions, there is a strong double-counting of fossil/CO_2 risks in this index.

Another distinct index methodology is the Supply/Demand index, proposed by Scheepers *et al.* (2006, 2007). This approach adopts an end-use perspective on energy security, implying that the thing to protect is not the energy systems as such but the services they provide. The index thus holistically includes all (or most) parts of the energy value chain, including both supply- and demand-side issues as well as the transport and distribution of energy, as "*from the consumer's point of view it is less relevant what causes the supply shortage or disruption*" (Scheepers *et al.* 2006:13). The core of the index is energy security scores, consisting of the capacity multiplied by the reliability of energy supply, distribution or demand, aggregated and normalised to a scale 0-100. The scores are weighted by both "*objective*" shares of each energy type (so that higher share of demand gives more weight) and "*subjective*" weights[18], so that more critical energy systems receive more weight[19]. These scoring rules can be defined either based on expert opinion or in consultation with policy-makers on a case-by-case basis in order to let the rules reflect actual and current policy preferences (Jansen and Seebregts 2010; Scheepers *et al.* 2006). The scores are summed up to one number – the Supply/Demand index – on the scale 0-100. The Supply/Demand index has been used to show that European security of energy supply decreases slightly until both 2020 and 2030 in the

[18] e.g. the weights for the relative importance of domestic and external gas pipelines are set at 0.2 (domestic) and 0.8 (import pipelines), thus assuming that the external part of the network is 4 times more important to energy security in that sector.

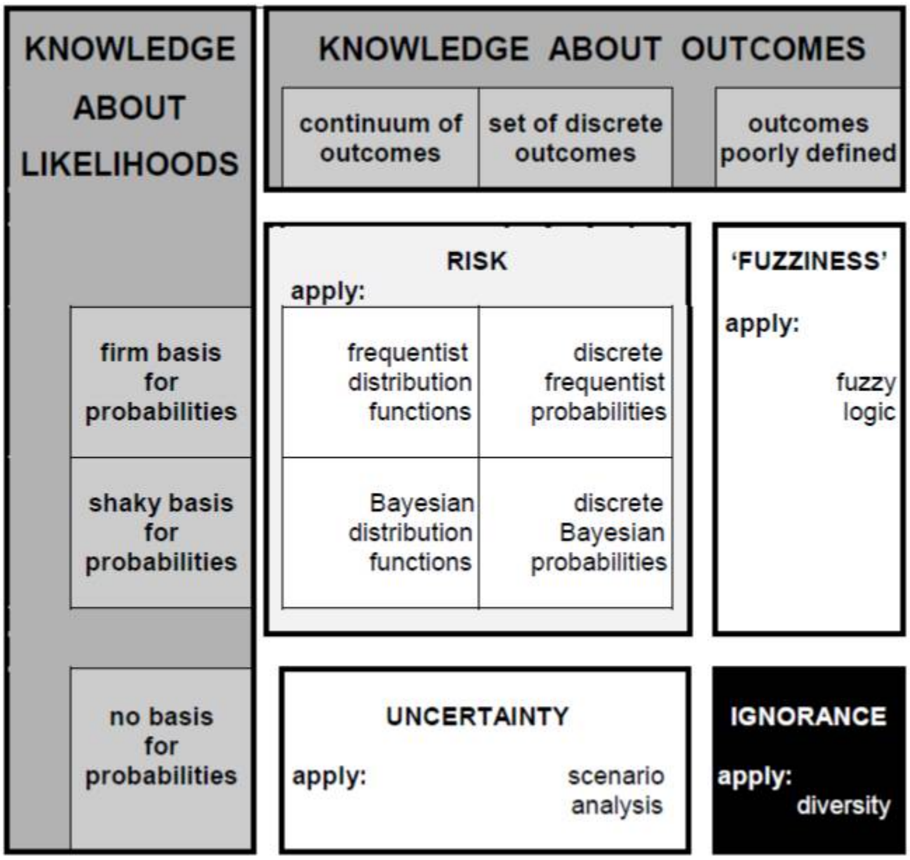
[19] e.g. the gas import sector gets a 0 score if less than 30% is domestically (EU & Norway) produced and 0% of the supply is based on long-term contracts, and the score increases linearly to 100 between 30% and 100% domestic production; nuclear power is considered secure and has a score of 100; an electricity generation buffer exceeding 20% above peakload gives a score of 100 or, if it is less than 20%, the score is proportional to the critical threshold (i.e. 15% buffer gives a score of 15/20*100=75).

Commission's business-as-usual scenario (Scheepers *et al.* 2006, 2007), and that the European energy security generally increases with stricter CO_2 emission reduction policies (Groenenberg and Wetzelaer 2006).

6.1.4 Diversity indices

The diversity index approaches, which form the mainstream of energy security assessments together with the indicator array approaches, build on the notion that neither the probability nor the outcome of future energy security events is knowable. The use of diversity indices to a large extent builds on the work of Andrew Stirling (e.g. Stirling 1994, 1999, 2010).

The cornerstone of Stirling's argumentation is that diversity is the most generic strategy for energy security when neither outcomes nor probabilities are knowable. Hence, it is also the most generic assessment methodology for energy security. The underlying principle is that the more numerous and disparate the options an energy system relies on, the smaller is the subset of options affected by any one event. This generic nature of diversity as an energy security measurement is particularly important, as it is impossible to know what energy security events will arise in the future and what their effects will be. Therefore, Stirling argues, diversity is the most effective, or even the only available, tool to hedge against and assess vulnerability to yet unknown threats to energy supply and even against "*surprises*", or threats that cannot be known in advance (Stirling 2001:63). In these cases, "*the use of probabilistic concepts like covariance and coefficients is by definition invalid*" (Stirling 2010:1628). As a consequence, "*when we don't know what we don't know*", assessing diversity "*is what we can do*" (Stirling 2010:1623): although event probabilities and outcomes are unknown, one can still state that a diversified system is likely to be more secure than a concentrated one (see Figure 2).



Source: Stirling (1999:15; with permission of the author).

Figure 2: Stirling's scheme for the four categories of incertitude and the related assessment tools.

Diversity in Stirling's definition consists of three parameters: *variety* (i.e. the number of available options), *balance* (i.e. the relative weight on each option), and *disparity* (i.e. the manner and the degree in which the options differ from each other). In particular disparity is "*an intrinsically qualitative, subjective and context-dependent aspect of diversity*" that is not easily measured (Stirling 1999:39). As a qualitative entity, disparity is ignored as an explicit variable in the creation of most diversity indices (Stirling's own index is an exception, see below). It is, however, implicitly considered when defining the groups of technologies or fuels which to measure for the building blocks of diversity indices: for example, authors defining oil and gas as two separate 'options' or 'fuels' in an index implicitly assume that they are completely disparate. The diversity indices are sometimes referred to as 'dual-concept' diversity indices, as they only consider variety and balance explicitly.

The two most commonly used indices are the dual-concept diversity indices Shannon-Wiener (SWI) index and the Herfindahl-Hirschmann (HHI) indices. Both can be written on the general form

Equation 1 $$\Delta_a = \sum_i (p_i^a)^{\frac{1}{1-a}},$$

with p_i being the share of option *i*. Setting a=1, leads to the SWI

Equation 2 $$\Delta_{SW} = -\sum_i p_i \cdot \ln(p_i),$$

whereas setting a=2 leads to the inverse of the HHI (Jansen *et al.* 2004),

Equation 3 $$\Delta_{HH,inv.} = \sum_i \frac{1}{p_i^2}.$$

Whereas the HHI is strictly speaking a concentration index, so that lower values indicate low concentration and thus high diversity, the SWI is a diversity index, with higher values indicating higher diversity.

Since there is no theoretical or otherwise compelling reason for choosing a=1 or a=2 in Equation 1, instead of, say, a=3 or something else, the choice of which index to use is largely a matter of taste and academic tradition (Skea 2010). However, the emphasis on small contributions is lower with higher values of a: this means that large suppliers or energy options 'count more' in the HHI than in the SWI. Depending on the aim of the study, a different index may therefore be more suited (Costantini *et al.* 2007), but the choice of index generally – meaning 'almost always' – does not impact the ordering of results (Grubb *et al.* 2006). Stirling argues strongly in favour of the SWI on the grounds that it is monotonic under change of logarithm base, which is important, he argues, as there are no strong arguments for or against a certain base (Stirling 1994, 1999). In later work, however, he concludes that both indices are "*no less arbitrary than the simple counting of variety*", because they ignore the disparity of options (Stirling 2010:1626).

The diversity indices are used in two distinct ways in the literature. First, a number of studies use diversity indices in their unrefined form (as in Equation 2 or the inverse of Equation 3), generally as one indicator among other energy security indicators in an array approach (e.g. Cherp *et al.* 2012; Cohen *et al.* 2011). Second, some authors add "*ad hoc factors*" (Lefèvre 2007:55; e.g. Löschel *et al.* 2010) to refine the diversity index and let it describe more factors than only diversity of options, such as market liquidity or political risk factors.

Pure diversity indices

A number of studies use diversity indices in their pure form, without adding any more terms. These approaches have in common that they use the diversity index as one indicator among a number of others, implicitly adhering to the notion that diversity is the most generic indicator of a system's vulnerability, and thus one that needs to be informed by additional data points to be correctly interpreted. This additional information is not aggregated into the index itself, but is only used to interpret the results: the pure diversity indices therefore do not (at least not in the step of creating the metrics) adhere to the assumption that different threats add to each other (see section 6.1.3).

Bhattacharyya (2009) uses both the HHI and the SWI for fuels going into the electricity sector of a country as a proxy for the vulnerability to supply interruptions. In a second step, he interprets the results together with an indicator of how severely a disruption would affect the country (defined as cost of fuels in the electricity sector/GDP). Similarly, Costantini *et al.* (2007) use the HHI and SWI for the diversity of world oil and gas trade and production as indicators for supply-side vulnerability and combine this with additional indicators such as value of gas/oil imports, net oil/gas import dependency, and oil used in the transport sector.

This study differs from most others, as the indicators are quantified for future scenarios, up to 2030, using the highly aggregated energy system data on energy supply, demand and trade coming out of four different energy system models.

The IEA uses the HHI for export countries as an indicator for importer country resilience against external supply disturbances, defining benchmarks of <0.3 (high diversity), 0.3-0.8 (medium diversity) and >0.8 (low diversity). The diversity index results (high/medium/low) are then used together with other metrics to arrive at energy security risk profiles. For example, having 40-65% oil import dependency is viewed as equally secure (risk profile B) as having >80% oil import dependency, if this is combined with having ≥ 5 oil ports, ≥55 days of oil storage and high exporter diversity (Jewell 2011, also section 6.1.2).

The GEA uses the SWI to assess the security of different vital energy systems. They find, for example, that almost a billion people live in countries where the electricity fuel diversity is low (SWI<0.4), indicating high vulnerability. A diversity index is also applied to assess, among other things, the vulnerability of the entire national energy supply (primary energy fuel diversity). Interestingly, the GEA applies the SWI to assess the vulnerability of the hydro power sector to attacks and technical failure, by measuring diversity of dams (Cherp *et al.* 2012). This last point is important: almost all studies use diversity indices to assess fuel or supplier country diversity, whereas an application to energy infrastructure is uncommon. As indicated by the GEA's application of these to hydro dams, as well as their use in a limited number of other studies (e.g. Daniel 2011), however, diversity indices are equally applicable to all parts of an energy system, including its infrastructure.

Refined diversity indices

Also among the refined diversity indices, there are studies using the Herfindahl-Hirschmann index, while others use the Shannon-Wiener index. I describe how these refined indices are constructed below.

Herfindahl-Hirschmann diversity index-based studies

The choice of HHI instead of SWI is motivated in different ways. Some authors see market risk to fossil fuel supply essentially as an issue of market power, for which the HHI is the standard measure (e.g. Lefèvre 2007). Others justify this choice by referring to it as the most used index (e.g. Cohen *et al.* 2011), whereas yet others argue that large suppliers are more important for a country's energy security and as the HHI puts stronger emphasis on these large sources than the SWI it is a more appropriate index (e.g. Frondel and Schmidt 2008; Le Coq and Paltseva 2009). The construction of an energy security HHI is typically done in a number of steps, which are described below. First, the basic HHI is defined as

Equation 4 $$\Delta_{HHI,i} = \sum_j p_{i,j}^2 ,$$

where $p_{i,j}$ is the market share of exporter country j of fuel i. In a second step, as not all countries are perceived as equally reliable, an indicator of political risk c_j of export country j is added:

Equation 5 $$\Delta_{HH,i} = \sum_j c_j p_{i,j}^2 .$$

Of the authors using a refined HHI diversity index as energy security metrics, almost all base their assessments on an expression of this form. Typically, the domestic political risk is set to zero, as there is no reason why a country would cut its own energy supply for political reasons (Frondel *et al.* 2009), or domestic supply is not considered at all.

Some authors add more '*ad hoc* factors' to depict the actual risks to energy supply more in detail. Blyth and Lefèvre (2004), for example, consider market liquidity as a proxy for the importer's possibilities to switch supplier. For this, they introduce the term e^{1/P_i} in their index, where P_i is the available world supply of fuel i divided by the domestic demand for the same fuel:

Equation 6 $$\Delta_{Blyth-HH,i} = \sum_j \left(c_j p_{i,j}^2\right) e^{1/P_i}.$$

Finally, they create an index for total energy supply by summing the sub-indices for all fuels, each weighted by the share f_i of each fuel i in total primary energy supply *TPES* (Blyth and Lefèvre 2004)[20]:

Equation 7 $$\Delta_{Blyth-HH,i} = \sum_i \left(\left(\sum_j c_j \cdot p_{i,j}^2\right) e^{1/P_i}\right) \frac{f_i}{TPES}.$$

Le Coq and Paltseva (2009) focus on energy transport risks and represent their index differently, as

Equation 8 $$\Delta_{LeCoq-HH,i} = \left(\sum_j \left(\frac{P_{i,j}}{M_i}\right)^2 F_{i,j} c_j d_j\right) \cdot NID_i \cdot f_i,$$

where $P_{i,j}$ is the net positive imports of fuel i from country j, M_i is the total imports of fuel i, $F_{i,j}$ is the fungibility of imports of fuel i from country j, d_j is the distance between import country and export country j, NID_i is the net import dependency of fuel i. In this, $F_{i,j}$ is defined as 1 for fuels traded on a liquid world market (i.e. oil, liquefied natural gas (LNG) and

[20] Lefèvre does essentially the same additions, but excludes the market liquidity index $1/P_i$ (Lefèvre 2007; Lefèvre 2010).

coal) and 2 for infrastructure-bound fuels (i.e. pipeline gas). The distance d_j is included as a proxy for transport risks as, the authors argue, the risk does not increase linearly with distance. Hence, each exporter is assigned a distance value of 1 (<1500 km between capitals), 2 (1500-4000 km) or 3 (>4000 km; Le Coq and Paltseva 2009).

Shannon-Wiener diversity index-based studies

Despite the argumentation of Stirling and his large impact on the energy security assessment literature, only few studies base their index on the SWI. Some use variations of the SWI for parts of their considerations (e.g. Cabalu 2010, who uses it for geopolitical risk only). In the following, I describe the widely cited index of Jansen *et al.* (2004). In a first step, the basic SWI is defined as in Equation 2, and a correction term k_i is added, so that:

Equation 9 $$\Delta_{SW} = -\sum_i k_{i \cdot} p_i \ln p_i \ ,$$

with

Equation 10 $$k_i = 1 - m_i \left(1 - \frac{-\sum_j^J c_j m_{i.j} \ln m_{i.j}}{-\ln 1/J} \right),$$

where m_i is the share of primary energy net import of primary energy source i, $m_{i,j}$ is the share of total net imports of source i from country j, and c_j is a political risk indicator for export country j.

In a further amended indicator, Jansen *et al.* also include resource depletion, which is expressed on the same form

Equation 11 $$\Delta_{SW} = -\sum_i K_{i \cdot} p_i \ln p_i \ ,$$

where

Equation 12 $$K_i = 1 - m_i \left(1 - \frac{-\sum_j^J r_{i,j} c_j m_{i.j} \ln m_{i.j}}{-\ln 1/J} \right) \cdot \left(1 - (1 - r_{i,k})(1 - m_i)\right),$$

with

Equation 13 $$r_{i,j} = \min\left\{ \left(\frac{R/P_{i,j}}{50} \right)^a ; 1 \right\}, a \geq 1,$$

where $r_{i,j}$ is the depletion index for fuel *i* in country *j*, $r_{i,k}$ is the same depletion index for fuel *i* in home country *k* (i.e. the assessed country or region), and $R/P_{i,j}$ is the resource/production ration of fuel *i* in country *j*. The '50' in Equation 13 represents a threshold: Jansen *et al.* assume that the markets start correcting their behaviour when the R/P ratio is lower than 50 years. The exponent *a* is "*admittedly arbitrary*" and set to 2 (Jansen *et al.* 2004:24).

Stirling's diversity index

Stirling criticises the use of dual-concept indices, as these do not explicitly consider disparity as the third dimension of diversity. Instead, dual-concept diversity indices implicitly and intransparently assume that all options are equally disparate. Stirling states that, although a disparity measure cannot be objective and universally accepted, the choice is "*not* whether *to respond to the challenge of accommodating divergent perspectives on disparity but* how – *and with what degree of rigour and openness*" (Stirling 2010:1629). He suggests defining a multidimensional disparity-space, for example with the three axes of environmental quality (based on criteria such as carbon emissions or health impacts), economic value (e.g. reliability or cost) and social wellbeing (e.g. equity or quality of life); the disparity is then the pair-wise disparity-space distance between options. Stirling introduces a balance-weighted disparity index, defined as

Equation 14 $$\Delta_{Stirling} = \sum_{i,j(i \neq j)} d_{i,j}(p_i p_j),$$

where $d_{i,j}$ is the disparity-space distance between the energy options i and j, and p_i and p_j are the shares of energy options i and j (Stirling 2010). In a pilot study, Stirling and colleagues show that expert elicitations can produce meaningful disparity structures, which can in turn be used for the triple-concept index, although expert meanings differ strongly between interviewees. They conclude that "*the value of such a framework lies not in prescribing decisions, but simply in informing more robust, rigorous and accountable policy deliberation*" (Yoshizawa *et al.* 2009:63).

The refined diversity indices have much in common from a methodological and epistemological perspective, although they incorporate a range of different issues and thus differ with respect to aim, scope, and in many other details. I find three issues particularly important.

First, the refined diversity indices build on the argumentation of Stirling, who bases his work on the notion of a 'state of ignorance' in which outcomes and probabilities of events are unknown. However, all refined diversity indices include '*ad hoc* factors', adding information about political risk, market structure, risk of depletion, etc. The authors thus all leave the 'state of ignorance' by adding things they believe to know in order to make the index a better representation of reality.

Second, most refined diversity indices use a political risk *ad hoc* factor, but different authors use different risk indicators and different normalisations:

- Le Coq and Paltseva (2009), Cohen *et al.* (2011) and Blyth and Lefèvre (2004) use the International country risk guide (ICRG) political risk index, on a scale 0-100; this index assesses "*the political stability of the countries covered by ICRG on a comparable basis*" (PRS 2010).

- Lefèvre (2007 and 2010) uses the average of two of the Worldwide Governance Indicators (Political stability/absence of violence and Regulatory quality), normalised to 1-3. These capture "*perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means*" and "*perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development*" (Kaufmann *et al.* 2009:6).
- Cabalu (2010) uses only the Political stability/absence of violence indicator, as described in the point above, but she instead normalises the score 0-1.
- Frondel and Schmidt (2008) and Frondel *et al.* (2009) use the OECD country risk classification, normalised to 0-1; this index "*measures the country credit risk, i.e. the likelihood that a country will service its external debt*" (OECD 2010).
- Jansen *et al.* (2004) propose the usage of the Human Development Index (HDI) as an indicator for long-term political stability. The HDI provides "*an assessment of country achievements in different areas of human development*", and consists of aggregated data of life expectancy, education, and GDP (gross domestic product; UNDP 2009:203). Due to data availability – there are no HDI forecasts – Jansen *et al.* instead use the square root of the projected GDP growth as an indicator for political risk.

These indices thus measure very different things, and none of the indices actually measures the risk of export interruptions due to coercion (the ‘energy weapon’), revolution or similar[21]. These differences are however hidden behind a similar terminology of ‘political risk’, so that only a close examination of the data reveals exactly what is assessed. Furthermore, the causality for instability being an energy security indicator is not

Third, as the core of the refined indices is the diversity of suppliers (and sometimes fuels), the core of the assessment is geopolitical vulnerability. In essence, a diversity index is a metric for dominance of an option, and in the cases here, this is market power of actors (in the entire energy market or in a single fuel market). Thus, the actual issue investigated is the market power, combined with a ‘hostility’ scalar (political risk factor) of each external supplier, which is a sovereignty perspective issue. In addition, however, some of the indices add robustness perspective factors, most importantly concerning depletion, and some add resilience *ad hoc* factors, like the liquidity of the global market. By doing this, they mix threat exposure (like import dependency and market power) with resilience variables (like market liquidity) in the same dimension- and context-less index, and assume that threats add to each other but without linking them together by describing how the one affects the other.

[21] In addition, it is not clear to me why instability necessarily threatens a country’s energy exports: it may, but there are also counter-examples. For example, during the Arab spring revolts in winter/spring 2011, the fossil fuel production (and exports) indeed stopped in Libya, when the civil war broke out, but it remained more or less constant during the revolution in Egypt (IEA 2012c, d); even during the fall of the Soviet Union in 1991, energy exports to Western Europe remained stable (Smeenk 2010).

6.1.5 Mean variance portfolio analysis

The portfolio approach assumes that it is possible to characterise future events with a distinct outcome and a meaningful probability based on past experience (Skea 2010). Although mean variance portfolio (MVP) analysis is essentially a diversity approach, as it builds on the disparity of characteristics and number of options, it is therefore located rather on the epistemological opposite of the diversity index approaches.

The MVP looks only at price risks, which are a "*crucial aspect of energy security*" (Awerbuch 2006:8), and aims at maximising expected return for a given level of risk or, conversely, at minimising risk for a given level of return. In doing this, authors using the MVP assume that the track record of past events can be a guide for the future: if this is true, then such a probabilistic approach can indeed be useful (Lefèvre 2007). Awerbuch *et al.* (2006) argue that this could be the case: although unexpected and unprecedented events may happen, the effects – an outage or a price increase, or both – of these events are known from past experiences. As the historic cost risks used in the MVP contain the cost effects of all past events, ranging from oil crises over storms and government changes to wars, the risk measure used by the MVP is the "*summation of the effects of all historic events, including countless historic surprises*" (Awerbuch *et al.* 2006:205).

The principle of the MVP is to consider economic performance as the expected value of the return, with a risk – the standard deviation of past returns – attached to it. Instead of focusing on the risk of supply interruptions, the MVP thus explicitly focuses on the price aspect of energy security, as, Awerbuch argues, price spikes can be similarly disruptive as outages.

In its general form, the expected return $E(r_p)$ is given as

Equation 15 $$E(r_p) = \sum_i w_i \cdot E(r_i),$$

where r_i is the return and w_i is the weighting of asset *i*. The other component, the portfolio risk σ_p is

Equation 16 $$\sigma_p = \sqrt{\sum_i w_i^2 \sigma_i^2 + \sum_i \sum_j w_i w_j \sigma_i \sigma_j \rho_{ij}}$$ **, i≠j,**

where $\sigma_{i,j}$ is the standard deviations of the returns of assets *i* and *j*, and ρ_{ij} is the correlation coefficient between the returns of assets *i* and *j* (Awerbuch and Berger 2003; Awerbuch 2006). Plotting every combination of assets produces a hyperbola, the efficiency frontier, along which it is not possible to lower risk without lowering expected return and vice versa. Portfolios in the space below the hyperbola are inefficient: here, the risk can be reduced without increasing costs, or costs can be reduced without increasing risk. The efficiency frontier is thus a Pareto optimum with respect to the trade-off between risk and return, giving the lowest possible cost for each risk appetite. This implies that it is not possible to identify a single optimal portfolio using MVP, but that a set of portfolios – for example energy mixes – are optimal.

In the MVP, therefore, not only the stand-alone cost of an asset, fuel or energy technology is important, but also its risk. Low-risk, or even risk-less, assets with very low default probability, like US treasury bonds in a financial portfolio, or electricity generation assets without variable costs in an electricity mix therefore have an important function: they reduce the price volatility of the portfolio. By adding low-risk assets to a portfolio, even if these are more expensive on a stand-alone basis when ignoring price risks, it may be possible to lower the portfolio risk so that the expected portfolio cost is not influenced – the higher cost is offset by the lower volatility.

6.2 *Modelling of system behaviour to assess critical infrastructure vulnerability*

The distinct energy security research field of critical infrastructure protection focuses on assessing the behaviour of a physical energy system, especially the size and duration of outages following the disabling of physical, critically important infrastructure components. This field is thus different from the 'classical' energy security research, which focuses on identifying and interpreting indicators for various aspects of energy security.

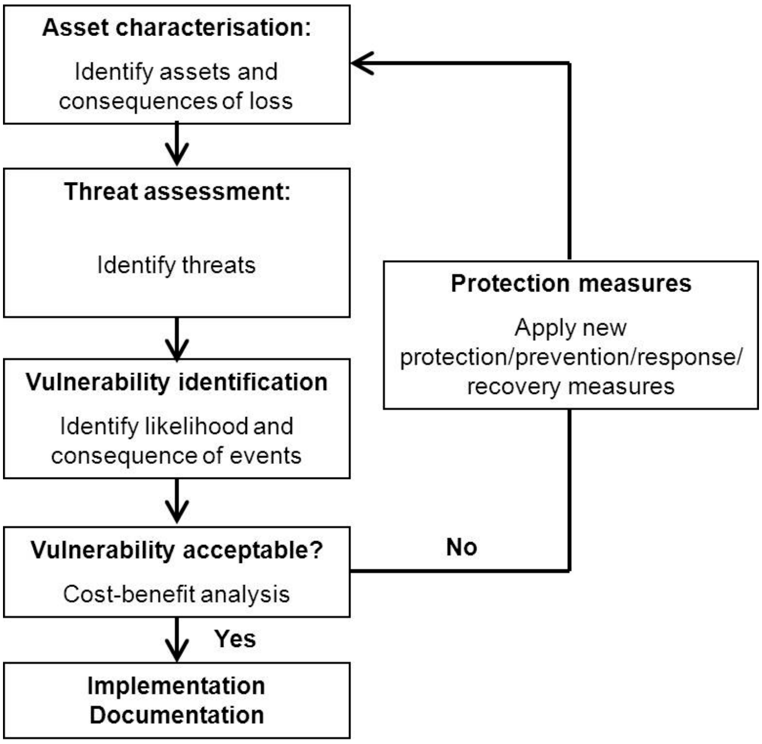
Just as the term 'energy security', the matter of defining which infrastructures are critical infrastructures is a matter of debate. The EU defines critical infrastructure as "*an asset, system or part thereof* […] *which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact* […] *as a result of the failure to maintain those functions*" (CI protection Directive 2008:Art. 2a). Such wide scopes have been criticised, because they do not necessarily exclude anything: a definition could even include "*toy manufacturers, etc. as these are important to the emotional well-being of people*" and as a consequence, "*no situations would be considered 'non-critical'*" (Hull *et al.* 2006:358; Popescu and Simion 2012). In academia, most CI definitions put the systems and functions – especially government, national security, national economy and public health – supported by the infrastructure in focus, instead of the infrastructure itself. Thus, although the subtleties may differ, an almost universally accepted definition of critical infrastructures is that they are any infrastructure component or system that is "*essential for the maintenance of vital societal functions*" (Yusta *et al.* 2011:6101; this is similar to vital energy systems, see sections 2.1 and 3.1). Disabling critical infrastructures would therefore have a debilitating impact on government, security, economic activity or public health and safety (Zimmermann 2006). The major energy infrastructures are viewed as critical infrastructures in Europe, and in the national perspective, most countries also include transport, water and telecommunications, and sometimes the health system, the government and the financial sector (Yusta *et al.* 2011, also Infracritical 2012). Many critical infrastructure systems depend on the functioning of each other – the electricity system relies on gas supplies for its power station, and the gas system relies on telecommunications, and so on. Practically all critical infrastructures, ranging from water and oil supply to telecommunications and health services, and indeed including the electricity system itself, depend on a reliable electricity system, so that the electricity system may be considered to be "*the most critical of all*" (van der Vleuten and Lagendijk 2010a:2053; Beccuti *et al.* 2012; Chiaradonna *et al.* 2011). In the following, 'critical infrastructure', or 'CI', only refers to critical energy infrastructure.

The CI research is strongly driven by engineers and technical experts. The terrorism part of the CI research is driven by American institutions and think-tank and is sometimes financed by political bodies, most prominently the US Department for Homeland Security (Jackson 2007, e.g. Bier *et al.* 2005; Shea 2004). Thus, the CI research is, perhaps even more so than the classic energy security research, methods-heavy and focused on practical results rather than on theory. A clear indication of this is that the research field is sometimes referred to as 'critical infrastructure protection', rather than 'critical infrastructure research' (e.g. Ghorbani and Bagheri 2008). The CI research field can be mainly assigned to the robustness and the resilience perspectives on energy security (Cherp and Jewell 2011b), as CI research focuses on systems' capability to absorb disturbances or to recover from outages if they happen, both following roughly predictable events such as storms and unpredictable ones, like terrorist attacks.

There are two main paradigms for protecting critical infrastructure, with important implications for how to assess its vulnerability. The first encompasses robustness measures aiming at allowing single units to remain intact and maintain their function following an event. Such measures are important to protect components against recurring natural events (e.g. storms), to make high-probability attack modes unfeasible, or to protect particularly important or exposed points (Holmgren 2007; de Vries *et al.* 2006). However, there are over 34,000 conventional electricity generation units in Europe, of which 268 exceed 500 MW, 6000 high-voltage transformers, 8000 transmission lines stretching over 260,000 kilometres and serving over 500 million citizens via several million kilometres of lower-voltage lines (Bompard *et al.* 2009; ENTSO-E 2011a, 2012b; Nordel 2009; Platts 2008). The gas system similarly vast: the European gas transmission grid measures over 187,000 kilometres, whereas the single import pipelines are up to 4500 kilometres each (Borisocheva 2007; ENTSO-G 2012). These enormous critical systems cannot be permanently and cost-efficiently physically protected, especially not against low-probability/high-consequence events. Furthermore, increased protection measures may cause attackers to change their attack mode or to choose a different, less well-protected target. Therefore, the "*the infrastructure cannot be made invulnerable*" (Farrell *et al.* 2002:49; Holmgren 2007; Romero *et al.* 2012; Stewart 2010a; Toft *et al.* 2010).

The second paradigm aims at improving the system's resilience. In this, the focus lies on protecting the functionality of the system following an interruption, rather than maintaining the function of single components (Farrell *et al.* 2004; Farrell *et al.* 2002; Greenberg *et al.* 2007). Resilience enables the system to "*adapt to regain a new stable position*" when one or more single components are disturbed by 'absorbing' the interruption (Holmgren 2007:34), or by allowing it to fail "*gracefully*" – i.e. slowly, and only in small contained segments of the entire system (Lovins and Lovins 1982:179). There are two principal ways to achieve resilience. First, the system buffers can be increased by creating redundancies in the system. Doing this, however, is expensive, and the removal of redundancies was indeed a main aim of the energy market liberalisation in Europe (Farrell *et al.* 2002; Kröger 2008; UCTE 2007). Instead, increasing diversity and avoiding overreliance on single system units – importantly also including control and communication systems – is broadly accepted as a generic path to increase the resilience of a system against both intentional attacks and random failure (Sterbenz *et al.* 2010, also Masera *et al.* 2006; Nai Fovino *et al.* 2011). Consequentially, most CI studies focus on a system's resilience and behaviour during disturbances.

Critical infrastructure vulnerability studies often follow a vulnerability assessment framework (such as stylised in Figure 3). Some follow this explicitly, but most do it implicitly, and many do not follow all steps. In most studies, the focus is the vulnerability identification stage. The methods used for this are diverse and may include as disparate tools as red-team exercises and optimisation modelling, identifying the most critical points in a system and disabling them to simulate an attack by a perfectly informed terrorist group (DOE 2002; Brown *et al.* 2006; Anderson 2010; NATO CCDCOE 2010).



Source: adopted from Holmgren (2007), based on Bajpai *et al.* 2010; Brown *et al.* 2006; DHS 2009; DOE 2002; McGill *et al.* 2007.

Figure 3: Stylised, generic vulnerability assessment framework.

In this, some authors use qualitative or semi-quantitative approaches. For this dissertation, the article by Smith Stegen *et al.* (2012) is the most interesting. In this paper, the authors assess the terrorism risks of the Desertec scenario (which I do, too), defining 'risk' as 'risk of blackout'. For this, they use a model developed by the US Department of Homeland Security, describing the level of risk of as

Equation 17 $$\boldsymbol{R = T \cdot V \cdot C},$$

where T is the threat, defined as the probability of an attack happening, V is the vulnerability, measuring the weaknesses of the targeted infrastructure and describing the probability of a successful attack, and C describes the potential magnitude of the consequences. They assess the risks in a qualitative manner, identifying higher/lower risks, in four attack scenario-types (the risks for Europe (importer) and MENA (exporters) of single and multiple attacks).

They find that the risk of single attacks is low for both Europe and MENA, as the redundant nature of meshed electricity grids make single attacks very unlikely to result in blackouts. Multiple attacks could cause serious and very expensive blackouts in both MENA and Europe, but are difficult to carry out: Smith Stegen *et al.* (2012:19) find that the risk of multiple attacks is "*negligible to low*". As blackouts are indiscriminate and strike an area, and not targeted individuals and organisations, these could affect and alienate supporters as well as enemies, so that attacks against electricity lines are unattractive to terrorists. However, if a group decides to attack anyway, the effects, both direct economical (especially in Europe, following multiple attacks) and long-term political (especially loss of investor confidence and lost future trade and investments in MENA), would be very high. They conclude that the main source of risk lies in the physical vulnerability of the electricity systems and the potentially dramatic effects of large-scale blackouts, and not in the possible plans of terrorist groups. Hence, increasing the resilience of the physical system and the contingency planning may be a more efficient way to reduce the risk of terrorist attacks against critical infrastructure than to combat the terrorist groups as such (Smith Stegen *et al.* 2012).

Most CI studies aim at describing the reality and the complexity of an energy system by modelling its responses and behaviour following the failure of one or more units. Such failures can happen due to technical failure, natural events or intentional, malicious action. The key difference between the threat of intentional attack and the threat of extreme weather events or technical failure is simple, but important: lightning strikes at a random location at a random time, destroying a random component, but a terrorist attack is consciously aimed at maximising damage (Bouwmans *et al.* 2006; Li *et al.* 2005; Murray and Grubesic 2007). Thus, "*random component failures offer a poor paradigm in a world with intelligent adversaries*" as "*infrastructure that resists single points of random failure* […] *may not* *survive an intelligently malicious attack*" (Brown *et al.* 2006:530). As it is difficult or impossible to account for attacker ingenuity and motivation, each terrorist attack is a surprise, and it is "*not possible to use traditional statistical tools*" to assess vulnerability (Tranchita *et al.* 2009:247). Some authors even view a probabilistic approach as misleading (Brown and Cox 2011), as the mainstream CI vulnerability assessment methods assume "*independence from contextual factors*" (Kröger 2008:1786). Consequentially, most of the literature agrees that a prudent CI vulnerability assessment must take "*what is possible, rather than what subjective assessments indicate is likely*" into account: "*worst-case analysis is critical*" (Brown *et al.* 2006:531). Most CI modelling studies are therefore little concerned with the reasons and probabilities of the failure and the different types of events, and rather seek to understand the impacts of worst-case failures. In doing this, the authors generally assume that the most critical, and not simply random, units fail. In a worst-case approach, it is not important whether the failure was caused by a well-informed, malicious attacker or by a random natural event impacting the worst possible point, as the effect – the failure of critical units – is the same (Rinaldi 2004). I use this notion in the vulnerability assessments of this dissertation as well (see section 7).

In general, critical infrastructure vulnerability models are energy flow models, depicting how energy moves around in a system following the failure of one or more components, but other approaches are also used, such as fuzzy sets (e.g. McGill and Ayyub 2007), multi-agent models or use methods from the complex network research field (e.g. Holmgren 2007, Bompard *et al.* 2009). Although there are many modelling strategies and techniques, these models perform essentially the same task: they represent an energy system and model its dynamic behaviour under stress. The models simulate attacks or failures by disabling critical nodes, lines or other system components, taking possible system responses and restoration time of system functionality and repair time for fixing damage components into account. In most cases, the results show the size and/or duration of a supply outage; a detailed overview of modelling approaches is given in Yusta *et al*. (2011).

These models thus aim to identify structural weaknesses in different types of actual or hypothetical energy systems and, when appropriate, give recommendations on how to improve the security of the system (e.g. Salmerón *et al.* 2004). This is in particular the case when actual systems are modelled (e.g. Rosas-Casals *et al.* 2007 (who model the continental ENTSO-E grid), or Greenberg *et al.* 2007 (New Jersey electricity grid)). However, these types of models are highly complex, and computing time and – especially – data availability are serious constraints (Rinaldi 2004). As a consequence, most authors model stylised and simplified systems instead of actual systems, which are often too large, too complex and too data-intensive to model in detail (e.g. Tranchita *et al.* 2009, Romero *et al.* 2012 or Zerriffi *et al.* 2007, who model 9 to 24 bus/node electricity and gas systems, as compared to the 40,000 conventional power plants and transmission nodes in the ENTSO-E system). Other simplifications include modelling DC instead of AC power flows in electricity systems. Despite this, many models are very detailed and generally give precise and realistic results (Ghorbani and Bagheri 2008).

A frequently used approach for assessing the vulnerability to terrorist attacks is the attacker-defender[22], or interdiction, models. Such models are optimisations of the cost/value of the defender's operations of an infrastructure system. The attacker-defender model assumes that the defender (the system operator, the government, etc.) aims to minimise the operating costs

[22] Sometimes these models are named defender-attacker-defender models, to reflect the order and number of moves of each side.

– including the costs for outages – of a system. The defender does this in two steps: *ex-ante* by hardening or otherwise protecting sensitive parts of the infrastructure, and *ex-post* by trying to restore possible outages and repair destroyed components. In between these two steps, the attacker carries out an attack with the aim to maximise the defender's minimum operating costs. The attacker knows where reinforcements were made in the preceding step, while at the same time acknowledging her own limited resources – the terrorist seeks to maximise her 'bang for the buck'. Attacker-defender models are mainly used to identify optimal defence strategies for constrained defence budgets by identifying which assets are the most critical, and where redundancies may be efficient (Bier *et al.* 2005; Brown *et al.* 2006; Romero *et al.* 2012).

6.3 Summary and critical appraisal

The dedicated energy security assessment literature is very diverse. As I have shown in this literature review, it is split into two broad but distinct methodological approaches.

The critical infrastructure research assesses the behaviour of physical energy systems during disturbances, generally through system modelling. This approach focuses on shocks in an infrastructure system and the system's responses to disturbances, thereby assessing its resilience and capability to maintain or restore system functionality during emergencies. The critical infrastructure research views energy security in a very direct sense: the vulnerability of a system is a direct function of the amount of energy not served, and the outage size and duration depends on the structure of the system. The approaches in the literature are generally of an engineering type, depicting full (but often simplified) systems, with high precision but also with very high data requirements concerning system topology and function.

The classic energy security research field focuses on indicators, which are used as proxies of various energy security vulnerabilities. In principle, as demonstrated by the ‘new dimensions’ frameworks, such indicator arrays can be very extensive, assessing all possible corners of energy security. Generally, however, indicator-based studies focus not on everything, but only on a few threats, like geopolitical threats (e.g. using a political risk indicator or import dependency, or both), threat of system failure (e.g. fuel diversity), and overall energy dependence (e.g. energy intensity). Numerous indicator methodologies are applied in the literature, but they can be assigned to one of two distinct methodological branches.

The first branch focuses on gathering indicators (sometimes tied directly to the items of the definition) without further aggregating them. These indicators are subsequently presented and compared to benchmarks, results from other cases, to historical data, or otherwise interpreted by the authors to produce a realistic picture of the vulnerability of a system.

The methodologies of the second branch focus on gathering indicators and aggregating them to a one-number index, which are easy to understand, also for non-experts. These approaches, which include the refined, but not necessarily the pure, diversity indices, thus implicitly assume that different threats, sometimes also uncorrelated threats (e.g. political risk and depletion) or threats to different energy systems (e.g. oil and coal supply), add to each other. In some cases, they also aggregate indicators for threat (e.g. market power) and resilience (e.g. global market liquidity) into one index. Such methodologies hold the risks of hiding important weakness in aggregation and of giving problematic results, as there is no theoretically or otherwise compelling reason to decide how the single indicator values should be aggregated.

The frameworks in the literature clearly have many advantages, but I also find a number of weaknesses. Just as in the definition literature, there is a tendency towards universality and generic metrics. The universality of ready-made indicators and easy-to-understand nature of generic metrics is a main reason for the attractiveness of these approaches in the literature. This practicality is indeed an important strength of such frameworks. However, achieving universality in metrics also removes the context of the assessed case, and does not say why events happen or how serious the impacts would be in a particular case. Many assessment frameworks focus mainly on constructing and manipulating indictors, but they rarely reflect in depth on the underlying mechanisms of the vulnerabilities they claim to assess. For example, the approaches reviewed in section 6.1 do not tell why, say, a high import dependency would be a threat in a particular scenario, as they do not say under which conditions the threat could materialise, how it could develop and what the impacts of the threat would be. To some extent, this is probably caused by the political nature of the energy security concept, which may explain why the energy security research field is to a large extent methods- and, especially, result-driven: methods first of all need to produce as policy-relevant and clear-cut results as possible. However, the context-less nature of generic metrics does not increase policy-relevance, but I would rather argue that it reduces policy-relevance: context-less frameworks are unsuited for analysing whether a particular development (i.e. a particular context!) introduces new vulnerabilities to a country or region.

Further, the assessment methodologies reviewed above may be useful for assessing energy security today, with well-known concerns and system configurations, but they may not be directly applicable to assessing the vulnerability in scenarios in which less (and less certain) data is available. This is in particular the case for most quantitative CI vulnerability assessment approaches: the model-based frameworks are (or can be) very precise, but the data – especially concerning energy system topologies – is not available in most scenarios. In principle, the indicators and indices can be applied using energy scenario data (as some, like

Costantini *et al.* (2007) and Lefèvre (2007) do), but as scenario data is generally highly aggregated, the data needed for a more contextualised assessment is not easily available. In some cases in the literature, authors thus rely on unknowable data. An example of unknowable data input is the political risk indicators sometimes used as a hostility scalar, especially in the refined diversity indices (section 6.1.4, e.g. Frondel *et al.* 2009; Jansen *et al.* 2004). These indicators may reflect the political stability or general 'reliability' of a country today (although already this can be seriously questioned), but they say nothing about the political reliability of an energy exporting country decades from now: this information is unknowable.

On the other hand, it is also not true that future energy security events take place in a "*state of ignorance*" (Stirling 2001:63) – in fact, quite much, although not everything, is known about future energy systems and possible threats and disruptions. By assuming ignorance, available knowledge (which is, again, context-dependent) is discarded and the precision and relevance of the assessment is unnecessarily reduced. Instead, an assessment should take place in the lower left quadrant ('uncertainty') of Stirling's incertitude matrix and not in the 'ignorance' quadrant (see Figure 2).

In this dissertation, I assess the European vulnerability to specific threats. As argued above, there is reason to believe that it is possible to construct context-specific metrics for assessing energy security in scenarios in greater detail than the frameworks in the literature, despite the limited data and knowledge about the future. Such an energy security assessment framework therefore needs to strike a balance between fully contextualised and disaggregated metrics of vulnerabilities to each single threat separately, which increases precision but also the data requirements, and more generic metrics adapted to the limited data availability from scenarios.

Although the metrics in the literature are either too generic for the objective of this dissertation or too detailed for the data availability, I find many concepts from the literature useful. The low data availability concerning system topology prohibits a scenario analysis using existing CI models, but the focus on the resilience of energy systems and the view that large and/or long outages are the ultimate sign of vulnerability are very useful building blocks for creating new metrics. The worst-case approach in the CI literature is also useful: as the worst case cannot be excluded, anything but a worst-case analysis could underestimate a threat. At the same time, the diversity index is generic and thus unspecific, but it offers a 'backstop' methodology: a diversity assessment building on Stirling's argumentation may still offer insights regarding the energy security of a scenario in case the data availability is insufficient for a contextualised and disaggregated assessment. Thus, building on concepts from the existing energy security literature, a methodology applicable to achieve the objective of this thesis should build on an understanding of the context of each single vulnerability: what is the threat and how does it develop, which system is threatened, how does this system react to disturbances, which and how serious disruptions could occur? In the next chapter, I develop an assessment framework that does precisely this.

7 Theory and methods: energy security assessments

In this chapter, I develop a new assessment framework, designed to be context- and threat-specific while at the same time being suited for assessing energy security in scenarios. I apply these new assessment frameworks to a Supergrid scenario with solar power imports (Desertec), a gas-import dependent scenario (GEA) and compare this to the current situation (Today benchmark; see section 7.3).

As described in section 5.3, European energy security policy focuses on 7 specific threat-types to its gas and electricity systems. Here, I develop vulnerability assessment metrics for the subset of two threats – coercion and export cut-offs as well as critical infrastructure failures – that can be meaningfully assessed in scenarios and contribute to the strategic choice between possible futures. This corresponds to the two research questions concerning vulnerability, see section 1.2. I do this by applying and adopting theories and concepts from both within the energy security research field and from other disciplines and research areas, following two general principles specifically addressing the limitations of the approaches in the assessment literature identified in section 6.3.

First, my starting point for the energy security assessments is a detailed understanding of why and under which conditions each single threat appears, how the threat unfolds and how it may affect a vital energy system, explicitly including the resilience of the system. Based on the deeper understanding of how each threat unfolds, I develop new, contextualised and disaggregated metrics to assess the vulnerability of specific systems to specific threats as closely linked to both causation and outcome of each single threat as possible. In this, I use the CI research focus on the resilience and flexibility of systems and on the potential size and duration of outages as the key evidence of vulnerability as an important starting point. I thus focus the assessments not only on the reasons why energy security-relevant events happen and how they unfold, but also on the resilience of vital energy systems and how these respond to disturbances in order to avoid or minimise potential disruptions.

Second, less is known about vulnerabilities in the future compared to those today or in the past. This is both because the wider context is missing, for example about international relations in 2050, and because the precise configuration and topology of future vital energy systems is unknown. At the same time, much information is available about scenarios and their potential vulnerabilities, both quantitatively (from the scenarios) and qualitatively (e.g. how energy systems work, how energy can be transported, what terrorists want, etc.). Therefore, a core principle of the work is to make use of all available knowledge to create the data sets I need and I apply this principle to increase the data resolution of the scenarios, if necessary and as far as possible. If the necessary data for contextualised and disaggregated metrics is unavailable or too uncertain, I may be forced to rely on metrics that are more generic. I will therefore use diversity indices, being the most generic assessment approach, as 'backstop' method alongside with the new, contextualised metrics: if the data is too uncertain to use more specific metrics, the diversity of a system may still say something about its vulnerability. I take particular care to match what is needed for an ideal, fully contextualised assessment and what is possible for scenarios, so that no useful information is unnecessarily discarded and that no unknowable data is used. As much information can be expected to exist only on a qualitative level, whereas quantitative ranges for what is feasible can only be assumed, a rigorous sensitivity analysis is a central issue to ensure robustness of the methods and results.

In the coming two sections, I develop the assessment metrics, based on a detailed understanding of how each specific threat unfolds and why it appears. These two sections thus include a description of the theoretical and conceptual underpinning of these metrics as well as the construction of the metrics themselves (sections 7.1 (vulnerability to coercion) and 7.2 (vulnerability to critical infrastructure failure)). I close the chapter with the selection and description of the scenarios (section 7.3), the principles for data mining in the scenarios (section 7.4) and the assessment cases, including the sensitivity analyses, for the vulnerability assessment methodologies (section 7.5).

7.1 Vulnerability to coercion

The threat of energy exporters cutting, or threatening to cut, supplies to Europe, is at the very heart of European energy security priorities. The fear that exporters might use this threat as a political tool to force Europe to concede to political, economic or other demands is particularly prominent (see chapter 4). Such events are colloquially referred to as the 'energy weapon', but here, I refer to such events as energy coercion, or simply coercion (see Drezner 2003; Smith Stegen 2011). In principle, the European energy sector has a high potential for such events, as energy is vital for modern societies and the European import dependency is high both presently and in most future scenarios.

In the past, European countries have been affected by a number of energy coercion events (see Table 10), most prominently the 1956 oil embargo during the Suez crisis, the 1973 oil crisis and the 2009 Russian-Belarusian/Ukrainian gas dispute. No coercion event has targeted Europe or the EU as such, but some events – especially the three mentioned events – have had impacts in Europe as well. Of the more recent coercion events directly or indirectly influencing Europe, only the 2009 Russian-Ukrainian gas crisis seriously affected final customers in Europe, with large gas shortages in the Balkan. Some historical coercion events were aimed at a single European country, especially the Russian-Baltic energy disputes in 2003-2007. All coercion events with supply effects in Europe have concerned the fossil fuel supply, whereas no significant coercion event involved electricity, as international electricity trade has historically been very limited.

Table 10: Large coercion events and events with effects on supply and/or price in Europe. The list is not exhaustive.

Year	Fuel	Caused by	Target	Triggering event	Resulting event; disruption	Peak size, duration
1956	Oil	**Saudi Arabia (also US, NATO)**	**UK, France**	Suez crisis	Saudi oil embargo Massive oil shortages in France and UK	2 Mbbl/d 4 months
1967	Oil	**Middle eastern oil exporters**	**US & UK (world)**	Six day war	Oil embargo No shortages, as other suppliers disregarded embargo	2 Mbbl/d 3 months
1973 - 1974	Oil	**Arab OPEC countries**	**US (later also the Nether-lands)**	US military support to Israel during the Yom Kippur war; wish to increase oil price	The first oil crisis: Oil / fuel shortage in US and European countries Oil price shock	4.3 Mbbl/d 5 months
1980 - 1983	Gas	**Algeria**	**Italy (France, US, Belgium)**	Algerian price demands, following oil price spike (Second oil crisis)	Delayed commissioning of TransMed pipeline (Italy); LNG supply interruptions (France, Belgium); no outages (as Italy was not supplied at onset)	TransMed: ~2 years LNG interruption in France small, short
2001	Oil	**Iraq**	**United Nations, world**	Protest against oil-for-food program	Iraqi oil export suspension Minor price increase	2.1 Mbbl/d (compens-ated by surge OPEC production; no net shortage) 5 weeks

Year	Fuel	Caused by	Target	Triggering event	Resulting event; disruption	Peak size, duration
2003	Oil	**Russia**	**Latvia**	Russia fails to take over ownership of oil terminal in Ventspils	Cut-off in Russian oil supplies to Latvia	Oil imported from other sources
2006	Gas	**Russia**	**Ukraine**	Pricing mechanism of Russian gas	Cut-off in Russian gas supplies to Ukraine; no final customer effects in EU	In EU: <80 mcm/d lost imports No outages 3 days
2006	Oil	**Russia**	**Lithuania**	Polish company bought Lithuanian refinery, beat Russian competitors	Cut-off in Russian oil supplies to Lithuania	
2007	Oil	**Russia**	**Belarus**	Customs mechanism of Russian oil deliveries to Belarus and transits to Europe	Russian interruption of the Druzhba oil pipeline Knock-on effects for downstream EU; no final customer shortage in EU	
2007	Oil / Coal	**Russia**	**Estonia**	'Statue crisis': removal of Soviet war memorial in Estonia	Cut-off in Russian coal supplies to Estonia and oil products for export via Estonian harbours	900,000 t coal; oil products mainly for export via Estonia
2008	Oil	**Libya**	**Switzerland**	Arrest of Libyan leader Gaddafi's son in Switzerland	Stoppage of Libyan oil deliveries to Switzerland; no final customer effects	3 days
2009	Gas	**Russia/ Ukraine (causing side unclear)**	**Russia/ Ukraine** **(EU)**	Pricing mechanism of Russian gas for Ukraine	Cut-off in Russian gas supply to Ukraine and transit to EU Large outages in south-eastern Europe	In EU: 300-350 mcm/d (up to 100% of national demand) 13 days

Sources: compilation based on Cherp *et al.* 2012; Flouri *et al.* 2009; López-Bassols 2007; Hayes 2004, 2006; Larsson 2006, 2008; Zhdannikov 2007; Stewart 2010b; Tagesanzeiger 2010; EC 2009b; Spiegel 2007; Hamilton 2011; EC 2009b; Kovacevic 2009; Pirani 2009; Pirani *et al.* 2009.

Many existing assessment frameworks focus on this threat, either explicitly or implicitly (see section 6.1). Most prominently, the studies focusing on import dependency and/or exporter diversity as a proxy of the market power of exporters do this, using it either as a single indicator or for a diversity index. However, these indices or indicators do not tell why and how the threat develops or what its impacts could be, and therefore they do not tell why and under which conditions a threat may be particularly serious. The refined diversity index approaches furthermore dilute the focus on power by adding "*ad hoc factors*" to the index (Lefèvre 2007:55), referring to issues such as resource depletion, political stability and market liquidity, thus aggregating resilience factors and different types of threats into a dimensionless, de-contextualised point value.

In the following, I develop a new assessment approach, circling around the issue of power: who has power over whom in an energy coercion event, how much power, and why? The following section is a discussion and description of theoretical and empirical insights regarding coercion, serving as the basis for the development of the new, contextualised metrics (section 7.1.2).

7.1.1 Nature of the threat: power and interdependence

Most industrialised countries have a large and growing energy import dependency: in 2009, the EU imported 55% of the energy consumed, compared to 43% 15 years earlier (Eurostat 2011). Since the oil crisis in 1973, if not before, energy importing countries perceive a threat to their security of supply. The formation of the IEA oil stocks and the ongoing build-up of European gas storages are examples of resilience- and security-increasing measures (López-Bassols 2007), showing that importing countries are not comfortable with being too dependent on single exporters. The sudden cancellation of energy deliveries from a major supplier, or a group of suppliers, could cause significant damages in the importing country. The threat of inflicting these costs (or actually inflicting them) on the importer by withholding energy deliveries and disrupting a vital energy system is the political pressure tool the exporter makes use of during an 'energy weapon' event. The 'energy weapon' thus is an attempt by an exporter to exert power on the importer country's political behaviour and to coerce her into accepting demands she would otherwise not have accepted (Smith Stegen 2011).

Equally, however, the energy exporting countries see security of demand as something vital to their economies. The formation of the Organisation of the petroleum exporting countries (OPEC) is an example of exporters trying to manage the oil export revenues (Yergin 2006). Whereas a reliable energy supply is the engine of modern societies, the economies of energy exporting countries often rely heavily on the revenues of their energy exports: Algeria and Libya, for example, gain 30% of their GDP and at least 95% of their hard currency export earnings from oil and gas exports (CIA 2010). Therefore, in many exporting countries, the energy export sector is a vital energy system, the failure of which could destabilise the economy or even the entire society (Cherp *et al.* 2012). This export dependence is the importer's tool in energy trade sanctions such as presently (December 2012) in place against Iran (EC 2012, see below for more on sanctions).

The relationship of energy exporting and energy importing countries should thus not be described as simple dependence, but rather as a relationship of interdependence (Keohane and Nye 2001). This interdependence can induce win-win situations, in which both parties benefit from a common and reciprocal issue, such as trade between countries. Interdependence can also be a mutual threat of imposing costs on both parties, such as the balance of terror during the Cold War. Both types of positive and negative symmetric interdependence are characterised by evenly distributed costs and benefits of non-compliance and compliance, respectively. Such a relationship is likely to be stable as no actor has bargaining power[23] over the other (Keohane and Nye 2001).

An example where interdependence theory has offered interesting insights and has helped to explain real-world developments is the gas trade between the Soviet Union (USSR) and Western Europe. In this, Western Europe was dependent on the USSR as a main supplier of gas, which –in the heated political atmosphere of the Cold War – raised concerns about European dependence and the threat of a Soviet gas cut-off. At the same time, however, the USSR was highly dependent on the hard currency income from the trade and had large investments locked down in gas infrastructure. This interdependence was a main reason for the absence of hostile interruptions in gas trade between the USSR and Western Europe, despite the strong political tensions between the two blocks and despite domestic Soviet domestic gas supply shortages during cold winters (Adamson 1985; Högselius *et al.* forthcoming; Mabro 2008).

In contrast to stable, symmetric interdependence, asymmetric interdependence may be a source of power: "*It is asymmetries in dependence that are most likely to provide sources of influence for actors in their dealings with one another. Less dependent actors can often use the interdependent relationship as a source of power*" over more dependent actors (Keohane and Nye 2001:10f). The relevant measure to characterise the interdependence symmetry is on the one hand the costs of non-compliance inflicted by the deal-breaking actor on herself, and on the other hand the opportunity costs of the other actor if she decides not to accept the

[23] In the following, I refer to bargaining power only as 'power'.

demands posed (Caporaso 1978; Keohane and Nye 2001). These costs, in turn, depend on the characteristics of the product and the availability of alternative options of exporting or importing the product.

The relationship can be a source of power for the exporter if a broken deal causes large damages for the importer, without damaging the deal-breaking exporter so much that it makes the threat non-credible. If the importer can substitute or buffer the lost imports, or if she can live completely without them, the dependence does not constitute a source of power for the exporter because a trade-cut does not cause high costs for the importer. And vice versa: if the exporter can do without or easily substitute the losses from the lost exports, an import embargo could not be a source of power as it does not cause high costs for the exporter (Caporaso 1978; Keohane and Nye 2001). Hence, it is not the mutual dependence in general that is important, but the interdependence *during the event*.

An interesting application of interdependence theory is the study of usefulness of economic coercion measures, or sanctions. These are "*the most visible exercise of the power that asymmetric interdependence can create*" (Drezner 2003:656). Drezner, in a widely cited study concerning 195 international disputes over labour standards, trade and environmental regulations, for example shows that sanctions can be a useful political tool: he finds that 41% of enacted sanctions and 67% of the threatened but not enacted sanctions were successful[24] (Drezner 2003, also Drezner 2001). Similarly, Hovi *et al.* (2005) find that the threat of sanctions have a high chance of success, but only if it is *potent*, *credible* and *non-contingent*: the target state must be certain that costly sanctions (more costly than yielding) will be

[24] Drezner defines 'success' as a change in the target country's laws in accordance with the sender's demands (trade, environment), or if the sender government and non-governmental organisations record a change in behaviour of the target country's labour standard behaviour.

enacted unless it concedes to the senders' demands, and it must be certain that the sanction will not be imposed if it does yield. The main reasons why sanctions that are only threatened are more effective than those actually enacted are simple. First, both sides will suffer costs if sanctions are enacted, so that both have incentives to solve the problem at the threat stage. Second, if a sanction is enacted, the target state has already resisted at the threat phase, because it perceives the demands as too expensive or believes that the threat is not credible. Hence, a target state that resists the threat is more likely to also resist the actual sanctions, whereas a state that would yield to actual sanctions is likely to yield already at the threat stage (Drezner 2001, 2003; Hovi *et al.* 2005). These conclusions thus support the notion that asymmetric interdependence indeed is a source of power and in many cases a useful political instrument, especially if the threat is credible and strong but not enacted. However, as discussed further below, having coercive power is not necessarily the same as having outcome power and being successful: other factors play a role, such as how well the game is played (this is further at the end of this section and section 10.5).

Keohane and Nye distinguish between interdependence on different power levels. On the lowest level is sensitivity interdependence, which describes the interdependence within an existing framework without adaptation of policies. On the second level is vulnerability interdependence, the interdependence after both sides have adapted their policies to respond to the new situation. These levels can also be seen as the time-dependency of energy standoffs. The initial outage shock, including the mitigating effects of buffers and other pre-defined measures on both sides, describes the sensitivity interdependence. The vulnerability interdependence, in contrast, is described by the longer-term effects, as "*an actor's liability to suffer costs imposed by external events even after policies have been altered*" (Keohane and

Nye 2001:11[25]). In the case of energy coercion, this would be after the activation of spare production capacities, re-routing of supply from other sources, rationing or other pre-defined emergency measures. Due to the short-term nature of sensitivity interdependence, this power level is "*less important than vulnerability interdependence in providing power resources to actors*" (Keohane and Nye 2001:13). This statement is highly relevant for energy coercion events, as most emergency response mechanisms are designed for short-term responses and are thus very fast to react. Most response mechanisms are fully operational within hours, and all within a day or so, so that it can be expected that it is either possible to remedy an outage rather quickly, or it is not possible to remedy it at all (see Appendix, sections 13.1.4, 13.2.4 and 13.3.4). In energy weapon events, the sensitivity interdependence may cause very high, but very short-term, costs for the importer, induced primarily by outages, so that the importer does not even have time to respond to any demands before her emergency responses have reduced the costs to acceptable levels, or completely eliminated them. Thus, although sensitivity-level interdependence can be important as a threat, the more relevant power level is the vulnerability interdependence. This terminology fits well also for the analysis of coercion events here: Europe is vulnerable if substantial costs remain after all responses have been activated and may be weakly vulnerable, or sensitive, if the costs are high but short-lived. The vulnerability of an actor thus depends on the answer to the question of how high the costs of an export interruption are after all responses have been activated, or, more simply, which actor can wait the other one out?

[25] Keohane and Nye also see a third and highest power level, military force. The cost-efficiency of this power resource is highly questionable and its usefulness is low in most cases (Keohane and Nye 2001). For the energy coercion events considered here, I do not consider military action here, due to the limited usefulness of military campaigns to remedy short-term energy supply disturbances.

In the Power and Interdependence theory I use here, the principal actor is the state[26], which is an internally homogenous actor whose "*behaviour can be interpreted as rational, or at least intelligent, activity*" (Keohane and Nye 1987:729). Both the importer and exporter states are likely to have at least a rough understanding of both their own dependence (i.e. the potential costs of a disruption) and the dependence of the other side. Each side thus have well-informed expectations of the power balance and the winning prospects, which strongly influence their decisions by casing a 'shadow of the future' back to guide their present behaviour (see Axelrod 1984).

One actor having power in a relationship is however not a sufficient condition for an 'energy weapon' event to take place: two further factors need to be fulfilled as well (Smith Stegen 2011, also Wagner 1988). First, the exporting state must have a *reason* to trigger the event. This can be for example economic (e.g. higher prices), political (e.g. achieving certain foreign or domestic policy goals) or personal demand (e.g. the arrest of a leaders son). Hence, an asymmetric relationship is a potential source of power, but this only means that this power can be used, not that it will be used (Keohane and Nye 2001). Second, the exporting state must have sufficient control over the energy sector to be able to access it as a foreign policy tool (*ability*). This is the case if the energy sector and its dominant companies are state-owned and if the trade takes place in a weak institutional setting. Liberalised and privatised markets, especially if it also embedded in strong international frameworks like the World trade organisation (WTO) or the European internal market, make it much more difficult and

[26] Note that this is not the case for Keohane and Nye's theory of Complex interdependence, which explicitly includes and focuses on non-state actors.

politically costly, although not impossible, for the state to access energy companies for foreign policy objectives (Smith Stegen 2011, see also Simmons 2000).

Both these issues are unknowable for scenarios ranging far into the future: one cannot know what reasons may appear, and one cannot know how the institutional setting and the participants' respect for market rules develop over the next 40 years. History shows that potential reasons are plentiful and can sometimes be somehow expected (such as the Arab oil export boycott during and following the Yom Kippur war in 1973), but sometimes reasons may appear as surprises (e.g. the Libyan-Swiss standoff of 2008, following the arrest of the Libyan leader Gaddafi's son in Switzerland). Presently, the institutional integration between the EU and most of its neighbours is high or increasing (Russia being among the possible exceptions), for example within the European energy charter or within the EU neighbourhood policy. Nevertheless, it will remain possible, although perhaps increasingly difficult or politically costly, for exporting governments to access energy companies for foreign policy goals. Thus, it cannot be ruled out that a reason for coercive action appears in future and that the exporting state is able to access the energy industry for its aims. Consequentially, I here assume that a state wishing to wield the energy weapon in the future will be able to do so as, if push comes to shove, states do have the possibility of such actions but must accept the political costs of doing so.

In addition to this, exporting states may coordinate their actions, so that more than one country – potentially even including all exporters – may participate in a coercion event. This would increase their leverage over Europe, but it is also associated with significant coordination difficulties. These difficulties can be seen already in the quota negotiations of the OPEC, with which the member countries do not always comply. Free-riders are a problem in such cartels, and it appears likely that it will be a problem for exporters also during a coercion event, both in terms of embargoing countries not sticking to the embargo agreement and of non-participating exporters increasing their exports to increase their own income. (Alhajji and Huettner 2000; Cairns and Calfucura 2012, also Drezner 2000; Mouawad 2008). Hovi *et al.* (2005) even find that a necessary precondition for successfully enacted sanction is that only a small number of sanctioning countries are involved. Further, the reason for joining such a multi-country export cut may be different for different countries: what is a valid reason in one case may not be valid in another. As indicated in history[27], only a massive European transgression of values, economic agreements, etc. against many countries at the same time appear to be a likely trigger of multi-country events. The probability of a multi-country coercion event thus decreases with a number of participating countries, as does the probability of it being coordinated and successfully carried out.

Finally, the coercive notion of bargaining power I use here is not necessarily equal to outcome power, as "*political bargaining is usually a means of translating potential into effects, and a lot is often lost in the translation*" (Keohane and Nye 2001:10; Nye 2004). Actors with power may, if the cards are played well, achieve the desired outcome, but if the cards are not played well also a powerful actor may fail its objectives (Wagner 1988). For example, Smith Stegen (2011), who analyses 5 'energy weapon' events involving Russia and its post-Soviet neighbours, concludes that Russia has been generally unsuccessful in achieving political demands, despite being in a powerful situation vis-à-vis the much smaller target states. She offers the possible explanation that the small target states – explicitly the Baltic states (which are today NATO members) and Georgia (which has an Individual Partnership with the

[27] The major multi-country events directed against Western countries in the past were caused by wars, or support for wars, against Arab countries: the Suez crisis (embargo against UK and France, who together with Israel attacked Egypt); the Six-day war (embargo against UK, US for their support for Israel); the Yom Kippur war (US and Dutch support for Israel). See Table 10.

NATO) – could resist Russian power through the backing of strong strategic alliances with the West.

An actor without power, however, will not be able to produce a credible threat. This actor is very unlikely to succeed in coercing the opponent into accepting her demands. Thus, having power may not always suffice to achieve an outcome, but not having power is an almost certain guarantee of failing: in order to understand the threat of coercion, "*it always helps to start by figuring out who is holding the high cards*" (Nye 2004:3; Drezner 2003).

7.1.2 Assessment metrics

As I have argued above, a useful assessment metrics for a country's or a region's vulnerability to coercion in energy scenarios should focus on the issue of power and the symmetry of dependence between the relevant actors during the event. Finding a balance between a generic metric, based on readily available data, and a specialised one with higher precision but also higher data requirements is a central task. In the quantitative vulnerability assessment here, I use both these end-points of the metrics spectrum: a diversity index for exporter market power, used as a first, generic estimate of European exposure to power, and a more detailed metrics describing the vulnerability as the dynamic behaviour of the cost- or power-symmetry during a coercion event.

Exporter diversity

Following the considerations of Stirling (see section 6.1.4), the most generic meaningful indicator of the vulnerability of a system is its diversity. Here, I wish to assess the threat that energy exporters interrupt (or threaten to interrupt) the energy trade as a political tool to put pressure on Europe. Therefore, I use a standard measure for market power – the Herfindahl-Hirschmann Index (e.g. EC 2011b) – based on the relative importance of each supplier of the assessed energy carrier to Europe as a proxy for vulnerability to coercion. Low diversity of a system indicates that single actors may have power, thus making Europe potentially vulnerable as exporters may be able to exert power over Europe. High diversity shows the absence (or low level) of such power, indicating a high level of security for Europe. The HHI for exporter power is formulated as

Equation 18 $$\Delta_{power} = \sum_j p_j^2 ,$$

where p_j is the share of electricity or pipeline gas exports from country j in the total supply of the assessed energy carrier (electricity or gas). For gas, I consider only the diversity of pipeline supplies (as a share of total gas supply), whereas I do not consider LNG imports here, for two reasons. First, the presence of storage facilities in the LNG gasification terminals enables continuous supply for several days even if no new deliveries arrive (see section 13.2.4). Second, I assume that LNG is traded on a liquid global market (see section 7.4): if the ships from one country (or group of countries) embargo Europe, a liquid market will be able to reroute other ships to Europe before the LNG terminal storages are empty. Hence, LNG is not well suited for coercive action (Goldthau 2007; Goldthau and Hoxtell 2012), and I here consider it secure. Similarly, I view all domestic supplies of electricity and gas as entirely secure. These therefore only affect the diversity score by reducing the share of supplies at risk.

I calculate the supplier diversity using the supplier structures described in Table A 1, Table A 7 and Figure A 7 in the Appendix. Variations in this supplier structure is tested along the sensitivity analysis rules for the max.- and min.-diversification for vulnerability to coercion as described in section 7.5.

This diversity index is the simplest form of assessing the power of an exporter, and explicitly ignores the exporters' dependence on the importer. The diversity index is thus a measure of the European exposure to exporter power, but not of the power balance between the two trading sides.

Power balance

To create a more precise metric of an importers vulnerability to coercion, I must explicitly consider the power balance between exporter and importer. Hence, I must assess the potential impacts and resulting costs of a coercion event on both sides. This requires much input data, some of which is uncertain and available only in a what-if scenario analysis, but produces better and more useful results. A scenario analysis such as done here, therefore, also follows Stirling's (see Figure 2) recommendation for assessing risks with bad/no knowledge about probabilities and some knowledge about impacts of events. In the following, I define a new metrics to assess the power balance in the trading relationship by conceptualising power as the direct costs inflicted on the importer and exporter during a coercion event, should the exporter decide to cut exports. In this, I take conceptual starting points – a focus on the potential impacts of events, including system resilience – from the critical infrastructure literature and apply the Power and Interdependence theory as described above. The central actors in this are the exporting countries and the importer, Europe[28]. I consider only the direct costs of an interruption, namely the costs of outages and counter-measures on the importer side and the lost income for the exporter side. I do not consider other indirect or long-term effects of non-compliance, like lost reputation from breaking international treaties, although these could essentially also be seen as costs. Similarly, as discussed above (section 7.1.1), I do not assess who will win the energy coercion stand-off, something which depends on unknowable issues like how the available power is played out in the specific event and the actors' willingness to accept damage, but merely who has bargaining power over whom. I discuss these limitations further in section 10.5.

The cost symmetry, or power balance, (C) is determined by the difference between exporter (c_{exp}) and importer (c_{imp}) costs:

Equation 19 $$\boldsymbol{C(t) = c_{exp}(t) - c_{imp}(t).}$$

If C is negative, the importer is the more dependent actor and may be subject to power from the exporter, especially if C remains negative over time. If C is positive, the exporter has no power, but instead the importer has power over the exporter. If C is close to zero, the relationship is stable and no actor has power over the other. I calculate the costs both in absolute (€) and in relative terms (% of GDP) in order to reflect both the magnitude of the potential costs and the dependence of the trade to each trading partner. The relative costs, describing the dependence of each actor on each other, are especially important to describe the power balance.

[28] Europe is defined in section 1.1; see also section 7.4. In the sensitivity analysis, I run bottleneck cases in which the 'importer' is a subset of Europe, see section 7.5.

The exporter's direct costs for a broken delivery deal are the lost income, determined by the amount of non-delivered energy (m_{exp}) and the price for this at the target market (p_{exp}). Here, I assume that no grid infrastructure to other significant markets[29] exists, so that exports cannot be rerouted to somewhere else. Further, I assume that the energy availability in the exporting country is sufficient to satisfy domestic demand without cutting exports. If the export country is also a transit country for an amount of energy (m_t) from somewhere else, for which it receives the transit fee (p_t), the costs of an export/transit embargo increases. The damage function for the exporter and/or transiter can thus be written as:

Equation 20 $$c_{exp}(t) = m_{exp}(t) \cdot p_{exp}(t) + m_t(t) \cdot p_t(t).$$

Importantly, if the importer relies on gas storages to compensate lost gas during a coercion event, I here assume that the gas storages are replenished with gas from exporters than the one(s) that caused the event. Hence, the exporter costs are directly proportional to the non-delivered gas, and the exporter is not compensated after the event.

The importer is prepared for technical contingencies and other disturbances and has access to buffers and various emergency response mechanisms to replace failed capacities, regardless of why these capacities failed. The size and specific cost of any outages, as well as the size and the specific cost of the emergency responses, determine the importer's direct costs. Here, I assume that the supply and demand are balanced before the interruption, and that the demand remains constant for the duration of the export cut. The outage size is determined by

[29] This could, potentially, for example be gas pipelines between Russia and China, or a trans-Saharan gas/electricity corridor from Algeria to Nigeria. Such developments are possible, and could have an impact on the exporter's power situation, but are not foreseen in the scenarios and are thus not considered here. LNG is increasingly traded on a global market and could in future offer possibilities for exporters to re-route exports. In the GEA, however, Europe is the by far dominant gas importer. Hence, I assume that the exporters cannot divert LNG to alternative export markets.

the non-delivered energy (m_{exp} + m_t), minus the emergency responses, consisting of supply-surge (m_{res}), storage-draw (m_s) and demand-response (m_{red}) capacities. The specific outage cost (p_{bl}) is the value of lost load (VOLL, see sections 13.1.5 and 13.2.5), whereas the specific response costs are described by the terms p_{res}, p_s and p_{red}. The price of the non-delivered energy (p_{exp}) is subtracted from all importer specific costs, as the importer does not pay for non-delivered energy. The importer costs are thus

Equation 21 $$c_{imp}(t) = \left(m_{exp}(t) + m_t(t) - \left(m_{res}(t) + m_s(t) + m_{red}(t)\right)\right) \cdot \left(p_{bl}(t) - p_{exp}(t)\right) + m_{res}(t) \cdot (p_{res}(t) - p_{exp}(t)) + m_s(t) \cdot (p_s(t) - p_{exp}(t)) + m_{red}(t) \cdot (p_{red}(t) - p_{exp}(t)).$$

All terms are constrained by $m_{exp}(t) \geq \sum_i m_i(t)$ and $p_{bl}(t) \geq p_i(t)$ so that $c_{exp}(t), c_{imp} \geq 0$. The emergency responses are only activated when the normal supply is disrupted.

For electricity, the system buffers are the primary control capacities. The emergency responses are the supply surge capacities, including the secondary and tertiary control, which are normally used to balance fluctuations and handle technical contingencies in the grid but can also be used to make up failed imports. They also include spare capacities, i.e. generation capacities that are unutilised at the time of the disturbance, and import surges from countries not participating in the coercion event. Disturbances long enough to make new-built capacity a factor to address are not considered here: building new power plants typically takes years, and if a blackout lasts that long, the importer is very likely to give in to the exporter long before new capacity is in place. There are also demand-reduction emergency measures. Such demand-responses here refer to voluntary demand reductions, whereas I consider involuntary demand reductions, such as rolling blackouts, as outages.

For gas, the system buffers are the storages. The emergency responses are primarily surge imports from countries not participating in the coercion event, both by pipeline and LNG. In contrast, I assume that the domestic gas production always operates at maximum capacity, without mentionable possibilities to increase during emergencies. The storage-draw is in principle constrained by the overall storage capacity (see sections 13.2.3 and 13.3.3), but are here *de facto* unlimited for the short time interval (hours-days) considered. The demand-response capacities available in the gas system are electricity sector fuel-switches, and industry demand-constraint measures. I consider involuntary demand reductions, like forced disconnection of customers, as outages.

I describe the data used for the calculations in section 7.5 (base case interruptions) and in the Appendix (the detailed supplier structure, the response capacity sizes and operation intervals). Importantly, as much of this data is uncertain, a rigorous sensitivity analysis is a key component of the assessment: I describe the sensitivity analysis case variations in section 7.5. As I elaborate there, the bottleneck variation for Balkan in the Today case (section 7.5.3), offers a test case – probably the only one possible for Europe – to validate the model with empirical data.

7.2 Vulnerability to critical infrastructure failure

Protection against end-user disruptions due to failures in the critical electricity and gas infrastructure is a strong priority in European energy security policy (see chapters 4 and 5). As a result, outages are uncommon: Europeans on average experience two blackouts per year, lasting around 100 minutes (CEER 2008). There is no comprehensive and publicly available data on gas outages, but they appear to be less frequent than blackouts: in total, there were 76 European transmission pipeline incidents with leakage in 2008-2010, or 25 per year (EGIG 2011).

In the literature, the vulnerability of CI systems is generally assessed by detailed modelling of entire systems and their reactions to disturbances (see section 6.2). Such approaches are very useful for assessing the vulnerability of existing CI systems, but for future systems, the necessary data on the system topology is not available. Hence, I need other ways of assessing the vulnerability to critical infrastructure failures.

Here, I develop new methods for the assessment of CI vulnerability in scenarios, reflecting the notion that the primary aim of energy security is to a) prevent detrimental events from happening, b) prevent unavoidable events from causing outages, or to c) minimise the size and/or duration of an unavoidable outage (as reflected in European energy security policy, see section 4.4.3). Applying the two overarching principles described in section 7 – to focus on why and how each single threat develops and to utilise all available information regarding this – requires an important distinction between two distinct types of threats to critical energy infrastructures. Outages can be caused by either random technical failures (e.g. a component breaking down) and natural events (e.g. a storm), or by intentional action (e.g. terrorism[30]). It is not fruitful to look at the causes of random events – instead, a focus on the potential impacts is the most meaningful way to assess such threats. For intentional attacks, however, it is possible to look at both the cause, which is guided by rational (or at least intelligent) and malevolent deliberations, and the potential supply outages caused by such events. In the following section, I describe the nature of these threat-types as the base for the construction of new metrics.

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[30] European energy security policy also makes reference to other intentional events, such as strikes (esp. UK) and war (esp. Sweden), but this focus is weak as protection against these threats are rather mentioned as positive side-effects of measures targeting terrorism or natural events (see chapter 4, especially section 4.4.2). In the following, therefore, I do not explicitly consider non-terrorism human-caused events; these can be seen as implicitly assessed together with the terrorism vulnerability.

7.2.1 Nature of the threats: random events and intentional attacks

As shown in the literature review (section 2.2), the threats to critical infrastructure fall into two groups: random natural or technical events and intentional, malevolent attacks. Here, I describe these threat-classes with respect to their significance and, in particular, with respect to how they unfold and how they may affect vital energy systems.

Random events: technical failures and natural events

In the electricity sector, natural events such as storms, snow or lightning are the most common causes for supply outages. For example, up to 90% of all blackouts in the Nordic electricity system are caused by natural events, especially lightning-strike (Nordel 2008). Technical failures, including accidents (e.g. construction workers digging through a cable) account for practically all other blackouts. Most blackouts are caused by events in the distribution systems (CEER 2008), both as the distribution system is much larger than the transmission system and as the lower voltage levels, closer to the final consumers, have less redundancy. In the gas sector, almost half of all transmission system failures leading to leakage were caused by "*external interference*", in particular accidents during ground works, whereas construction faults and corrosion were responsible for 1/3 of pipeline failures (EGIG 2011:21). Natural events thus appear less important to gas supply reliability[31], probably as pipelines are generally buried underground and not exposed to most weather events. About 4.5% of all European pipeline ruptures ignited (EGIG 2011, see also Flouri *et al.* 2009).

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[31] However, the available data only includes leakage events and may underestimate the outage frequency: it is possible that some failure events have caused outages without causing leakage.

Natural events strike at a random time at a somewhat random place. Each event cannot be predicted a long time in advance, but some events, like storms, can be anticipated hours or days in advance. Nevertheless, most natural events have a meaningfully quantifiable probability: storms or floods, for example, have a fairly well-defined frequency (leading to common terms like 'storm of the decade' or 'one-hundred-year flood', etc.). Other events, like earthquakes, can generally not be predicted even in the very short term, but their general frequency is roughly definable, and serious earthquakes are very improbable outside seismically active areas. Many of the forceful natural events affect an area and all the physical components within it, so that a single severe storm event can bring down several separate power lines. However, the severity of natural events follow a power law distribution, so that very forceful and/or large events may happen, but they are much less frequent than weak and/or small events (Clauset and Wiegel 2010).

Technical failures – either components breaking down or accidents – are similar to natural events in the sense that they also happen largely at random, but with a rather well defined probability. Generally, issues like component age affect this probability, so that older components have a higher probability of failing, but how rapidly the reliability is lost depends on several factors, especially on the maintenance. An interesting exception from this rule of thumb is that the European domestic gas transmission pipelines fail much less frequently with increasing age, due to technical improvements (especially modern corrosion protection, see EGIG 2011). Technical failures differ from natural events in the sense that they generally affect only one component at the time: it is very unlikely that two independent components fail simultaneously. Consequently, component failure usually does not lead to outages other than for the customers directly served by the damaged component. Technical component failures are therefore particularly important for failures in the local distribution systems, where customers directly rely on only one single line or distribution station. On the transmission level, large and sustained supply outages are the very uncommon consequence of single component breakdown, as the systems are designed to withstand the failure of any one unit (n-1 principle, see Appendix sections 13.1.4 and 13.2.4). In almost all cases, the damaged transmission unit can be circumnavigated and energy supplied through other routes so that overall system functionality is maintained.

Intentional attacks: Terrorist target selection

Intentional attacks, prominently terrorism, are fundamentally different from natural and technical events. Such attacks are not random, but man-made events, carried out with the malicious and intelligent intent to cause maximum damage by deliberately choosing the target and the time of the attack, and by finding ways to go around existing protection measures (Bouwmans *et al.* 2006; Brown *et al.* 2006; Li *et al.* 2005). Terrorist attacks against critical energy infrastructure thus have the potential to cause massive disruptions of vital energy systems with potentially grave impacts on the affected society, so that energy systems are sometimes described as "*a dominant target for terrorist attacks*" (Tranchita *et al.* 2009:246).

A key characteristic of terrorism is that it has a "*symbolic quality, which distinguishes it from conventional forms of violence* [and gives it an] *indirect and psychological character. Terrorist actions are ultimately designed to influence one target by attacking another*" (McCormick 2003:474). A crucially important defining issue of terrorism is therefore that the attacker seeks to achieve a distinct political objective by creating fear – terror – in an audience wider than the one immediately affected by the attack, in order to coerce policy into accepting political demands (Ruby 2002; Jackson 2007; McCormick 2003; Schmid 2004; Turk 2004).

Consequentially, understanding the fear of terrorism is the key to understanding terrorism itself. For example, in 2000, 405 people were killed in terrorist attacks worldwide, to be compared with the 56,500 deaths in car accidents in the EU in 2007 – still, few Europeans are more afraid of the much more dangerous traffic than of terrorist attacks (Eurostat 2010; Ruby 2002). This is a well-known and much studied phenomenon: increasing the emotional salience of an event shapes human perception by massively devaluing knowledge and experience of past events, causing perceptions that greatly overestimate both the probability and the impacts of emotionally laden events such as terrorist attacks. Thus, as devastating as the immediate impacts of an attack can be, the main impact of terrorism, and indeed the principal aim of terrorist attacks, is the creation of fear in the wider population (Sunstein 2003; McGraw et al. 2011).

A further characteristic of terrorism is that the attack capacity of terrorist groups is limited, whereas the defence capacity of the defender – which is ultimately a state (or a number of states) – is very much larger (Schmid 2004). This asymmetry requires the attackers to select their targets carefully, so that terrorist targets are typically soft, or easy-to-attack, high-profile objects (Erickson 1999). The target typically fulfils at least one of five attributes (Branscomb 2004, also Drake 1998): a successful attack may either

1. cause large human casualties
2. disrupt the functioning of the government or society
3. inflict great economic damage
4. destroy physical facilities
5. destroy a symbol of the culture/country the terrorists detest

These points, and especially points 2-4, could in principle be achieved by a large-scale attack on critical energy infrastructure, and point 1 could in principle be achieved if an outage is very large and last long. The energy system may face increasing importance, as undercutting the enemy's economic capability is an increasingly important objective of international terrorism (Libicki *et al.* 2007). In addition, each single pipeline or power line is a soft target that cannot be permanently protected (see section 6.2). Therefore, critical energy infrastructure may indeed be a potentially attractive target for terrorists.

However, during the research for this dissertation, I could not find any reports of terrorist attacks with mentionable effects on energy supply in Europe. Two bomb attacks in 1997 and 2006 interrupted gas exports from Algeria to Europe for a few days, but without any impact on end-consumers in Europe (Lacher and Kumetat 2011, also Flouri *et al.* 2009). In 2013, an al-Qaeda group of some 30 attackers stormed the En Amenas gas field and took 800 workers hostage. The crisis (in particular the rescue operation) led to the death of 40 hostages and temporarily stopped gas production at the facility, which produces 10% of the Algerian gas, but did not cause gas supply outages in Algeria or abroad (Beaumont and Gallagher 2013; Chikhi 2013). This low incidence data is confirmed by data from the US: one source reports that 0.7% of all registered blackouts in the US between 1984 and 2006 were caused by "*intentional attack*", including sabotage, but it does not explain further what this means (Hines *et al.* 2009:5251f). Another source states that no terrorist attacks against the energy systems have happened in the US or Canada although "*such attacks are common in other countries*" (Simonoff *et al.* 2007:547).

Also outside Europe, however, terrorist attacks causing supply outages are uncommon, despite intermittent calls for such attacks, such as the al Qaeda call to target "*the umbilical cord and lifeline of the crusader community* [the US and US-friendly Muslim governments]" (Osama bin Laden, in: MacAskill and Whitaker 2002; al Qaeda however has a complicated record on this issue, due to the importance of oil revenues to Muslim MENA countries).

Generally, attacks go without supply effects, either because the disabled assets are not large enough to seriously interrupt supply, or because it is difficult to successfully attack multiple or large chokepoints. For example, the 2006 attack on the Saudi Arabian Abqaiq oil processing facility, with a capacity of 7 million bbl/d, or 8% of the global oil demand, could have been truly spectacular, but the attack failed as the two attacker groups' bombs exploded within the compound but far from the oil-handling assets and the attackers were shot (Al-Rodhan 2006; Jamali 2006). In contrast, the 14 consecutive, successful bomb attacks on the Arab gas pipeline in Sinai 2011-2012 stopped Egyptian deliveries to Israel and Jordan during 291 days between March 2011 and March 2012. Israel, the probable target of the attacks, could satisfy all its demand by storage draw and other emergency measures. Jordan, which may have been only collateral damage of the attacks, however experienced gas supply outages during winter/spring 2012, as it draws 100% of its gas from this pipeline and has no mentionable gas storage capacity (al-Ahram 2012; BBC News 2012; Kessler and Keinon 2012; Kessler and Usadin 2012; Luck 2012; Numan 2012; NYT 2012; Sheizaf 2012).

Just as most terrorist attacks against energy assets go without supply effects, I could not find evidence that energy targets are a dominant terrorist target (see Table 11): only 3% of all terrorist attacks registered in the US governmental National Counterterrorism Center's database (WITS) affected CI, including gasoline trucks and the employees of CI facilities (WITS 2011).

Table 11: Registered terrorist attacks between January 2004 and June 2011.

	Number of registered attacks	of which in EU27	of which in North Africa	of which in Russia
Total registered terrorist attacks 01.2004-06.2011	82,594	2415	479 (434 Algeria, 38 Egypt)	2296
Attacks affecting energy infrastructure/employees	2572	18	22 (17 Algeria, 5 Egypt)	70
of which against electricity assets	638	14 (10 Spain, 2 France, 2 Greece)	3 (2 Algeria,1 Egypt)	14
of which against power stations	63	1 (Spain)	2 (Algeria, Egypt)	1
of which against gas pipelines	354	0	6 (3 Algeria, 3 Egypt)	30
of which against gas wells	7	0	0	0

Source: WITS (2011).

Almost ¾ of the CI attacks took place in Pakistan, Iraq, Afghanistan or Nigeria, indicating, not surprisingly, that war, insurgency and civil unrest are spawning factors of terrorism. Only 12 of the 2572 registered CI attacks caused 'heavy damage' (damage >$20 million[32]), whereas almost all attacks caused 'light damage' (<$500,000), or 'none'. Most CI attacks – at least 60% – and all attacks causing heavy damage affected energy transmission facilities, pointing out these chokepoints of the energy system as the most attractive target. However, many of the CI attacks seem to have mainly targeted not the technical assets, but rather the energy system's softest targets – the personnel of the energy installations (Lacher and Kumetat 2011).

[32] These were 9 oil pipeline attacks in Nigeria, 2 oil pipeline attacks in Iraq, and 1 gas pipeline attack in Mexico.

Hence, there is a strong discrepancy between the theoretical high attractiveness and observed low incidence of terrorist attacks against energy infrastructure. Three explanations for this have been offered recently. First, terrorist targets generally have some symbolism attached, connected to the group's enemy – generally 'the state', certain government institutions, or a foreign nation. Toft *et al.* (2010:4419) argue that critical energy infrastructure is "*rarely a strong messenger of ideological symbolism*", which to them helps explain the low CI attack frequency. Second, some argue, energy outages are indiscriminate, affecting target audience and supporters alike. Spectacular attacks on CI may thus alienate supporters, which greatly reduces the attack attractiveness. Both Smith Stegen *et al.* (2012) and Toft *et al.* (2010) emphasise this is a main contributor for the low attractiveness, and hence frequency, of terrorist attacks against energy systems (see also section 6.2). The third explanation refers to the limited impacts of attacks against energy infrastructure. Although an outage "*is costly and annoying* […] *it pales in comparison with the effect of large-scale loss of life that is often the purpose of terrorist acts*" (Farrell *et al.* 2004:459). In this view, attacks against the energy system are unattractive because the impacts of attacks against even softer, human targets are much higher: igniting a bomb at a crowded market generally fits terrorist objectives better than felling an electricity pylon.

However, it is unclear whether these explanations hold in the future: they may, but one cannot know. It is not possible to know whether future terrorists attach symbolism to CI in the future, but it is known that at least some groups do that today (see e.g. the bin Laden quote above). In a future world with significant energy trade, such as the one assessed in this dissertation, it cannot be ruled out that terrorists attach symbolism to energy assets. Further, the non-discriminatory nature of energy outages does not apply to all energy system designs. A configuration with point-to-point interconnections, such as HVDC lines or dedicated export pipelines, in which the destruction of a link would cause outages only at the receiving end, is possible. Such a configuration is very likely in the case of a Supergrid, which is based on HVDC links (see section 1.1 and Appendix section 13.1.3). Although the third explanation – the limited impacts of CI attacks – appears valid for past events, the knowledge that the impacts of terrorist attacks were small in the past gives no guarantee that the impacts of future terrorist attacks will also be small.

Large-scale attacks against the energy system are possible, and – reversing Farrell *et al.*'s argument – such attacks could potentially cause "*hundreds of even thousands of deaths due to heat stress or extended exposure to extreme cold* [and entailing] *costs of hundreds of billions of dollars* [thus playing] *directly into the hands of terrorists*" (Crane *et al.* 2012:1). Fear-creation and significant economic damage however only result from attacks with high impacts: "*the greater the loss* [to the defender] *the more attractive*" to the attacker (Woo 2002:13). Woo (2002) even circumscribes 'attractiveness' with 'utility', and introduce a proportionality between utility and potential impacts to highlight what terrorists aim to do.

Hence, events with spectacular potential impacts are more attractive to terrorist than minor ones. Just as having power in a coercion event is necessary, but not sufficient, to successfully push through political demands (see section 7.1.1), a terrorist group must be able to cause spectacular damage in order to have a chance at success in terms of achieving their political demands, but this is not sufficient. Governments have good reason not to negotiate and yield to terrorist and are generally resistant to 'blackmail' by terrorists (see section 10.6 for further discussion of this). As a consequence, as shown by Abrahms (2006), less than 10% of the world's major terrorist groups have been successful in achieving significant political concessions.

Nevertheless, groups set to attack energy infrastructure are, as spectacular impacts are a necessary condition for political success, likely to find multiple simultaneous attacks attractive. However, not many terrorist groups have the capacity for a high number of attacks. It is very difficult to carry out a large number of attacks successfully, so that a higher number of attacks have a lower probability. Therefore, the high attractiveness of the spectacular potential effects of high-number attacks is counter-acted by the low attractiveness of having to coordinate multiple attacks. It has been shown that the severity terrorist attacks follow a power law distribution, so that the probability decreases rapidly with the size of the targeted interruption (and with the number of coordinated attacks), but the probability never reaches zero (Clauset and Wiegel 2010; Clauset and Young 2008).

Therefore, understanding whether a scenario has inherent vulnerabilities that may be exploited to cause such significant damage, as expressed by the possibility of spectacularly large and lasting impacts, is the key to understanding its vulnerability to terrorism. If an energy pathway holds significant inherent vulnerabilities, the impacts of a reasonable number of coordinated terrorist attacks may be large. This, in turn, would increase the attractiveness of such targets, making attacks against them more likely, and the system could be seriously vulnerable to attack.

7.2.2 Assessment metrics

The nature of the threats as described above has strong implications for the definition of metrics for the assessment of the vulnerability to critical infrastructure failure. Natural events have some probability of happening (e.g. on average one severe storm per year in a region), but one cannot know exactly when, with what force and where they strike. This also means that one cannot exclude that it strikes at the worst time at the worst place, so that anything but a worst-case assessment would underestimate the vulnerability (see Brown *et al.* 2006, section 6.2). In addition, as natural events may affect an area, and not just a single place, one single natural event has some probability of affecting numerous infrastructure components, with a rapidly decreasing (power law distribution) probability for increasing number of affected units.

Terrorist attacks, in contrast, have no meaningful probability. Here, I assume that terrorists aim to maximise damage – blackouts or gas supply outages – so that one can expect a terrorist attack to happen at the worst possible place at the worst possible time. Also here, this reflects a worst-case attack scenario, as alternative terrorist objectives, for example to punish an exporting energy company, would have the same or lower effects for Europe (see section 10.6 for a discussion of diverging terrorist objectives). Numerous terrorist attacks, simultaneously aimed at several CI components are possible and could pose a risk (Smith Stegen *et al.* 2012), but such events also follow a power law so that the probability decreases rapidly with an increasing number of attacks.

The worst-case assumption for both random and intentional events means that a vulnerability assessment of both event-types must first consider what happens after the failure of the most sensitive point, then of the second-most sensitive point, and so on. Both event-types may cause multiple unit failure, with decreasing probabilities of higher numbers of disabled units, but the probability never quite reaches zero. These two points together mean that despite the different natures of natural and intentional events, the metrics to assess a system's vulnerability to them is identical.

In reality, CI security is only one of many issues competing for scarce policy attention and funds. Hence, a worst-case assessment may give an exaggerated view of the actual CI vulnerability, as the probability that true worst-cases happen is very small, thus diverting funds to CI protection. If the worst-case results show a high vulnerability, this may be the case. However, if the results show that even a worst-case event does not lead to high vulnerability, one can be certain that higher-probability events, which have smaller impacts, also do not make Europe vulnerable. Such results would not contribute to the unjustified diversion of funds and attention from more pressing societal issues, despite the worst-case focus.

I carry out the assessment of vulnerability to critical infrastructure from three perspectives: (1) chokepoint diversity, (2) a comparison of the size of chokepoints and buffers, and (3) a dynamic assessment of potential impacts of chokepoint failures. There are two main reasons for this.

First, it reflects an intuitive sequence to minimise vulnerability:

1. avoid dependence on single components to reduce the seriousness of each single failure
2. buffer disturbances to avoid outages if serious failures occur
3. reduce the magnitude and duration of outages

These three points are also found in the energy security policies in the three European cases, reflecting the priority ranking to prevent disturbances from developing into disruptions and, if this fails, to mitigate the consequences (see chapters 4 and 5, also e.g. EC 2004).

Second, analysing vulnerability from these three perspectives is interesting from a methodological and uncertainty point of view. The first perspective, the diversity assessment, has comparatively low data requirements, it is the most generic energy security indicator, and it is frequently used in the literature (see section 6.1.4; also Stirling 2010). It however ignores the context of the assessment, so that it is hard to determine benchmarks of 'secure enough', something that is exaggerated by the ordinal scale of indices. A diversity index can by definition not tell how vulnerable a system is, or whether the system is secure enough, as ordinal scale indices can only compare the diversity between systems. The diversity index thus acts as a backstop metric: if other perspectives are too uncertain, a diversity analysis may still say something.

In the second perspective, I add knowledge about how critical energy infrastructure systems are designed and operated and create a new metric that includes the systems' immediate emergency response mechanisms ('buffers') and compares these to component failure scenarios. If a system can buffer a high number of failed chokepoints, the system may be secure although each chokepoint itself is vulnerable. Adding this knowledge gives more realistic results that are easier to interpret, but they are based on more uncertain data than the diversity index.

In the third perspective, the disruption assessment, I develop another set of metrics to assess the vulnerability of a system as the potential size and duration of an outage. This perspective produces the most relevant results, but it requires large amounts of data – some of which must be assumed or estimated – which may make the result uncertain. As the input data from the scenarios is uncertain, I run a rigorous sensitivity analyses based on qualitative and semi-quantitative knowledge about what is *possible* rather than what is probable concerning the uncertain parameters.

One can expect the infrastructure systems underlying the assessed scenarios to consist of hundreds of thousands of units, and – as discussed before – the topology of the system is unknowable. To make the assessment manageable, although still useful, this data requirement must be reduced. Here, I do this using the notion of chokepoints.

On a component level, all energy and electricity scenarios have very much in common. For example, all scenarios assessed here rely on domestic transmission and distribution AC electricity grids and domestic gas transmission and distribution systems. For example, a massive failure in the domestic electricity or gas grid would be similarly disastrous in all scenarios. Thus, I exclude all domestic components with similar vulnerabilities in all scenarios, such as the abovementioned and assess only the inherent vulnerability of *the CI characteristics that differ* between the scenarios, not the total CI vulnerability of a scenario. This is consistent with the perspective that a vulnerability assessment of scenarios should inform the strategic choice between different pathways (see sections 1.2 and 5.3).

These differences originate in the characteristic features that distinguish them from each other, features that are enabled by specific technical components. In some cases, these components are *chokepoints* – critical components that bundle the energy flow. I define chokepoints as the largest single points along an energy supply chain. For example, a trunk gas pipeline is a chokepoint, as many gas wells feed into it, and many smaller pipelines or customers draw from it. Disabling a point along the trunk line could disable the entire flow of this energy stream, whereas disabling another point of the energy chain would cause smaller impacts (McGill *et al.* 2007). A disabled chokepoint is, therefore, the worst-case situation.

The characteristic feature of the Desertec Supergrid scenario is the solar power imports. These are supported by the CSP stations in the MENA deserts and HVDC transmission lines between Europe and MENA. Of these components, only the HVDC links are chokepoints:

they feed into the high-voltage alternating current (HVAC) grid, which has many smaller customers, and more than one CSP station feed into each HVDC link. In addition, HVAC grids exist in similar ways in all scenarios. Thus, the HVDC links are the chokepoints in the CSP import chain of Desertec.

The high reliance on gas power and gas imports distinguishes GEA from Desertec. As argued above, the gas chain chokepoints are the import points, i.e. the pipelines and the LNG terminals, where the gas supply is bundled. For the Today benchmark, the same argumentation as for GEA applies: compared to Desertec, its chokepoints are the gas import points.

Chokepoint diversity

As argued in the literature by Stirling and others (section 6.1.4), the most generic indicator for security is diversity. High diversity indicates low reliance on single critical system components, which, in turn, means that a lower share of the system is likely to be affected by any single event. Conversely, high diversity means that more options are likely to remain functional after a disturbance. Hence, a more diverse system is likely to be less vulnerable, or more secure.

Here, I assess the vulnerability to the threat of infrastructure chokepoints failing. Consequently, the diversity of chokepoints is the relevant measure. For the diversity assessment, I use the Herfindahl-Hirschmann index, similarly to the assessment of the exposure to exporter power (see section 7.1.2). This is defined as

Equation 22 $$\Delta_{CI} = \sum_i p_i^2 ,$$

where p_i is the relative share of chokepoint i of the entire supply capacity (incl. domestic supply capacities) in the relevant European vital energy system. For Desertec, I assume that only the dispatchable capacities constitute the reliable supply basis for electricity in Europe to avoid underestimating the CI vulnerability.

The chokepoint data for the diversity analysis is described in Table A 2 (Desertec), Table A 5 and Table A 8 (GEA) as well as Table A 12 and Table A 13 (Today). I perform the sensitivity analysis according to the rules for min.- and max.-diversification for the CI vulnerability assessment described in section 7.5.

Buffers/interruptions

Immediately when a failure happens, various emergency responses start operating. Thus, a component failure does not always lead to an outage, and low diversity may not constitute a serious vulnerability if the buffers are large. The buffers are automatic mechanisms that prevent an outage from happening, i.e. the primary control for electricity (the base for the n-1 principle) and storage-draw for gas (ENTSO-E 2009b; Gas security Regulation 2010, see sections 13.1.4 and 13.2.4). If the failed capacities exceed these buffers, an outage is the likely result.

This perspective is a resilience, or *what-does-it-take*, analysis, showing how many – starting with the largest – units need to be disabled in order to overcome the buffers and cause outages. If the system can withstand a high number of failed chokepoints, it is more resilient and thus more secure. It is also more secure due to the decreasing (power law distribution) probability of higher-number failure events (see section 7.2.1).

I describe the chokepoint data for the buffers/interruptions analysis in Table A 2 (Desertec), Table A 5 and Table A 8 (GEA) as well as Table A 12 and Table A 13 (Today). I do the sensitivity analysis according to the rules for min.- and max.-diversification as well as half/double responses for the CI vulnerability assessment in section 7.5.

Disruption assessment

The third perspective assesses the potential impacts – the outage size and duration – of different failure cases. Large and/or long potential impacts of failures are the ultimate sign of high vulnerability (see EC 2004), especially if they result from a low number of chokepoint failures. Also here, the power law argumentation applies: a high number of attacks/failures is much less probable than a small number.

It is not possible to foresee the exact impacts, but it is possible to describe the general behaviour of a system following a disturbance and how fast an outage can be remedied, considering all responses. This is also coherent with Stirling (see Figure 2): a what-if scenario analysis for various interruption cases is an appropriate assessment approach. I assume that disabled units remain non-available, so that surge imports can only come via non-disrupted routes. Further, I assume that supply and demand match when the failures happen and that the demand remains constant for the duration of the interruption.

I describe the impact as

Equation 23 $$m_{out}(t) = m_d(t) - m_s(t) - m_{res}(t) - m_{red}(t),$$

where m_d is the lost energy from the disabled components (depends on component capacity, load, and number of disabled units), m_s the storage draw, m_{res} the other supply-responses (control capacities, spare capacity, and surge import by re-routing imports through non-disturbed import channels), and m_{red} is the demand-reduction. The response capacities have a dynamic behaviour, both with respect to start-up and maximum operation duration, as well as with respect to the size of the available response capacity. The responses are the same as summarised for the power balance analysis, with the exception that also the affected exporter will try to maintain deliveries to Europe, if alternative, non-disrupted routes are available. The base interruption cases, including the rules for the sensitivity analysis, are described in detail in section 7.5, whereas the data for chokepoint structure and the response mechanisms are described in detail in the Appendix.

7.3 Scenarios

The research aim of this dissertation is to investigate how a Supergrid future would affect European energy security and as specified in section 1.2, the vulnerability of a Supergrid scenario must be compared to that of alternative pathways. For this comparison to be interesting for the strategic choice between diverging futures, the scenario selection must cover substantially different scenarios, describing a range of diverse pathways for the future, although not all possible futures can be assessed within the frame of this dissertation. In this section, I select and describe the scenarios for the vulnerability assessments.

As described in section 1.1, a number of European Supergrid scenarios with renewable electricity imports have been published, but one of these stands out as being a strongly dominant scenario: the Desertec scenario. In the following, I use **Desertec** as the quantitative description of a European Supergrid future.

The base for what is today known as Desertec is a series of studies conducted by the German Aerospace Centre (DLR). Particularly important are the studies *Med-CSP*, describing a pathway for sustainable electricity supply in the MENA and the European countries at the Mediterranean Sea, and *Trans-CSP*, which is a scenario for sustainable electricity supply for Europe partially relying on imports of dispatchable solar power from MENA (DLR 2005, 2006). The vital energy system in focus in this scenario is the European electricity system. For 2050, Desertec foresees a European electricity supply relying on 17% imports of dispatchable solar power from the MENA, whereas 63% of the supply is domestic renewables and the rest is fossil fuel power generation. The Trans-CSP scenario was further specified, in particular by adding more detail on the infrastructure, by the same research team at the DLR (Trieb *et al.* 2009; Trieb *et al.* 2012). For the aims of the present thesis, the Trans-CSP study is the most relevant, but I use data from the other studies as well (see section 13.1 in the Appendix). Hence, the term 'Desertec' here refers to the Trans-CSP scenario and the specifications in the other studies mentioned above.

A large number of decarbonisation pathways alternative to Desertec are imaginable (e.g. EURELECTRIC 2009, 2010; Fischedick *et al.* 2012; Luderer *et al.* 2012; WWF and Ecofys 2011). As described in the introduction, all decarbonisation scenarios however have some common features: they all consist of some combination (although the share of some components may be zero in particular scenarios) of renewables, fossil fuels equipped with CCS, nuclear power as well as increased energy efficiency (Bruckner *et al.* 2010; Edenhofer *et al.* 2011; Solomon *et al.* 2007). Consequently, the diversity among decarbonisation scenarios is not as large as it first may appear.

Here, I choose a scenario from the **Global Energy Assessment (GEA)**, the GEA MESSAGE_Mix pathway, as an alternative decarbonisation scenario without electricity imports, to contrast the Desertec Supergrid scenario. This scenario contains all decarbonisation components: domestic renewables, as well as both gas power with CCS and, to a lesser degree, nuclear power on the supply side, and strongly increased efficiency on the demand side. All GEA decarbonisation pathways are driven by sustainability criteria, such as avoiding climate change and achieving full global access to modern energy. Its scope is the entire global energy system, of which the European electricity system is only one part. GEA is therefore similar but wider in scope than Desertec, which is only driven by decarbonisation of the European and MENA electricity systems as well as increased electricity availability in MENA.

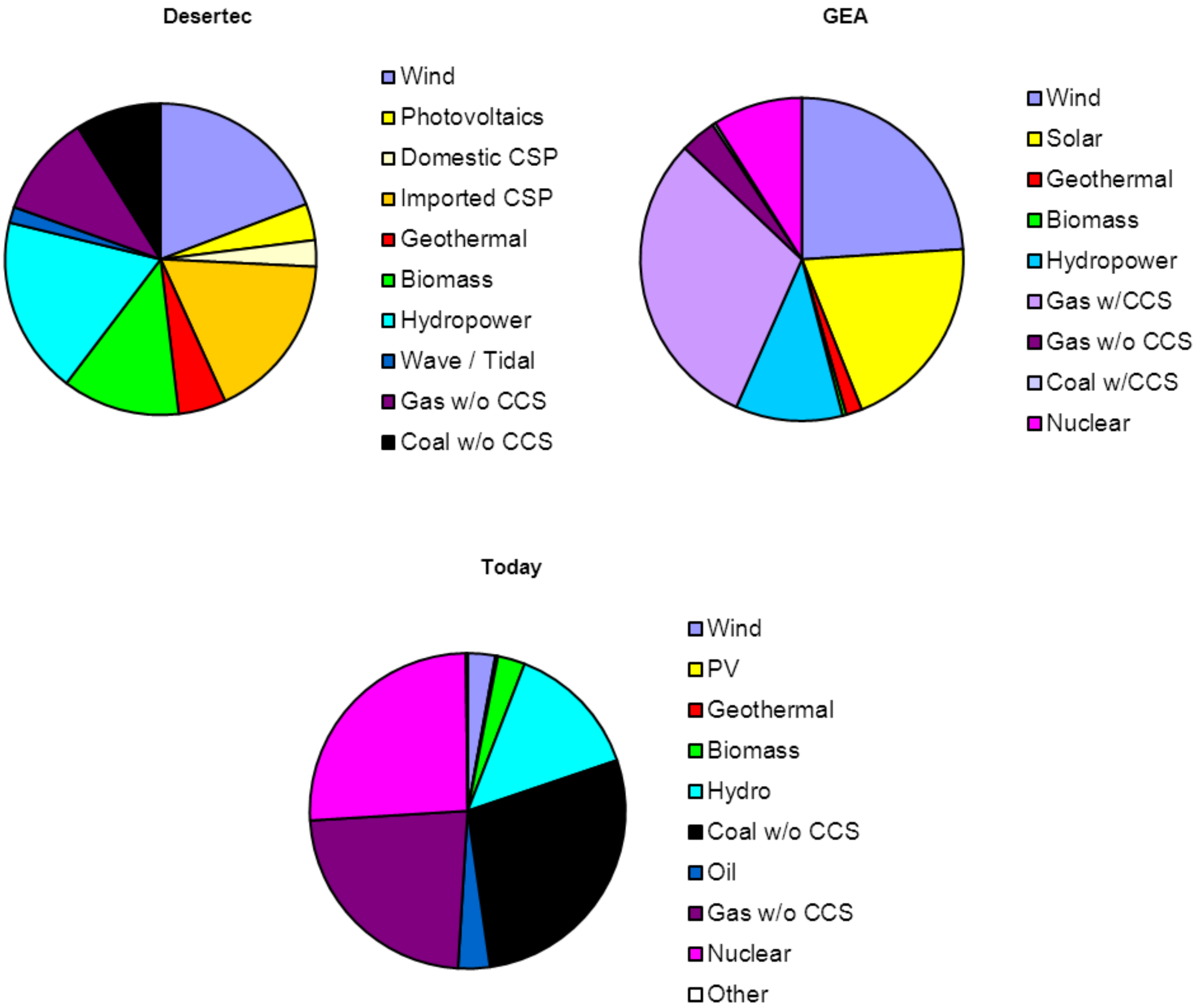
The **GEA decarbonisation pathway** I use here emphasises both supply- and demand-side measures in a balanced manner in order to achieve decarbonisation of the global energy system. By 2050, this leads to an almost completely decarbonised electricity supply relying primarily on domestic renewables (57%) and gas power coupled with CCS (31%) and without CCS (3%). Almost 85% of the gas is imported from the former Soviet Union (FSU) and the MENA, and 60% of the European gas demand is in the electricity sector (Johansson *et al.* 2012; also section 13.2). Hence, the largest substantial difference between Desertec and the GEA decarbonisation pathway is that Desertec imports electricity to Europe whereas this GEA pathway uses imported gas to generate electricity in Europe. They share a strong reliance on domestic renewables (around 60% in both scenarios). Whereas the parts of this pathway relevant for the purposes here focus on two vital energy systems – the electricity and gas systems – the part that is different from Desertec, and hence interesting for a comparison, is its vital gas system, in particular the gas imports. The gas system fuels a large part of the electricity system, which makes it interesting here, but disturbances in the gas supply would also be noticed outside the electricity sector. Therefore, to fully compare the vulnerabilities of the two decarbonisation scenarios, the vulnerabilities of two different vital energy systems –

electricity supply (Desertec) and gas supply (GEA) – must be compared. In addition, this scenario selection also allows for an analysis of a more fundamental nature, one that has not been done in detail before: whether directly importing electricity is more or less risky than importing gas for gas power generation.

However, other electricity and energy futures are possible, including scenarios without decarbonisation. The **GEA baseline pathway** (GEA MESSAGE Baseline) describes a future without carbon constraints, in a business-as-usual scenario reflecting the continuation of ongoing and expected trends in the absence of new policies. This scenario is in some aspects very different from the GEA decarbonisation pathway described above. For example, Europe has a 50% higher primary energy demand in the baseline than in the decarbonisation pathway, including a 24% higher gas demand and a three times higher coal consumption. The electricity demand is practically identical in the two pathways, but the electricity mix is different: in the baseline, Europe draws its power mainly from gas power without CCS (60%) and renewables (33%). The absence of CCS in the baseline, however, does not affect a vital energy system, and hence not the energy security of the pathway. Therefore, the relevant aspect of the baseline for comparison to Desertec is the gas system, in particular the gas imports. The gas imports in the GEA baseline and the selected GEA decarbonisation pathway are almost identical: the European baseline gas imports are only 4% higher than those of the decarbonisation pathway, as the domestic gas production is higher in the baseline. In addition, Europe is the largest importer (64% of all imports in the baseline, 77% in the decarbonisation pathway), and the gas export regions are the same in both pathways (the former Soviet Union (67% of all gas exports in both pathways) and MENA (18% in the baseline, 22% in the decarbonisation pathway), see Johansson *et al.* 2012).

Therefore, the assumptions regarding gas export countries and import infrastructure would be practically identical for assessments of the GEA decarbonisation and baseline pathways. The two scenarios would only differ in terms of fuel-switch response capacities, which is the smallest gas emergency response mechanism (see section 13.2.4). The vulnerability assessments and the results would therefore be very similar in both GEA scenarios. Consequentially, I do not explicitly consider the baseline in the assessments, but I implicitly analyse it together with the decarbonisation pathway, which I in the following refer to as 'GEA' only.

In addition to these three scenarios, I also assess the vulnerabilities of **the current situation** to provide a benchmark against which to compare the scenarios. I refer to this case as 'Today'. The present electricity supply is dominated by fossil fuels and nuclear power, which together supply about ¾ of the European electricity. However, both coal and nuclear fuel are easily storable energy carriers, and they are much less dependent on dedicated large-scale infrastructure outside Europe than gas. These two fuels are thus not particularly vulnerable to either coercion or chokepoint failure, and I do not consider them further in the vulnerability assessment. The relevant aspect in Today's system for comparison with Desertec and GEA is thus the gas supply – which fuels 22% of the European electricity generation – and in particular the gas imports, amounting to 50% of the gas demand (BP 2011; Eurostat 2011 see also section 13.3).



Sources: DLR (2006); Trieb *et al.* (2012); Johansson *et al.* (2012); TEIAS (2009); EWEA (2011); IEA (2012a).

Figure 4: European electricity mixes in the Desertec and GEA decarbonisation scenarios, as well as in the current European electricity system.

7.4 Data mining and data set construction

The assessment metrics, in particular the new metrics I have developed for this dissertation, require much data, some of it at a high level of resolution. Here, I describe the principles for the data set construction for the vulnerability assessments, whereas I present the detailed final data sets and the specific information for the completion of scenario data with too low resolution in sections 13.1-13.3 in the Appendix.

The primary principle for the data mining is to first use data directly from the scenarios, for the year 2050. If this is not available in the necessary detail, I use as much data as possible from the scenarios, and then modify or extend the data sets based on quantitative, semi-quantitative or qualitative knowledge about how the electricity and gas systems function today.

In particular, this refers to the import structures of electricity and gas. To construct concrete import infrastructure topologies, I here use the knowledge that gas can only come from countries with large gas reserves, which are known with some precision, and that it must be imported by some combination of pipelines and LNG. Similarly, electricity must be transported and imported via power lines; in the Desertec scenario, these are HVDC lines. Transmission investments are very bulky and time-consuming, so that there is considerable inertia in the system: hence, the assets in place today and those already in construction or planning are likely to still exist in a few decades. I thus assume, unless more precise information is available from the scenarios, that the existing and planned infrastructure form the backbone of the future import transmission systems. Further, electricity and gas lines and LNG terminals cannot be arbitrarily large or small, and these boundaries can be known with some precision: I use these boundaries to test the robustness of the infrastructure and source country structures in the sensitivity analysis (see section 7.5).

The response capacities are also not described in detail in the scenarios. Here, therefore, I assume that the characteristics and operation mode of these remain as they are today and construct response data sets based on that (e.g. gas can be stored in large amounts, and electricity cannot; electricity emergency responses consist of control capacities, unutilised capacity and demand-response). I test the robustness of the response mechanism data sets in the sensitivity analysis (section 7.5).

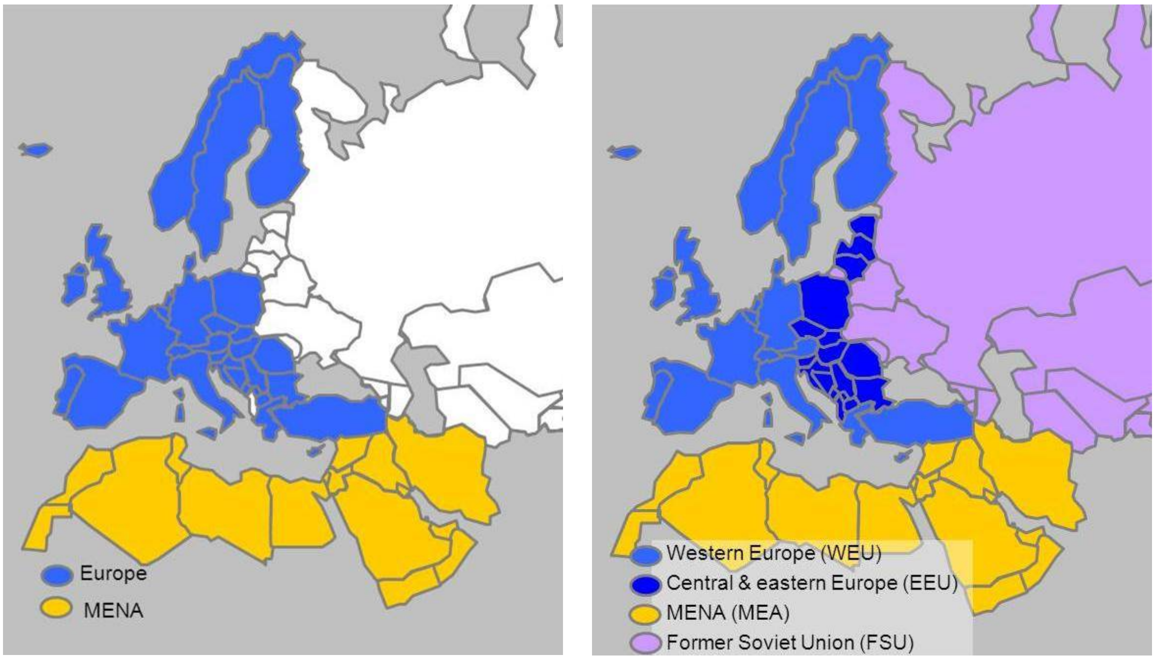
Two further high-level assumptions underlie the data mining and data construction process. First, I assume that the European internal markets in gas and electricity are completed well before 2050, the year for which the assessments are made. Second, I assume that these European markets are liquid and undistorted, and that the imported energies are bought from liquid and undistorted global/regional energy markets.

The first assumption means that the unit of assessment is Europe, and not a collection of more than 30 individual countries. It also means that the physical gas and electricity systems I assess are true systems, operated as European systems without significant internal bottlenecks: when an interruption occurs, the response is a European one. This is largely the case for electricity already today: the buffers and operation rules are fully europeanised. The other emergency responses are nationally regulated but are operated in a europeanised way to the extent the system allows it. There are still bottlenecks in the system, especially between countries and between Eastern and Western Europe. Presently, intense policy and industry efforts are underway to complete the European internal electricity market and effectively merge the physical electricity systems. The same applies for the gas system: while there are significant bottlenecks in the system today, in particular between Eastern and Western Europe, massive work is presently being done to alleviate this and better integrate the physical systems, both to enable a fully europeanised emergency response and to facilitate the internal electricity and gas markets (e.g. EC 2010c, 2011e; Gas security Regulation 2010; Schellekens *et al.* 2011, see chapter 4). Therefore, the one-system assumption is not a radical one, but an optimistic assumption that the ongoing market and system unification process in Europe is successful before 2050. As the systems are not yet fully integrated, the sensitivity analysis for both vulnerability assessments holds variation cases in which peripheral parts of

Europe are separated from the rest of Europe via intra-European transmission bottlenecks (see section 7.5).

The market liquidity assumption implies that, in the case of an emergency, the response capacity restrictions are the European import and replacement capacities, whereas the global/regional systems supplying Europe with energy can supply the amount of energy Europe needs and is able to import. For the gas system, this is increasingly the case today, following the rise of a liquid global LNG market and low utilisation of the import pipeline system (see sections 13.2.3 and 13.3.3), which makes the supply much more flexible than in the past. In the current electricity system, there is no liquid global/region market, as there are currently no mentionable electricity imports to Europe. For the Desertec scenario, however, this assumption means that there is some slack in the export generation fleet in MENA during average load (see section 13.1), so that MENA can increase supply to Europe to the extent that the chokepoints allow. Presently, considerable efforts are underway to increase the liquidity and competition in the European domestic energy markets, and improving the functioning of international energy markets is a focus of European energy security policy (EC 2010c, 2011a, also chapter 4). Thus, the market-liquidity assumption is also not radical, but an optimistic assumption that currently ongoing policy processes are successful before 2050.

I define Europe as all present (December 2012) members and observers of the European Energy Community, including Switzerland and Iceland, but excluding the post-Soviet Energy Community members Ukraine, Moldova, Georgia and Armenia (see Figure 5).



Sources: based on DLR (2005, 2006), Johansson *et al.* (2012).
Figure 5: Geographical definitions in Desertec (left) and GEA and the Today benchmark (right).

This definition is identical to the Western and Central & Eastern Europe regions of GEA[33]. The regions relevant for electricity and gas imports are the Middle East and North Africa (the GEA's MEA region, here referred to only as MENA) and the Former Soviet Union (FSU) regions. Within these exporter regions, not all countries export energy in the scenarios and Today: I define the specific supplier country structures in the Appendix (sections 13.1.3, 13.2.3 and 13.3.3).

[33]The Desertec and GEA definitions of Europe are identical, except for Desertec's exclusion of the Baltic States and Albania. As these countries are very small, the impact on the European supply and demand structure also is very small. Hence, the two definitions are henceforth considered synonym. For the Today benchmark, I use the same definition of Europe as for GEA.

7.5 Cases and sensitivity analyses for the vulnerability assessments

In this section, I describe the base case interruption data for the vulnerability assessments. The scenarios, especially concerning response capacities and import structures, are described in detail in the Appendix.

As the base cases in both assessments (vulnerability to coercion and vulnerability to critical infrastructure failure) are based on uncertain data, I carry out a rigorous sensitivity analysis. For this, I vary the most uncertain data between end-points of what can be viewed as *possible*, rather than what is *probable*, based on qualitative and semi-quantitative knowledge of the scenarios and of how electricity and gas are supplied and traded. I describe the variation cases for the sensitivity analysis below.

7.5.1 Desertec

The base for the power balance (vulnerability to coercion) assessment is the simultaneous and instant interruption of all electricity from each of the 7 exporting countries, and of all electricity passing through each of the 2 transit countries. In addition, I run an extreme case in which all 7 exporters join in coercive action against Europe (see Table 12). In all cases, the interruption happens at t=0 and remains constant for the entire assessed period, as does demand, whereas the response capacities are dynamic and may change over time.

Table 12: Lost imports in the base (peakload) and average load cases for the Desertec power balance assessment. Rounded.

	Lost imports (GW), peak	Lost imports (GW), average
Source country		
Morocco	32.0	21.5
Algeria	32.2	23.5
Tunisia	10.9	7.3
Libya	10.8	7.3
Egypt	10.2	7.1
Jordan	10.4	6.1
Saudi Arabia	10.4	7.4
Transit countries		
Jordan	10.4 (transit) + 10.4 (own exports)	7.4 (transit) + 6.1 (own exports)
Syria	20.8	13.5

For the CI vulnerability assessment, I use interruption cases in which the 3, 5 and 10 largest chokepoints with the highest capacity are simultaneously disabled. In addition, I run an extreme case in which all chokepoints fail simultaneously, see Table 13.

Table 13: Lost imports in the base (peakload) and average load cases for the Desertec critical infrastructure disruption assessment. Rounded.

	Lost imports (GW), peak	Lost imports (GW), average
3	11.2	8.6
5	18.6	14.2
10	36.6	27.9
All	116.9	80.3

The Desertec data for all cases, including the sensitivity analysis case-variations, are described below. Throughout the sensitivity analysis, I vary only one parameter at the time, while keeping all other parameters as they are in the base case. I do not test the variations for average load – this is only a variation of the (peakload) base case. The Desertec base case and the variation cases for the sensitivity analysis are summarised in Table 14 at the end of this section.

- **Power balance: base case.** The base case describes the peakload power balance, using the interruption cases as described above and the response capacities as described in the Appendix.
- **Power balance: average load.** The interruptions happen during average load times. All interruptions are as described above and the responses as described in the Appendix for average load.
- **Power balance: max.-diversification case.** Each exporting country exports the same amount of electricity (about 100 TWh/a, or 16.7 GW per country). This case describes the maximum exporter diversification within the same export country structure as in the base case.
- **Power balance: min.-diversification case.** I aggregate the exporting countries into three larger regional units, which coordinate their behaviour. The regions are Maghreb (Morocco, Algeria, Tunisia), North-Eastern Africa (Libya, Egypt) and Arabian Peninsula (Jordan, Saudi Arabia). This represents a low diversification within the exporter country structure of Desertec.
- **CI vulnerability: base case.** The base case describes the size and duration of potential outages following the failure of chokepoints during peakload as described above and the utilisation of all responses as described in the Appendix.
- **CI vulnerability: average load.** The chokepoint failures happen during average load times. All failures are as described above and the responses are as described in the Appendix for average demand.

- **CI vulnerability: min.-diversification case.** All HVDC export links are 8 GW (doubling of base case). This represents the lowest chokepoint diversification, as much larger lines seem unfeasible: the currently strongest HVDC line is the 7.2 GW Xiangjiaba Dam-Shanghai HVDC link. All other existing HVDC links are much smaller than this (ABB 2010). In this case, there are 17 HVDC import lines, which gives a slightly (3%) higher import capacity than in the base case. In this case, I double the primary control to 8.6 GW (and subtract the extra primary control capacity from the spare capacity), to fit the HVDC links under the n-1 criterion.
- **CI vulnerability: max.-diversification case.** I maintain the transmission structure, but split each line from the base case into two separate lines. There are therefore 66 single HVDC import lines of 2 GW each at the starting point in this variation. This is the size of currently planned sub-Mediterranean HVDC lines, like TuNur (Nur Energie 2012), and represents the highest reasonable chokepoint diversification.
- **Power balance/CI vulnerability: half response capacity.** In this variation, used for both the power balance and the CI vulnerability assessments, I halve the response capacities (except primary control) compared to the base case. This case represents a situation with extremely low margins, or a situation with a second interruption, after the first interruption has already bound half of the available responses.
- **Power balance/CI vulnerability: double response capacity.** In this variation, I double the European response capacities (except primary control) compared to the base case. In this case, security concerns dominate economic efficiency.
- **Power balance/CI vulnerability: internal bottleneck cases:** In this variation, Europe does not have an internally homogenous electricity system, but some regions are separated from the rest of Europe by bottlenecks. I run three bottleneck cases in both

vulnerability assessments, for the regions with the presently strictest bottlenecks to rest-Europe[34] (ENTSO-E 2011b). For this, I assume that the bottlenecks remain as they are today (autumn 2011). The regions are the Balkan (south-east of Hungary and Austria, north-west of Turkey; bottleneck of 2.4 GW), Poland (3.1 GW) and the Iberian peninsula (1.3 GW). I allocate the response capacities between the affected region and rest-Europe proportionally to peakload, whereas the disrupted lines are only those ending in the affected region (see Appendix, Table A 2).

Table 14: Summary of the demand, response and supply structures in the base case and sensitivity analysis variations in Desertec.

	Demand	Responses	Supply structure
Base case	Peakload	As in Table A 3	As in section 13.1.3
Average demand	Average load	As in Table A 3 (for av. demand)	As in section 13.1.3
Min.-diversification (coercion)	Peakload	As in Table A 3	Exporters coordinate; 3 supplier 'regions'
Min.-diversification (CI)	Peakload	As in Table A 3	All chokepoints twice the size of the base case
Max.-diversification (coercion)	Peakload	As in Table A 3	Every exporter supplies 1/7 of all exports
Max.-diversification (CI)	Peakload	As in Table A 3	All chokepoints half the size of the base case
Half responses	Peakload	Half the size of the base case	As in section 13.1.3
Double responses	Peakload	Double the size of the base case	As in section 13.1.3
Bottlenecks (Balkan, Poland, Iberia)	Peakload	Same as base case, proportional to regional peakload	The chokepoints ending in the respective region (section 13.1.3)

[34] The Baltic, Iceland and the Mediterranean European island states do not have any interconnections to rest-Europe, and are thus even more separated than the bottleneck case regions. However, Desertec does not foresee any HVDC lines ending in these areas, which makes them uninteresting here.

7.5.2 GEA

The base for the coercion vulnerability assessment is the interruption of all gas from each of the 6 pipeline gas exporters, and all pipeline gas passing through each of the 5 transit countries during peak demand. I do not test LNG supply in the coercion assessment: LNG is not very useful for coercion because it comes from a global market rather from a particular supplier. However, I run a further case in which all Russian gas is interrupted, including its pipeline and LNG exports. The Russian share of the LNG market in GEA is 62%, so that the liquid LNG market assumption may not be valid if Russia decides to embargo Europe; consequently, this case includes the loss of all Russian pipeline exports and 62% of the European LNG capacity. I also run two extreme cases in which all pipeline gas exporters and all exporters (pipeline and LNG) join in coercive action against Europe (see Table 15). In all cases, the interruption happens at t=0 and remains constant for the entire assessed period, as does the demand, whereas the importer response capacities are dynamic and may change over time.

Table 15: Lost imports in the base (peak demand) and average demand cases for the GEA power balance assessment. Rounded.

	Lost imports (GWh/d), peak	Lost imports (GWh/d), average
Source country		
Russia pipe	10,213	8170
Russia all	20,733	13,856
Azerbaijan	619	495
Algeria	1944	1555
Libya	376	301
Iran	433	346
Iraq	936	749
All pipe	14,521	11,617
All	31,489	20,780

	Lost imports (GWh/d), peak	Lost imports (GWh/d), average
Transit country		
Ukraine	4406	3524
Belarus	1481	1185
Morocco	355	284
Tunisia	1088	870
Georgia	619	495

For the CI vulnerability assessment, I use interruption cases in which the 3, 5 and 10 largest chokepoints (both pipelines and LNG gasification terminals) are simultaneously disabled, as well as an extreme case where all chokepoints fail (see Table 16).

Table 16: Lost imports in the base (peak demand) and average demand cases for the GEA critical infrastructure disruption assessment. Rounded.

	Lost imports (GWh/d), peak	Lost imports (GWh/d), average
3	6556	5245
5	8671	6936
10	12,240	9463
All	31,489	20,780

I describe the data for all GEA cases, including the sensitivity analysis case-variations, below. The GEA interruption cases for the sensitivity analysis are summarised in Table 17 at the end of this section.

- **Power balance: base case.** The base case describes the power balance during peak demand using the interruption cases as shown above and the response capacities as described in the Appendix.

- **Power balance: average demand.** The interruptions happen during average demand. All interruptions are as described above and the responses are as shown in the Appendix for average demand.
- **Power balance: max.-diversification case.** Each pipeline-gas exporting country exports the same amount of gas (peak: 2420 GWh/d, average: 1936 GWh/d). This case describes the maximum diversification within the same export country structure as in the base case.
- **Power balance: min.-diversification case.** All pipeline gas from each of the two exporting regions comes from only one pipeline gas-exporting country, namely Russia (FSU) and Algeria (MENA). This represents the minimum possible diversification within the GEA's two-region gas supply structure.
- **CI vulnerability: base case.** The base case describes the size and duration of potential outages following the failure of chokepoints as described above, including the utilisation of all responses as described in the Appendix for peak demand.
- **CI vulnerability: average load.** The failures happen during average load times. All interruptions are as described above and the responses are as shown in the Appendix for average demand.
- **CI vulnerability: min.-diversification case.** All imports come from FSU and MENA through pipelines the size of the currently largest existing pipeline from each region (3100 GWh/d from FSU, 1100 TWh/d from MENA). The allocation of arriving exports to each region is the same as in the base case. I determine the average chokepoint utilisation to give integer numbers of pipelines, and is 63% for FSU and 67% for MENA gas; the current average pipeline utilisation of 51%. Consequently, the gas is imported through 8 pipelines from FSU and 7 from MENA.

- **CI vulnerability: max.-diversification case.** All European gas imports come by LNG and is handled by 121 import terminals, each of the average size of all existing and planned gasification terminals (270 GWh/d). The LNG capacities have an average utilisation of 60% (compared to 41% today).
- **Power balance/CI vulnerability: double response capacity.** I double the European storage withdrawal and demand-response capacities compared to the base case. This reflects a situation in which security takes precedence over economics.
- **Power balance/CI vulnerability: half response capacity.** I halve the European storage withdrawal and demand-response capacities compared to the base case. This would require existing storages to close, which is very unlikely in a scenario with higher gas demand than today; this case thus marks the extreme lower bound for what is feasible in terms of gas response mechanisms. Alternatively, this case could represent a second incident, after a first incident has already bound half the response capacity.
- **Power balance/CI vulnerability: internal bottleneck cases:** In this variation, Europe does not have an internally homogenous gas system, but some regions are separated from the rest of Europe by bottlenecks the same size as the bottlenecks in the present gas system. I run three bottleneck cases: Balkan (including Hungary, but excluding Slovenia), Baltic/Finland, and the Iberian Peninsula. These regions are separated from the rest of Europe by bottlenecks the same size as the present (December 2012) bottlenecks (183 GWh/d (Balkan), 0 (Baltic) and 100 GWh/d (Iberia) (ENTSO-G 2011a, b). The response capacities in these regions are as they are planned for 2020, and only the pipelines and LNG terminals entering Europe in the affected bottleneck region are disrupted (see Table A 5 and Table A 8). I assume that the surge import gas from rest-Europe arrives at the same speed as other surge import gas.

Table 17: Summary of the demand, response and supply structures in the base case and sensitivity analysis variations in GEA.

	Demand	Responses	Supply structure
Base case	Peak	As in Table A 10	As in section 13.2.3
Average demand	Average	As in Table A 10 (for av. demand)	As in section 13.2.3
Min.-diversification (coercion)	Peak	As in Table A 10	2 exporters ('FSU'=Russia; 'MENA'=Algeria)
Min.-diversification (CI)	Peak	As in Table A 10	All chokepoints the size of largest existing pipeline
Max.-diversification (coercion)	Peak	As in Table A 10	Every pipeline gas exporter supplies 1/6 of the pipeline exports
Max.-diversification (CI)	Peak	As in Table A 10	Chokepoints the size of medium LNG terminal
Half responses	Peak	Half the size of the base case	As in section 13.2.3
Double responses	Peak	Double the size of the base case	As in section 13.2.3
Bottlenecks (Balkan, Baltic, Iberia)	Peak	The storages in each region; fuel-switch as base case proportional to regional demand	The chokepoints in the respective region (section 13.2.3)

7.5.3 Today

The base for the coercion vulnerability assessment is the interruption of all gas from each of the 5 countries exporting pipeline gas to Europe, and all gas passing through each of the 5 transit countries. I also run extreme cases, in which all pipeline gas exporters and all pipeline and LNG exporters in the world join in coercive action against Europe (see Table 18). In all cases, the interruption happens at t=0 and remains constant for the entire assessed period, as does demand, whereas the response capacities are dynamic and may change over time.

Table 18: Lost imports in the base (peak demand) and average demand cases for the Today benchmark power balance assessment. Rounded.

	Lost imports (GWh/d), peak	Lost imports (GWh/d), average
Source country		
Russia	8290	6632
Azerbaijan	619	495
Algeria	1703	1362
Libya	349	279
Iran	433	346
All pipe	11,394	5784
All	17,706	7808
Transit country		
Ukraine	4251	3401
Belarus	1481	1185
Morocco	355	284
Tunisia	1088	870
Georgia	619	495

For the CI vulnerability assessment, I use failure cases in which the 3, 5 and 10 largest chokepoints are simultaneously disabled, as well as an extreme case where all chokepoints fail, see Table 19.

Table 19: Lost imports in the base (peak demand) and average demand cases for the Today benchmark critical infrastructure disruption assessment. Rounded.

	Lost imports (GWh/d), peak	Lost imports (GWh/d), average
3	5876	2997
5	7853	3910
10	10,806	5292
All	17,707	8383

For the Today benchmark, I do not run a sensitivity analysis, as the situation today is well known so that I can base the assessment on certain data. However, the same three bottleneck cases as in GEA are tested, but with today's demand, supply and response mechanism structure. These cases are: Balkan (including Hungary, but excluding Slovenia), Baltic/Finland (which I assume are integrated by the Baltic interconnector), and the Iberian Peninsula. These regions are separated from the rest of Europe by the present bottlenecks (0 GWh/d (Baltic/Finland), 100 GWh/d (Iberia), and 183 GWh/d (Balkan). The bottleneck to Balkan is however effectively zero, as it is needed to satisfy peak demand already during undisturbed operations. There is no mentionable domestic production capacity in the Baltic countries, Finland, Spain or Portugal, but the domestic production capacity in the Balkan is presently 473 GWh/d (ENTSO-G 2011a, b). The response capacities in these regions are as they exist today, and only the pipelines and LNG terminals entering Europe in the affected bottleneck region are disrupted (see Appendix section 13.3.3).

The Balkan bottleneck case is particularly important, not only because it assesses a potential real-world vulnerability, but because it offers a test case to validate the model. In the past, there has been only one 'gas weapon' event with serious supply effects in Europe: the 2009 Russian-Ukrainian gas dispute. During this event, serious gas shortages appeared in South-Eastern Europe (which I refer to as Balkan). Although there was enough replacement gas available in Europe, intra-European bottlenecks prohibited these countries from accessing this gas, and outages followed (EC 2009b; Pirani *et al.* 2009). Hence, the Today benchmark holds a real-world test case: if the new model I have developed here is valid, the coercion vulnerability assessment should produce results indicating 'no outages' in Europe as a whole when all gas transiting Ukraine is interrupted, but serious outages in the Balkan in the bottleneck case.

8 Results: vulnerability to coercion

In this chapter, I present the results of the coercion vulnerability assessment. In the following, I show the results of the exporter diversity (section 8.1), and of the new power balance assessment method I have developed in this dissertation (section 8.2).

8.1 Exporter diversity

The diversity analysis shows that Desertec is much more diversified, or less concentrated, than GEA and Today; the difference to GEA is up to two orders of magnitude, see Table 20 (the different cases are described in section 7.5 and the supplier structure tables in the Appendix). The min.- and max.-diversification variations do not change this result, which is thus robust and does not critically hinge on uncertain supplier structure data.

Table 20: Results of the exporter diversity analysis (Herfindahl-Hirschmann index) for Desertec, GEA and the Today benchmark.

	Desertec	GEA	Today
Min.-diversification	0.015	0.138	
Base	0.006	0.115	0.063
Max.-diversification	0.004	0.037	

It is not possible to say whether these results mean that one, or all, scenario is insecure, due to the ordinal scale of the results. However, the results can be compared to concentration benchmarks: for example, ‘moderately’ and ‘highly concentrated’ energy markets in Europe are defined as having HHI values of 0.075-0.18 and 0.18-0.5, respectively (EC 2011b). This indicates that Desertec and Today are highly diversified systems in which exporters have no (market) power, whereas GEA (not the max.-diversification case) is a moderately concentrated system where some exporters may have power.

The results in Table 20 strongly indicate that Desertec is more diversified than GEA and Today. This indicates that Desertec is much less vulnerable to coercion than GEA, and slightly less vulnerable than the Today benchmark.

8.2 Power balance

The results of the power balance assessment confirm the result of the diversity analysis that no scenario is very vulnerable to coercion. However, these results contradict the diversity results by showing that although the overall vulnerability is low, Desertec is more vulnerable to coercion than the, in most cases, practically invulnerable GEA and Today.

8.2.1 Desertec

The power balance assessment shows that in the Desertec base case, no single country is able to exert sustained power on Europe by cutting the electricity exports, see Figure 6. Europe is thus not vulnerable to coercion events by single countries. In all cases, the exporters cause significant initial damage in Europe, amounting to about 1.5% of GDP during the first hour of blackouts (cases of Tunisia, Libya, Egypt, Jordan and Saudi Arabia) or 6.5% (in the cases of Morocco and Algeria, which export more electricity than the other countries). These blackouts can however be removed fast, within 1-4 hours, so that Europe only sees very limited costs over time, originating in the slightly higher costs for the back-up generation capacities. The exporters, in contrast, experience constant costs for the entire duration of the export interruption. These costs are significant, due to the constancy of the costs and the lower GDP in the exporter countries, and range from 0.2-0.5% in the cases of Saudi Arabia and Egypt to about 3.5% of GDP/hour in the cases of Jordan and Morocco. Jordan even loses 4.4% of GDP/hour, when cutting both transits and exports. Hence, the power balance during an export interruption is clearly not beneficial for the exporters, and no single country has power over Europe.

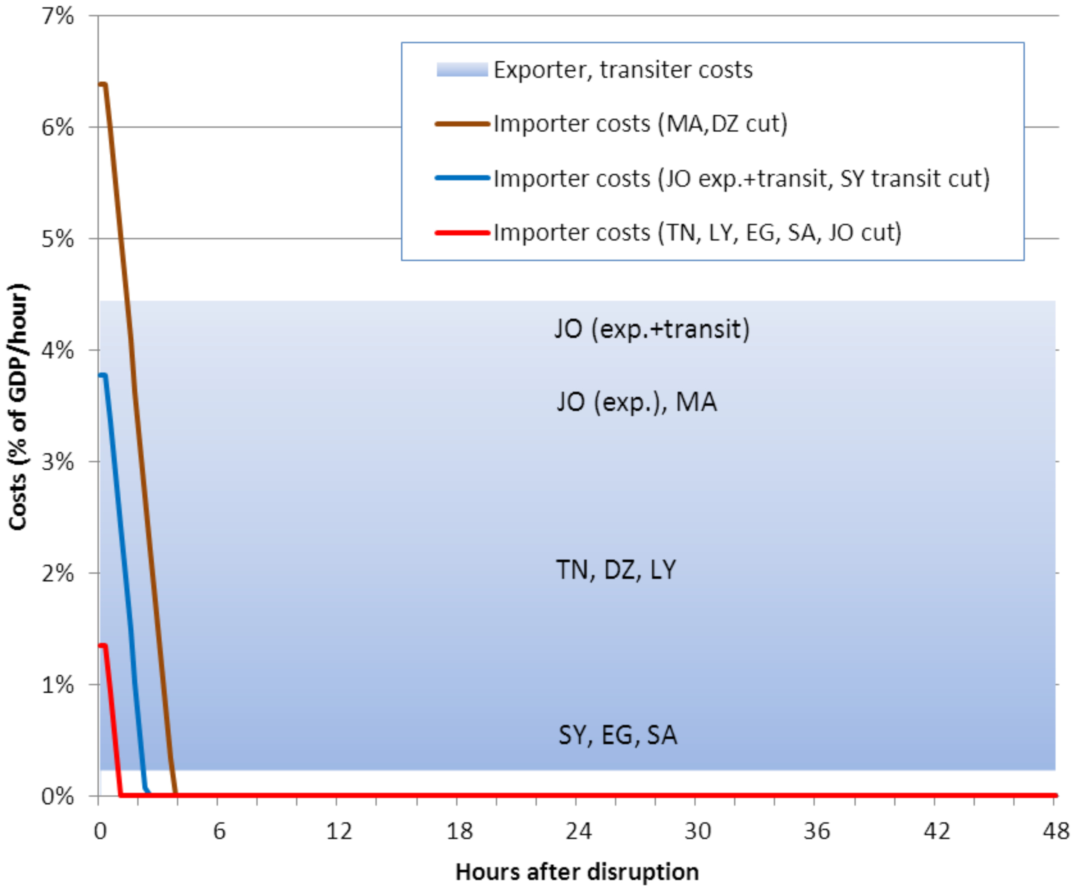


Figure 6: Relative costs for the importer and exporters/transiters in the Desertec base case for the first 48 hours following an interruption.

The abbreviations in the graphs refer to the exporters/transiters. The approximate position of the exporter/transiter costs is indicated by the country abbreviation in the graph. The importer costs in the MA and DZ cases are almost identical, as are the TN, LY, EG, SA and JO cases; such almost identical cases are depicted with only one line per group, in all power balance graphs. Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

Nevertheless, an interruption would be very costly to Europe (see Figure 7): these costs rapidly increase to up to 500 million €, but once the blackouts have been removed the importer costs flatten out. The exporter and transit country costs do not spike like the European costs, but increase steadily for as long as the interruption continues: they intersect the European absolute costs after 400 hours (Morocco, Algeria) or 100-110 hours (all other exporters).

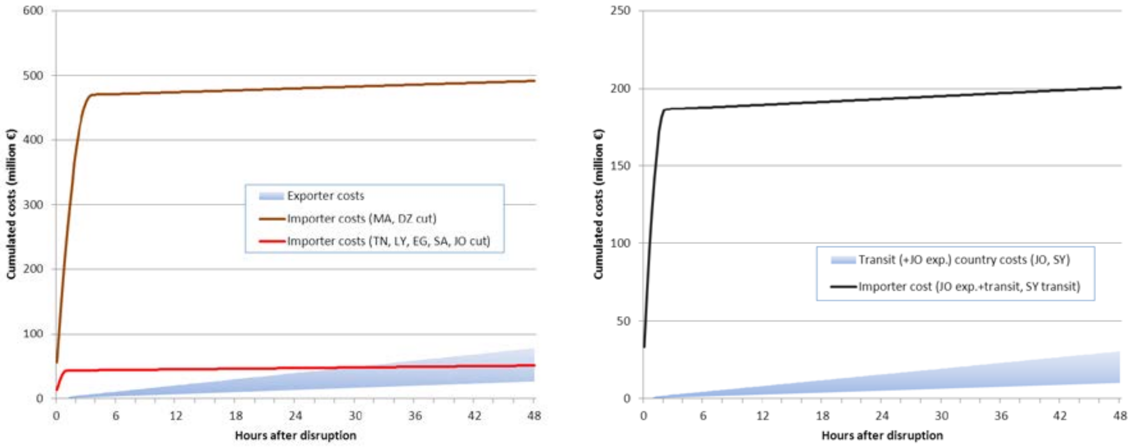


Figure 7: Absolute cumulated costs for the importer and exporters (left) and the importer and transit countries (right) in the Desertec base case for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

If all export countries participate in coordinated coercion against Europe, the impacts in Europe would be devastating (see Figure 8). The initial blackout would be very large, causing damages exceeding 25% of hourly GDP, and Europe would not be able to restore system functionality without the imports being resumed. This causes high lasting costs of 125 million €/hour, or 3.6% of GDP/hour. The exporters, on the other hand, would only see costs of some 6 million €/hour. If all exporters successfully coordinate their action during peakload, they would have power over Europe, and Europe would be vulnerable to coercion.

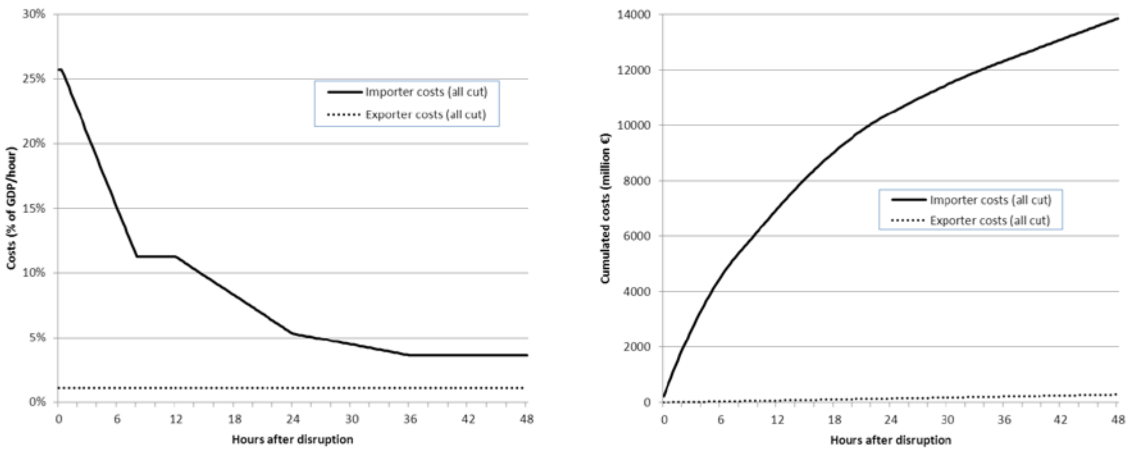


Figure 8: Relative (left) and absolute cumulated costs (right) for the importer and all exporters in the Desertec base case for the first 48 hours following an interruption.

If the interruption happens at average demand times, the European blackouts (and hence the costs) are smaller than in the base case, as less capacity is disrupted. Further, the outages can be remedied faster, within 1-3 hours, as more back-up capacities are available, see Figure 9. The exporter costs are lower as well, but the remain constant at up to a few percent of GDP/hour. Hence, the exporters do not have power in the average load case.

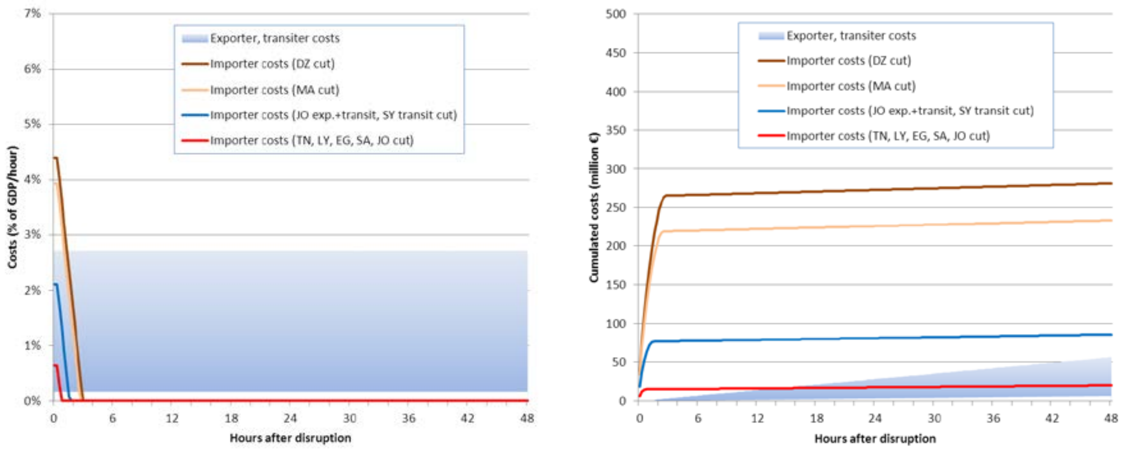


Figure 9: Relative (left) and absolute cumulated costs (right) for the importer and exporters/transiters in the Desertec average load case for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

Importantly, a coordinated cut of all export countries during average load causes large but temporally limited blackouts in Europe: reserve and demand-reduction capacity can eliminate the blackout after 15 hours, see Figure 10. Hence, Europe is not particularly vulnerable, even to a full embargo, during average load.

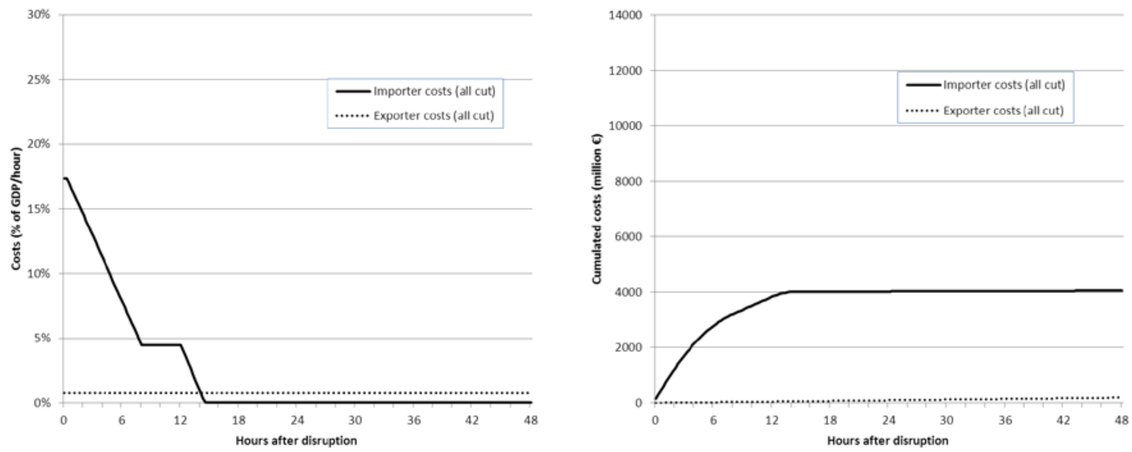


Figure 10: Relative (left) and absolute cumulated costs (right) for the importer and all exporters in the Desertec average load case for the first 48 hours following an interruption.

The results are numerically sensitive to changes in the export country structure of the min.- and max.-diversification variations, but these variations do not change the conclusion.

In the max-diversification variation (Figure 11), the costs for Europe behave as in the base case, but at a lower level: the initial costs are around 3% of hourly GDP and are reduced to almost zero within 2 hours. The exporter and transiter costs, however, are generally higher than in the base case (except for Morocco and Algeria) and range from 0.5 to 7% of hourly GDP. For some exporters (Tunisia and Jordan), the relative costs are higher than the initial European costs, due to their low GDP and large income losses. Also in this case, no single country, including the transit countries, has power over Europe.

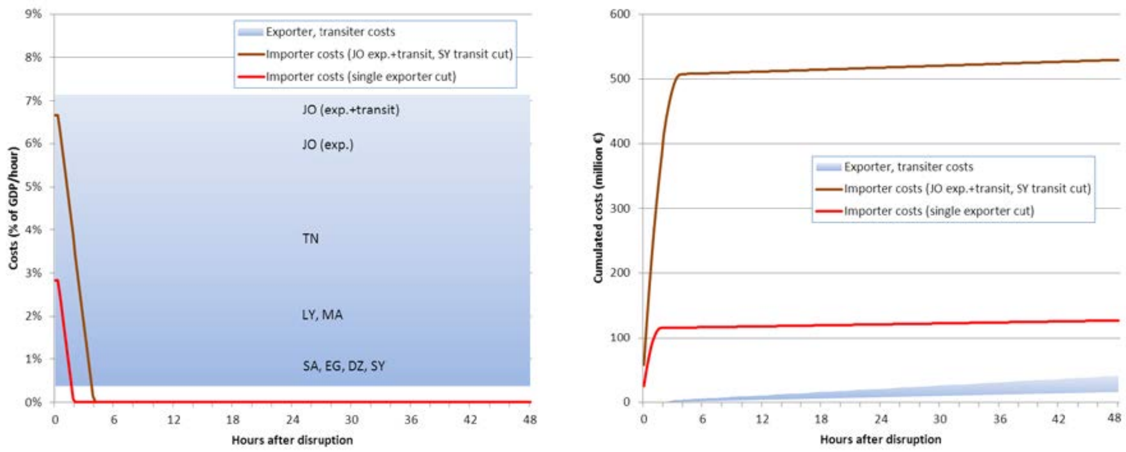


Figure 11: Relative (left) and absolute cumulated costs (right) for the importer and exporters /transiters in the Desertec max.-diversification case for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

In the min.-diversification variation, the cut of the three Maghreb countries shows a case with initially very high (16% of hourly GDP) but rapidly reduced importer costs. The two other exporter groups can cause significant, but much lower costs. In all three cases, the blackouts can be remedied (after 2-15 hours), so that Europe is not vulnerable, see Figure 12.

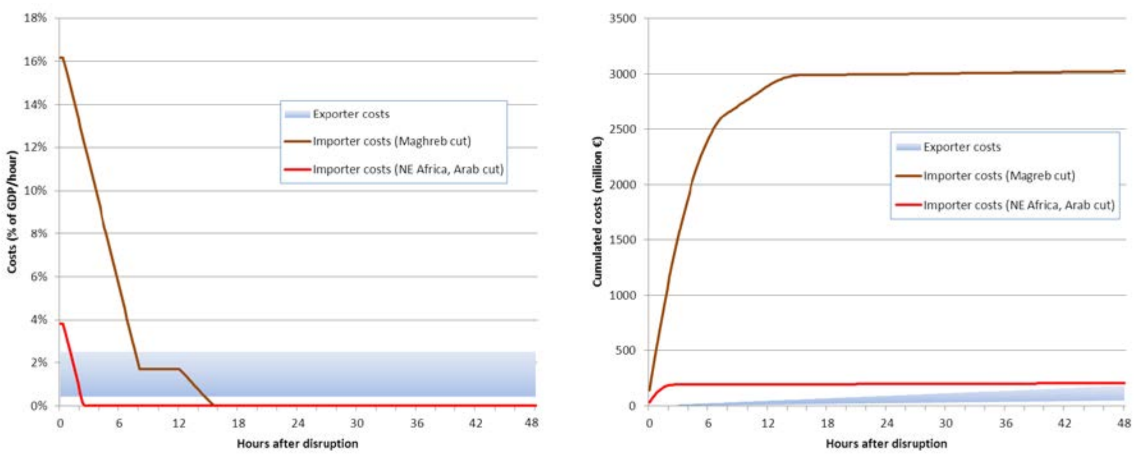


Figure 12: Relative (left) and absolute cumulated costs (right) for the importer and exporters in the Desertec min.-diversification case for the first 48 hours following an interruption.

The half and double response variations show that the results are, in part, sensitive to changes in the response capacity assumptions. In the double responses case, the initial blackouts are the same as in the base case, but they can be removed faster (all single country cuts are remedied within 1-2 hours). The exporters face the same costs as in the base case. As the importer's blackout costs are lower than in the base case, see Figure 13, the small cut cases (Tunisia, Libya, Egypt, Saudi Arabia, Jordan) reach the same cumulated costs as Europe after just above two days.

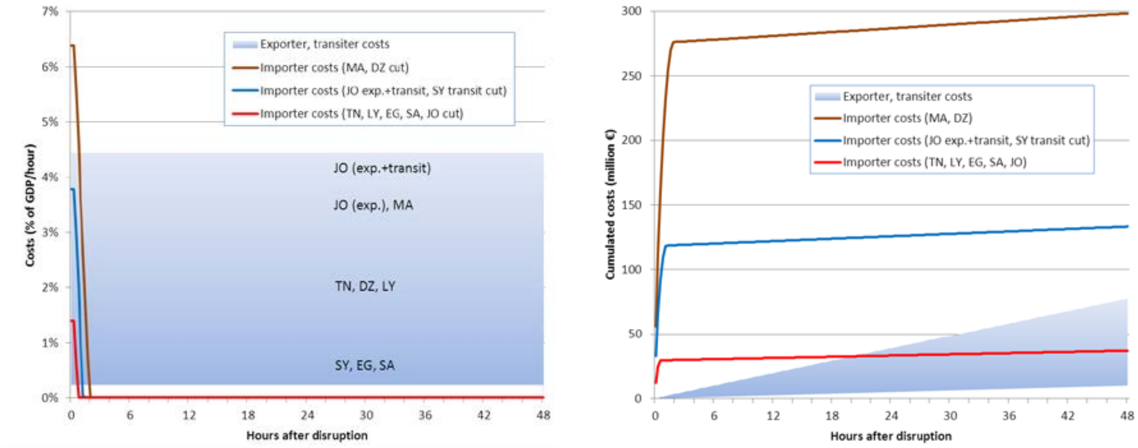


Figure 13: Relative (left) and absolute cumulated costs (right) for the importer and exporters/transiters in the Desertec double response case for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

Importantly, the blackouts of the all-cut case can be remedied within 7 hours in the double responses variation, see Figure 14. Hence, Europe is not vulnerable in the double-responses case, even if all exporters join an embargo.

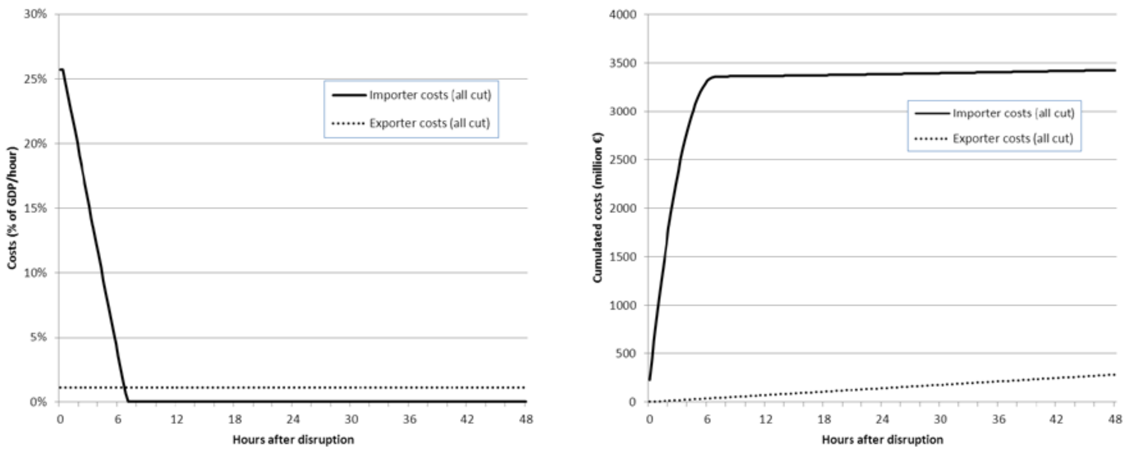


Figure 14: Relative (left) and absolute cumulated costs (right) for the importer and all exporters (only producing countries) in the Desertec double response case for the first 48 hours following an interruption.

In the half responses case, the initial blackouts are identical to base case, but the duration of the blackouts in the single country cases is significantly longer (2-7 hours), see Figure 15. Hence, the cumulated costs are much higher in the half responses case than in the base case.

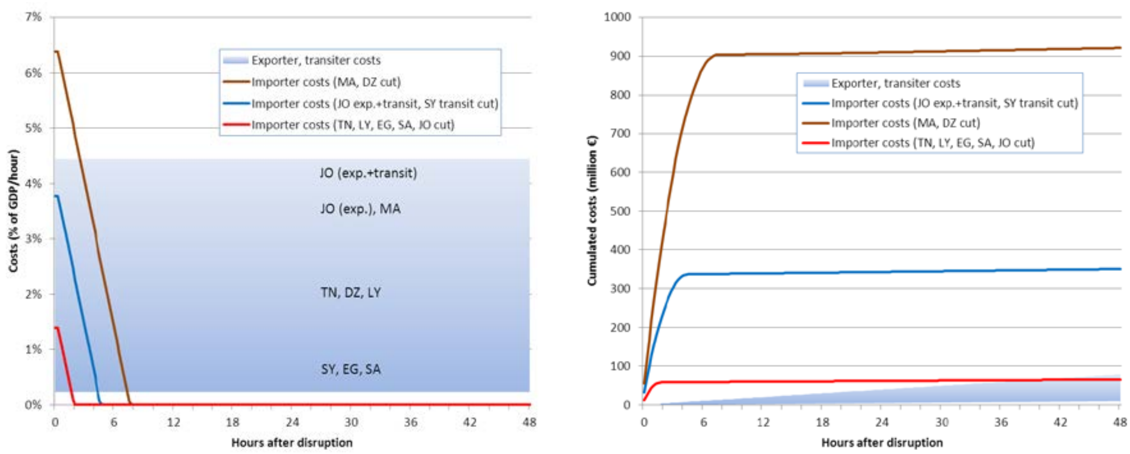


Figure 15: Relative (left) and absolute cumulated costs (right) for the importer and exporters/transiters in the Desertec half response case for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria; TN=Tunisia; LY=Libya; EG=Egypt; JO=Jordan; SA=Saudi Arabia; SY=Syria.

Dramatic effects of lower responses are seen in the all-cut case: although the initial blackout is identical to the base case, the half responses case sees extreme and sustained importer costs of 15% of hourly GDP after all responses are activated. The cumulative importer costs increase very fast, reaching almost 30 billion € after 2 days, while the exporter costs remain modest, see Figure 16. Such a case would mean considerable power for the exporters, if they successfully coordinate their actions.

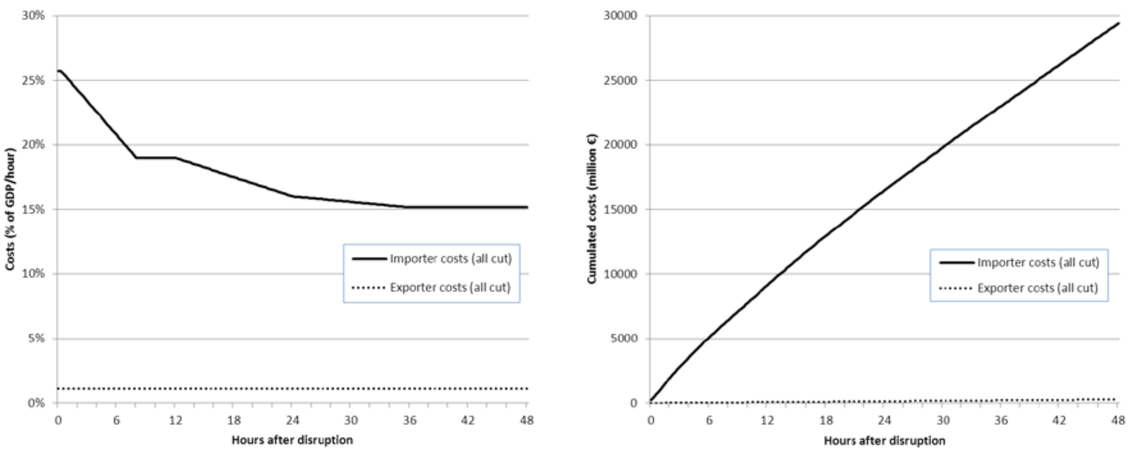


Figure 16: Relative (left) and absolute cumulated costs (right) for the importer and all exporters in the Desertec half response case for the first 48 hours following an interruption.

In the Balkan bottleneck case, the vulnerability to single country coercion is miniscule, as each country only exports to the Balkan through one power line and thus fall under the n-1 principle. The exporters, on the other hand, see low but steady costs of between 0.2-1.3% of hourly GDP, see Figure 17. If all three exporters coordinate their actions, the blackouts are very large and costly to the Balkan, initially reaching almost 40% of hourly GDP. However, the blackouts can be removed, also by relying on imports from neighbouring European countries through the bottleneck. Hence, all exporters together can cause very large, but short-term, damage in the Balkan, which is not very vulnerable to coercion.

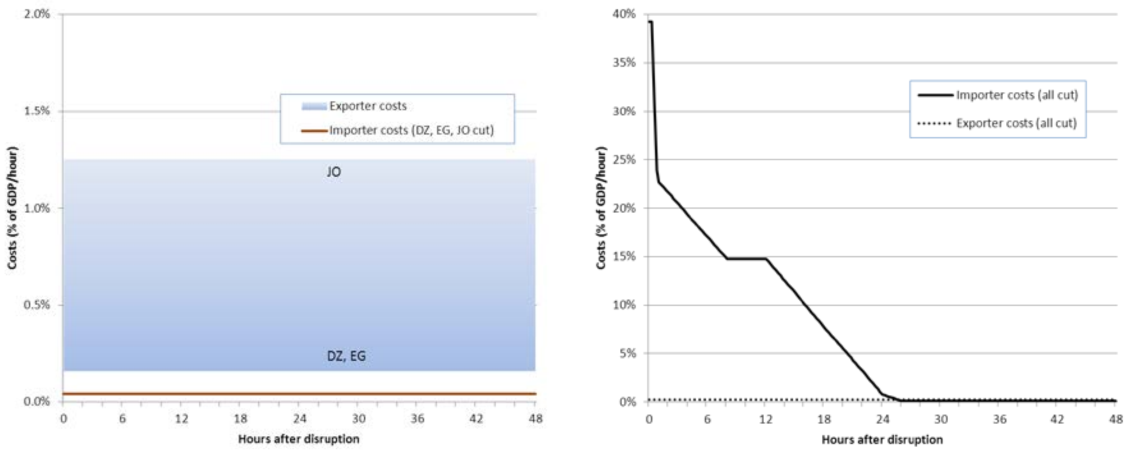


Figure 17: Relative costs for the importer and exporters in the single- (left) and all-country interruptions (right) in the Desertec bottleneck case for Balkan for the first 48 hours following an interruption.

Country abbreviations: DZ=Algeria; EG=Egypt; JO=Jordan.

Also in the Iberian Peninsula, each exporter transmits its electricity by a single line, and thus fall under the n-1 principle, see Figure 18. If both exporter countries coordinate, very short blackouts occur, causing high cost of initially up to 8% of hourly GDP. Hence, the exporters, not even if they coordinate, do not have power over the countries on the Iberian Peninsula.

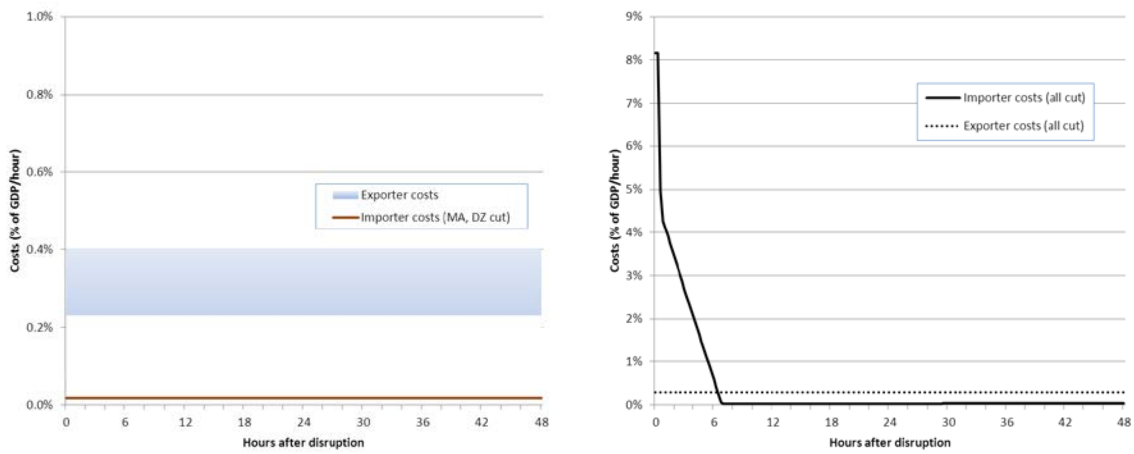


Figure 18: Relative costs for the importer and exporters in the single- (left) and all-country interruptions (right) in the Desertec bottleneck case for the Iberian Peninsula for the first 48 hours following an interruption.

Country abbreviations: MA=Morocco; DZ=Algeria.

Poland is very vulnerable to coercion and is the most threatened country in Desertec, due to the large number of HVDC import lines ending there, entailing a high import dependency, see Figure 19. In this case, the single countries Jordan and Saudi Arabia cannot cause blackouts in Poland, but Egypt, exporting through two links, can. These blackouts are very large, causing damages initially exceeding 20% of hourly GDP, but they can be quickly removed, in part by relying on intra-European imports through the bottleneck. If all three exporters coordinate their actions, the impact on Poland would be devastating: initially almost 80% of hourly GDP are lost, and blackouts causing damages of almost 50% of hourly GDP remain even after all response mechanisms are fully utilised. Hence, Poland is very vulnerable to power of the exporters in Desertec, if they coordinate. As only three exporters are involved, their coordination difficulties may be manageable, indicating that this could be a serious vulnerability for Poland and, by extension, for Europe.

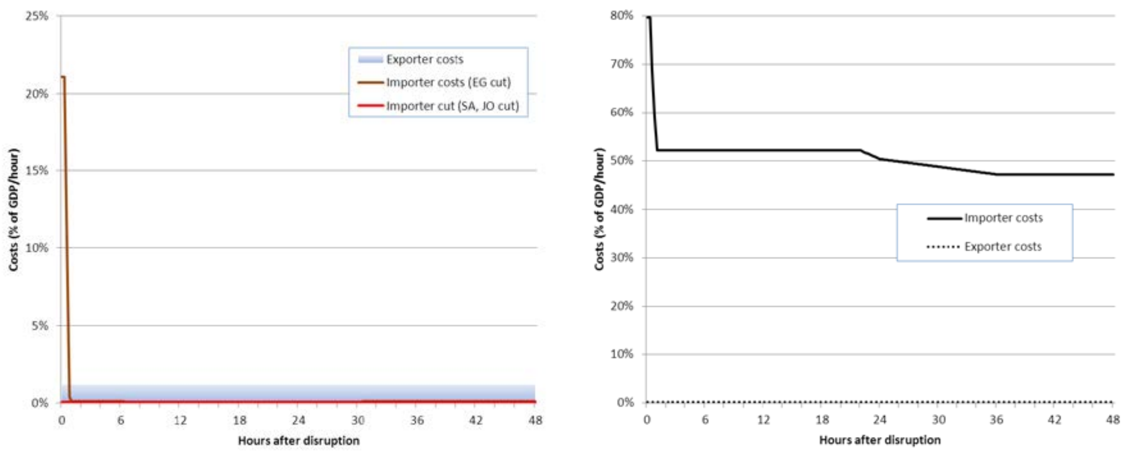


Figure 19: Relative costs for the importer and exporters in the single- (left) and all-country interruptions (right) in the Desertec bottleneck case for Poland for the first 48 hours following an interruption.

Country abbreviations: EG=Egypt; JO=Jordan; SA=Saudi Arabia.

In sum, I have shown that Desertec does not cause high European vulnerability to coercion. Single countries can cause short, but expensive, blackouts, but the costs inflicted on the exporters themselves are, after the blackouts are eliminated, higher than the costs inflicted on Europe. Europe would be vulnerable to coercion if all exporters manage to successfully coordinate their action. The intra-European transmission bottlenecks, in particular to Poland, pose a main vulnerability to coercion.

8.2.2 GEA

In the GEA base case, no single country can cause mentionable costs in Europe (see Figure 20). The exporters and transit countries, in contrast, experience costs in the range of 0.1-1.6% of hourly GDP for the duration of the event. Only Russia cutting all LNG and pipeline gas supplies ('RU all') causes short-lived and very small outages in Europe, but at the cost of inflicting high costs on itself. Thus, no single country has power over Europe. Also a cut of all pipeline gas exporters goes without supply effects in Europe. Hence, also this group of 6 countries, including Russia, do not have power over Europe.

Only the case in which all suppliers in the world – i.e. all pipeline and all LNG exporters – join an embargo during peak demand could cause significant and lasting gas outages in Europe. The European damages are considerable, initially almost 2% and after about a day 0.9% of hourly GDP. This is higher, although not by much, than the exporter costs, which are constant at just below 0.5% of their combined hourly GDP: the similar size of importer and exporter costs diminishes the credibility of the threat, and hence of the exporters' power over Europe.

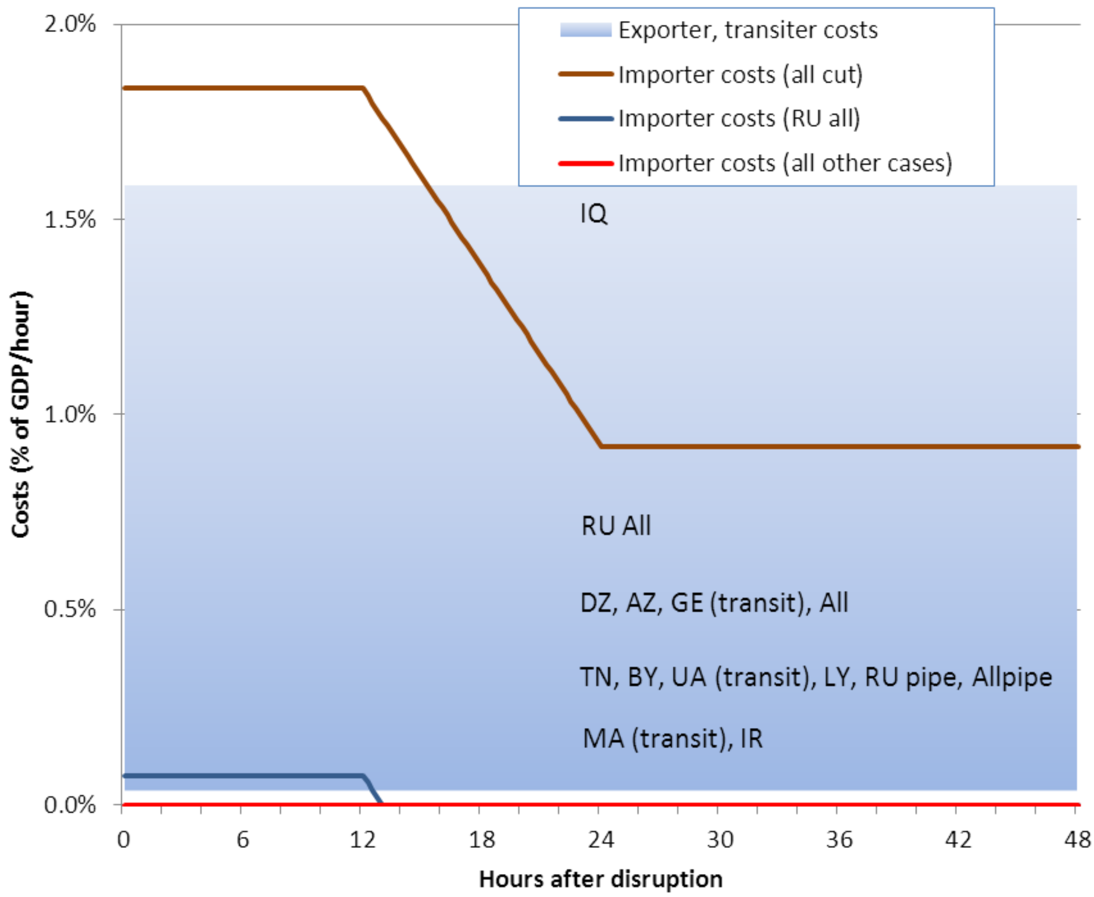


Figure 20: Relative costs for the importer and exporters/transiters in the GEA base case for the first 48 hours following an interruption.

The abbreviations in the graph refer to the approximate position of the costs of each exporter/transiter. Country abbreviations: AZ=Azerbaijan; BY=Belarus; DZ=Algeria; GE=Georgia; IR=Iran; IQ=Iraq; LY=Libya; MA=Morocco; RU=Russia; TN=Tunisia; UA=Ukraine.

Consequently, costs arise only for the exporters in the single country interruption cases, although in all cases except the Russian interruption, they rise at a low pace, see Figure 21. The importer costs cumulate faster than the exporter costs only in the all-countries interruption case. This highlights the finding that only a global gas embargo can put Europe under immediate pressure in GEA.

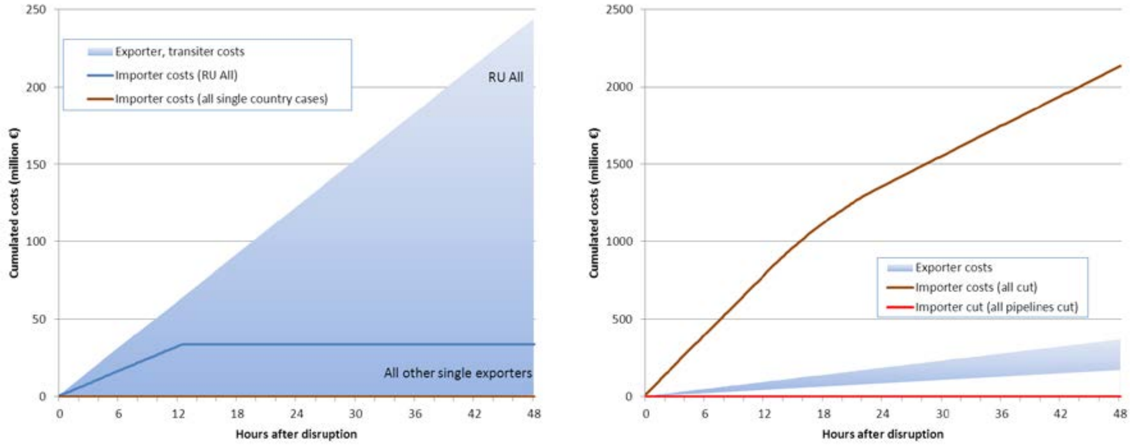


Figure 21: Absolute cumulated costs for the single- (left) and the multi-country interruptions (right) for the importer and exporters/transiters in the GEA base case for the first 48 hours following an interruption.

Country abbreviation: RU=Russia.

The results are sensitive to changes in demand, as average demand removes any European vulnerability to coercion, see Figure 22. In the average demand variation, the lower demand compared to the base case frees up storages in Europe, so that these can buffer all disturbances. Hence, no event, including a global embargo, can cause outages in Europe.

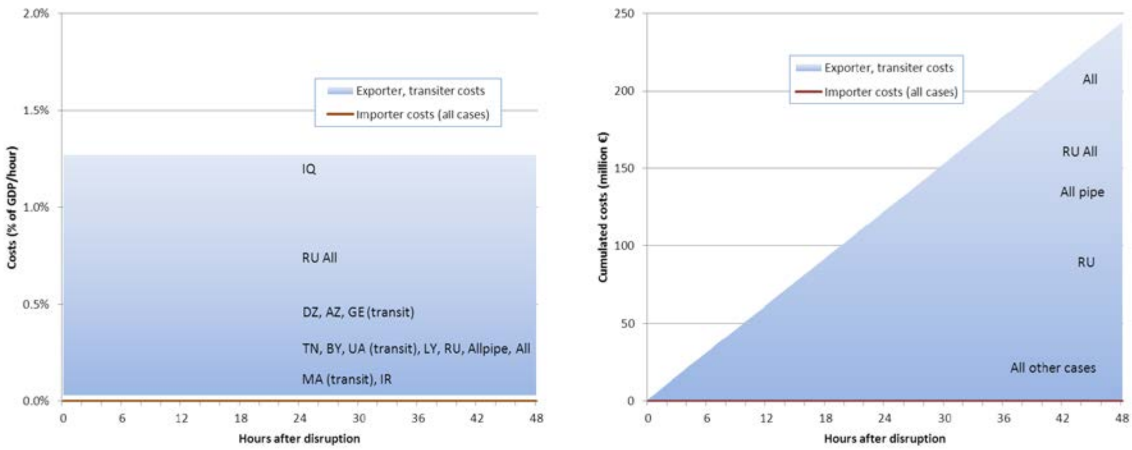


Figure 22: Relative (left) and absolute cumulated costs (right) for the exporters/transiters in the GEA average demand case for the first 48 hours following an interruption.

Country abbreviations: AZ=Azerbaijan; BY=Belarus; DZ=Algeria; GE=Georgia; IR=Iran; IQ=Iraq; LY=Libya; MA=Morocco; RU=Russia; TN=Tunisia; UA=Ukraine.

No interruption case in the max.- and min.-diversification variations, except the all-cut case (which is identical to the base case, see Figure 20), leads to outages in Europe, so that the importer costs are zero, see Figure 23 and Figure 24. Hence, Europe is not vulnerable to power from the exporters in any of the max.- or min.-diversification cases, and the results are not sensitive to changes in the supplier country structure.

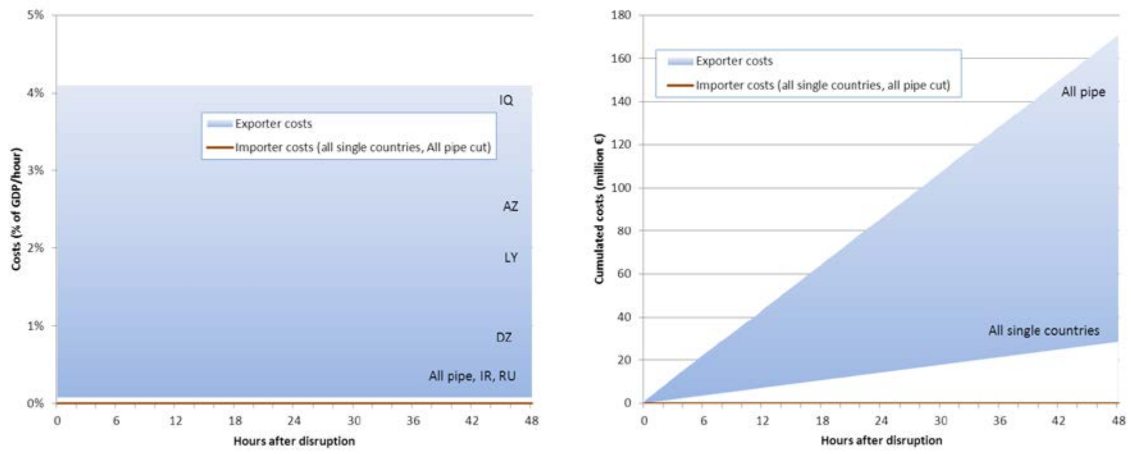


Figure 23: Relative (left) and absolute cumulated costs (right) for the exporters in the GEA max.-diversification case for the first 48 hours following an interruption.

Country abbreviations: AZ=Azerbaijan; DZ=Algeria; IR=Iran; IQ=Iraq; LY=Libya; RU=Russia.

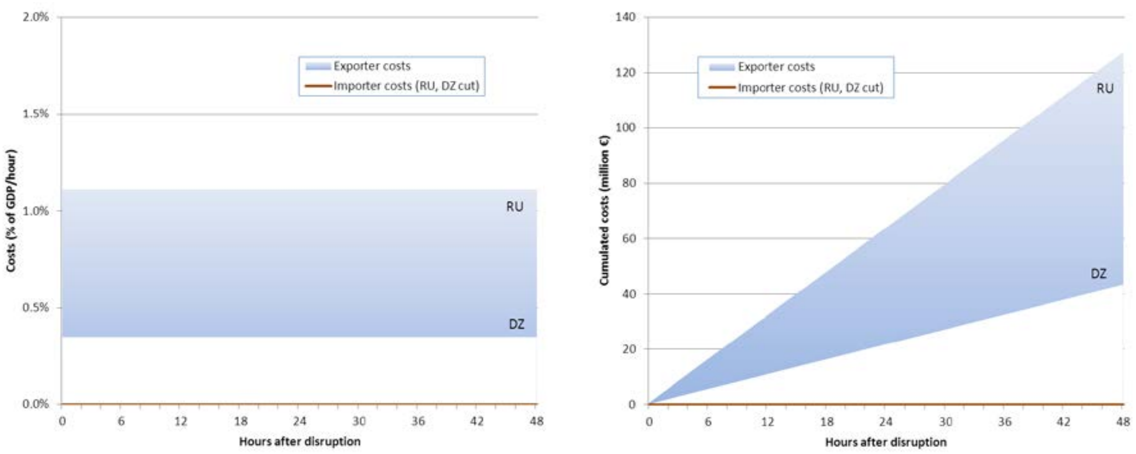


Figure 24: Relative (left) and absolute cumulated costs (right) for the exporters in the GEA min.-diversification case for the first 48 hours following an interruption.

Country abbreviations: DZ=Algeria; RU=Russia.

The results are sensitive to the strong response capacity variations carried out here. In the double responses case, no case, also not the case in which all countries embargo Europe, cause gas outages in Europe, making Europe fully invulnerable.

If the responses are halved compared to the base case, the European vulnerability is greatly increased. In this variation, a Russian pipeline gas export cut during peak demand causes lasting outages in Europe, and a Russian pipeline and LNG embargo ('RU all') causes large lasting outages (see Figure 25). However, only the pipeline and LNG cut case causes higher relative costs in Europe than in Russia, indicating that Russia needs to cut its share of LNG supply to the global market to put Europe under serious pressure. Just as in the base case, large groups of exporters have power over Europe if the coordinate their action.

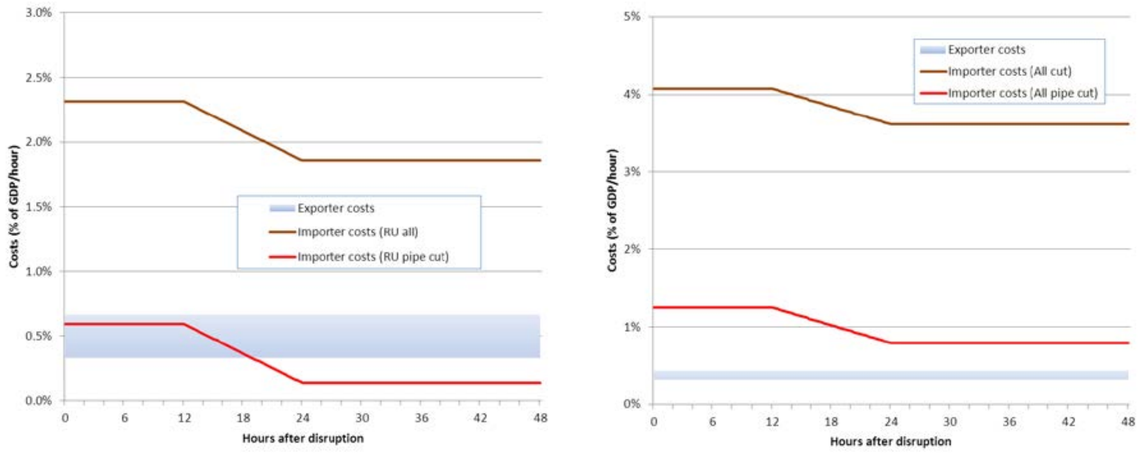


Figure 25: Relative costs for the single- (left) and the multi-country interruptions (right) for the importer and exporters in the GEA half responses case for the first 48 hours following an interruption.

Country abbreviations: RU=Russia.

Consequently, the costs cumulate slowly for the exporters (identical to the base case), but rapidly for the importer in the four interruption cases Russia, Russia-all, all pipeline exporters and all exporters, see Figure 26.

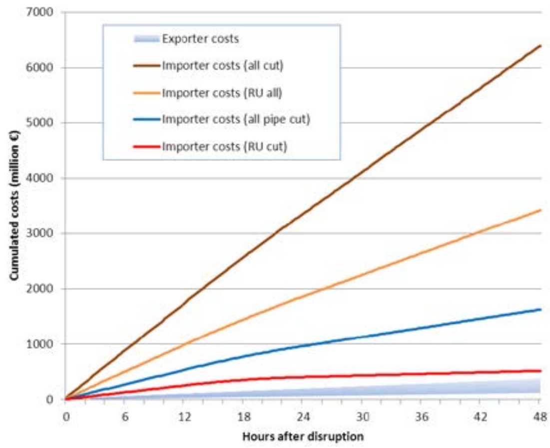


Figure 26: Absolute cumulated costs for an interruption from Russia (pipeline only, all (pipeline+LNG)) and the multi-country interruptions for the importer and exporters in the GEA half responses case for the first 48 hours following an interruption.

Country abbreviation: RU=Russia.

In the bottleneck case, the Baltic countries are not vulnerable, despite their high dependence on Russian pipeline gas. In this case, large storages and some LNG capacity avoids outages even following a complete export cut, see Figure 27. The costs for Russia also low, but in GEA, Russia does not have power over the Baltic countries.

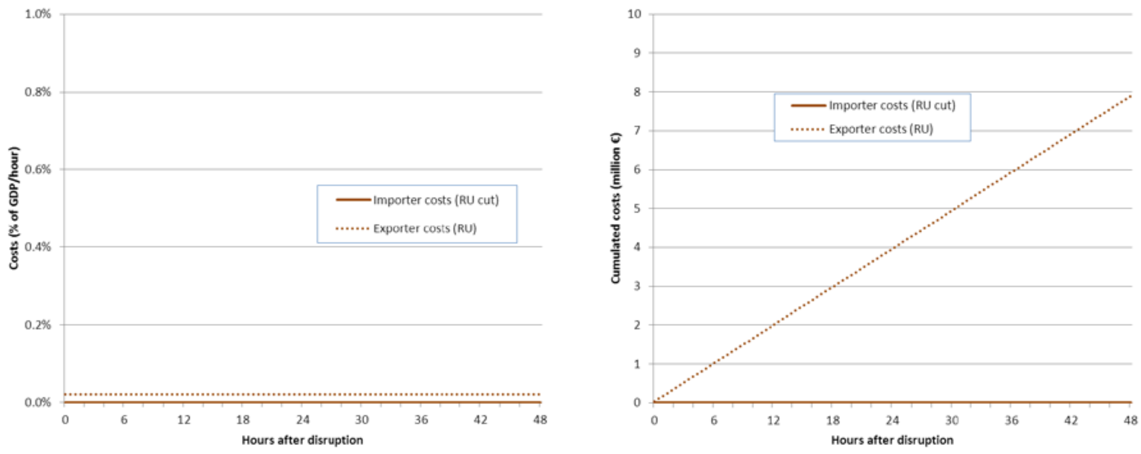


Figure 27: Relative (left) and cumulated absolute costs (right) for importer and exporter in the GEA bottleneck case for the Baltic countries for the first 48 hours following an interruption.

Country abbreviation: RU=Russia.

The Iberian bottleneck case shows a similar picture: despite its strong reliance on Algerian pipeline gas (parts of which transits through Morocco), its large storages and LNG capacities effectively buffer all pipeline gas import interruptions, see Figure 28. As Algeria is not capable of causing outages, the Iberian Peninsula is not vulnerable to coercion.

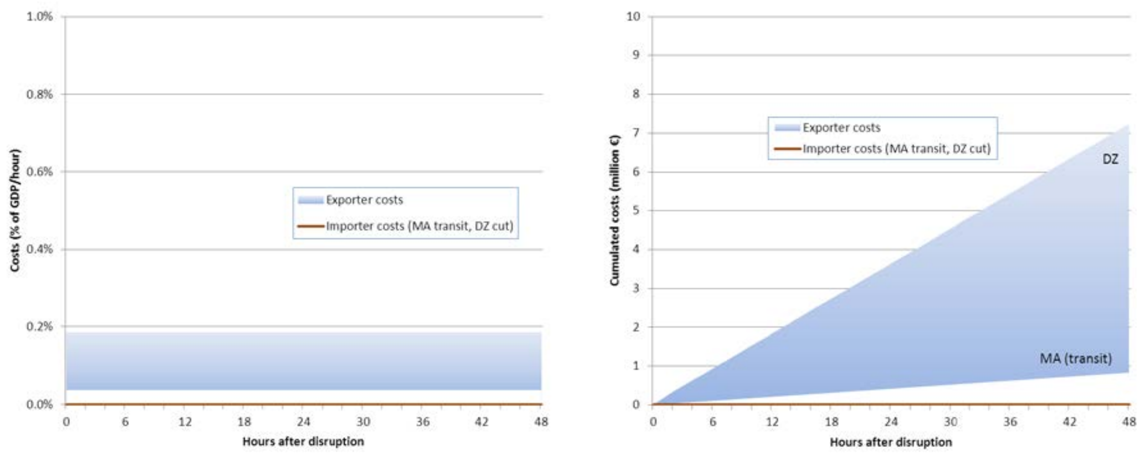


Figure 28: Relative (left) and cumulated absolute costs (right) for importer and exporter in the GEA bottleneck case for the Iberian Peninsula for the first 48 hours following an interruption.

Country abbreviations: DZ=Algeria; MA=Morocco.

Only the Balkan bottleneck case deviates from the no-power results above. All pipeline gas imports originate in Russia (some of which is transited through Ukraine), and these imports amount to almost 70% of the Balkan's import capacity. Ukraine, as a transit country, does not have power over the Balkan countries, but due to its comparatively low storage capacities and its weak interconnection with the rest of Europe, the Balkan is vulnerable to a cut in Russian gas supply. If Russia stops deliveries during peak demand, permanent outages in the Balkan would be the effect, see Figure 29. The importer costs, initially amounting to 3.5% of hourly GDP, remain at about 1% of hourly GDP after all responses are activated until the supplies from Russia are continued. Hence, the Balkan is vulnerable to power from Russia.

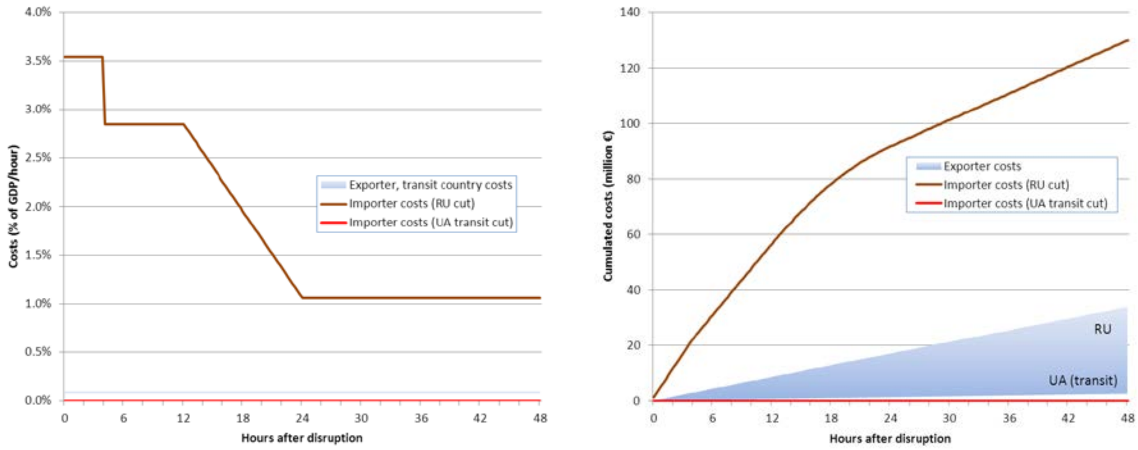


Figure 29: Relative (left) and cumulated absolute costs (right) for importer and exporter/transiter in the GEA bottleneck case for the Balkan for the first 48 hours following an interruption.
Country abbreviations: RU=Russia; UA=Ukraine.

In sum, I have shown that Europe is not vulnerable to coercion in GEA. Single countries cutting exports cannot cause mentionable costs to Europe, but would inflict lasting costs on themselves. Only a global gas embargo during peak demand would make Europe vulnerable to power of all exporters together, if they can successfully coordinate their actions. At off-peak times, Europe is completely invulnerable. The Balkan region is vulnerable to coercion, unless the intra-European transmission bottleneck is removed.

8.2.3 Today

In the Today benchmark, no single country has power over Europe, see Figure 30. Russia, being the primary supplier, can cause small outages in Europe during peak demand, but these can be remedied after about 16 hours through a combination of storage-draw and demand-reduction. Importantly, the Russian costs are, in relative terms, always higher than the European costs: hence, although Russia could inflict small damages on Europe today, it would not do so from a strong power position.

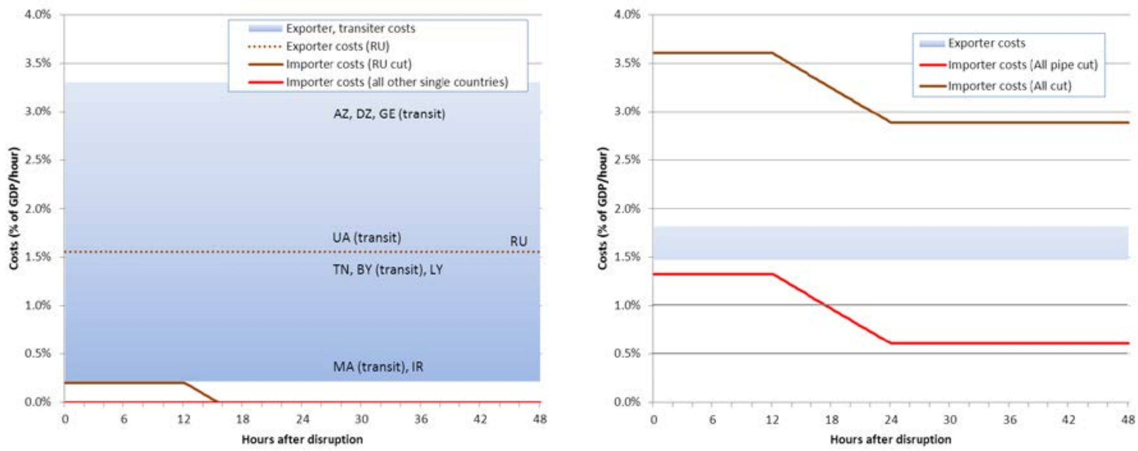


Figure 30: Relative costs for the single- (left) and the multi-country interruptions (right) for the importer and exporters in the Today benchmark base case for the first 48 hours following an interruption.

The abbreviations in the graph refer to the approximate position of the costs of each exporter/transiter. Country abbreviations: AZ=Azerbaijan; BY=Belarus; DZ=Algeria; GE=Georgia; IR=Iran; LY=Libya; MA=Morocco; RU=Russia; TN=Tunisia; UA=Ukraine.

The five pipeline exporters together have limited power over Europe: a combined embargo would cause significant damages in Europe (0.6-1.3% of hourly GDP), and the outages would remain until the embargo is lifted. However, the exporter costs are higher than the importer costs relative to GDP, indicating that they do not have power. Only if all exporters (pipeline and LNG) coordinate their action will Europe see lasting costs at a higher level than what the exporters inflict on themselves, indicating a vulnerability to this coordinated threat.

This is reflected in the absolute costs, see Figure 31. Whereas the Russian case inflicts costs on Europe, the breakeven point in absolute costs is at 23 hours, after the outages have been remedied in Europe. The multi-country cases, however, cause rapidly increasing costs in Europe, and slowly increasing costs in the exporter regions. This adds to the result above, that Russia does not have power, whereas the pipeline exporters may have some power, but only if they are willing to accept the higher relative damages compared to Europe.

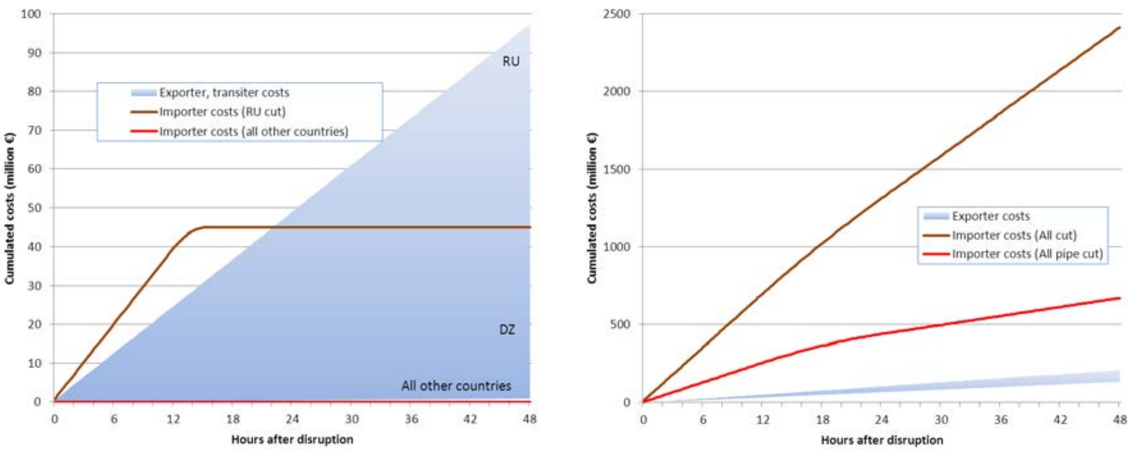


Figure 31: Cumulated absolute costs for the single- (left) and the multi-country interruptions (right) for the importer and exporters/transiters in the Today benchmark base case for the first 48 hours following an interruption.

Country abbreviations: RU=Russia, DZ=Algeria.

No single country and no combination of countries is able to cause gas outages in Europe during average demand: the storages, which are designed to support peak demand, are large enough to buffer any disturbance (see Figure 32). There is a wide margin between the full average imports and the maximum storage withdrawal capacity: hence, even if only half of the storage withdrawal capacity is available (e.g. because the storages are beginning to empty), the storages would be sufficient to buffer even this extreme disturbance.

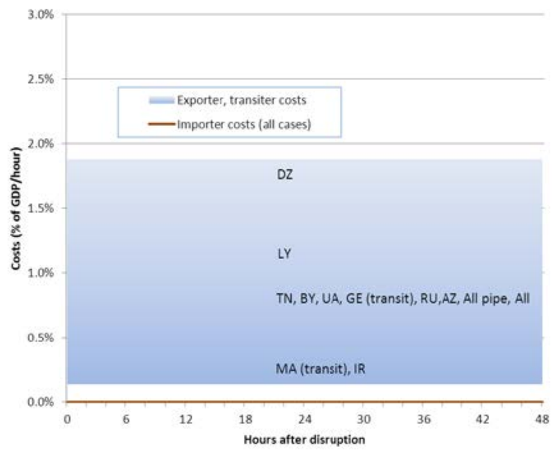


Figure 32: Relative costs for the single- (left) and the multi-country interruptions (right) for the exporters in the Today benchmark average demand case for the first 48 hours following an interruption.

Country abbreviations: AZ=Azerbaijan; BY=Belarus; DZ=Algeria; GE=Georgia; IR=Iran; LY=Libya; MA=Morocco; RU=Russia; TN=Tunisia; UA=Ukraine.

The Iberian Peninsula, is much less vulnerable than Europe as a whole, despite the tight transmission bottleneck separating it from France. Due to large storages and very high LNG import capacities, the only pipeline gas exporter to this region, Algeria, has no power as it would not be able to cause gas outages, see Figure 33.

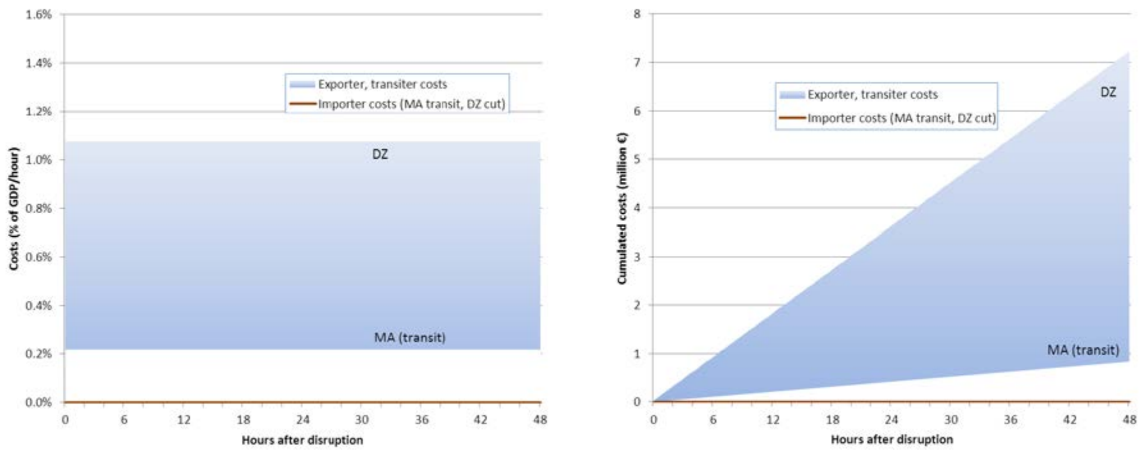


Figure 33: Relative (left) and cumulated absolute costs (right) for importer and exporter/transiter in the Today benchmark bottleneck case for Iberia for the first 48 hours following an interruption.

Country abbreviations: DZ=Algeria; MA=Morocco.

The Baltic countries and Finland, which are completely separate from the European gas system and import all their gas from Russia via pipeline, are much more vulnerable to coercion than Europe as a whole. An import embargo during peak demand times would cause serious outages, leading to lasting costs of between 8 and 11% of hourly GDP, see Figure 34. The Baltic region is thus very vulnerable to coercion by Russia.

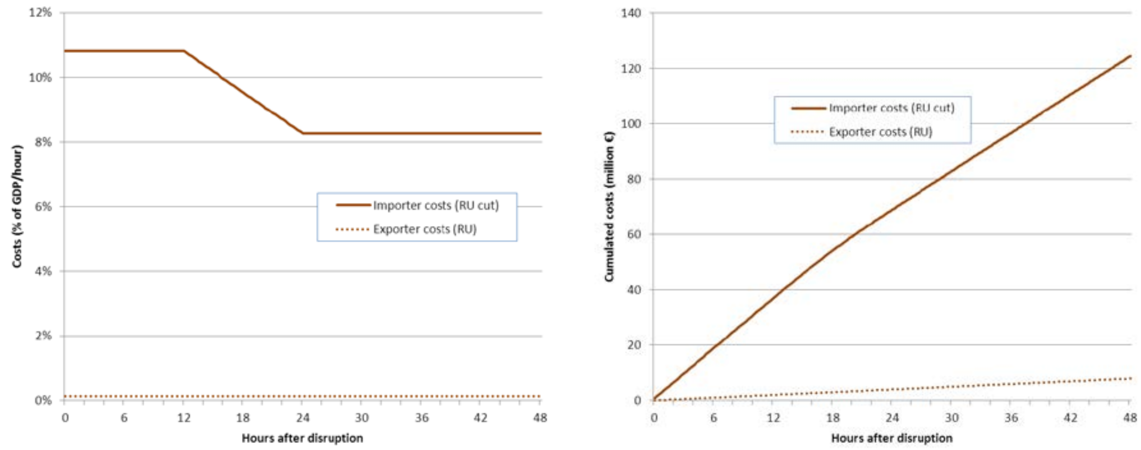


Figure 34: Relative (left) and cumulated absolute costs (right) for importer and exporter in the Today benchmark bottleneck case for the Baltic and Finland for the first 48 hours following an interruption.

Country abbreviation: RU=Russia.

The Balkan, which imports 90% of its gas via pipelines from Russia, is similarly vulnerable as the Baltic region. Due to its low import and storage capacities, the Balkan depends on intra-European imports (from Austria, Slovenia and Turkey) already to satisfy peak demand during normal operations, which greatly reduces its capability to respond to disturbances. Hence, the interruption of supplies from Russia (all of which transits through Ukraine) would cause large and irremediable outages: the costs would remain at just below 6% of hourly GDP until the external supplies are resumed, see Figure 35. Russia and/or Ukraine experience much lower costs and may thus have considerable power over the Balkan region.

This result shows the empirical validity of the model I developed and use here: just as was the case during the 2009 Russian-Ukrainian gas crisis, an interruption of all gas transited through Ukraine to Europe does not cause gas shortages in Europe as a whole (Figure 30) but large outages in the Balkan (Figure 35; see also section 10.3).

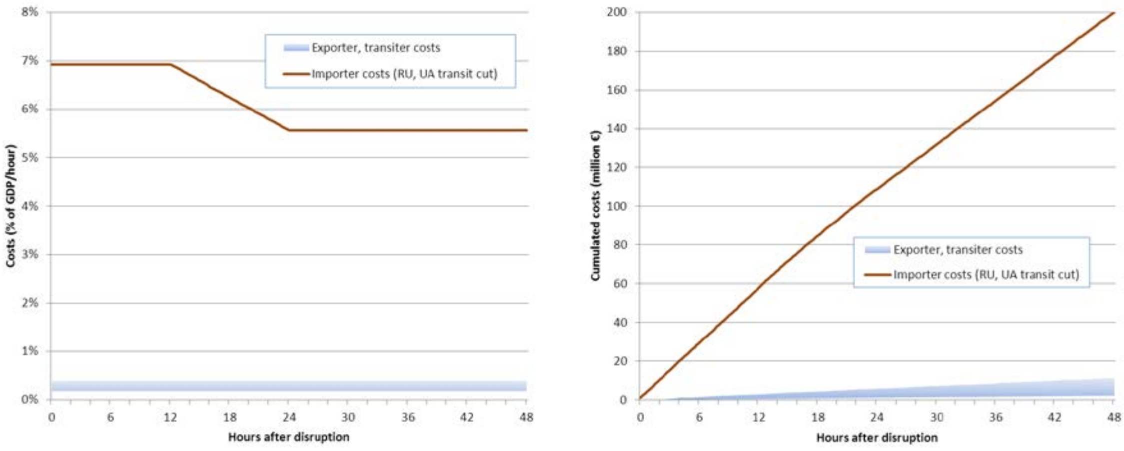


Figure 35: Relative (left) and cumulated absolute costs (right) for importer and exporter/transiter in the Today benchmark bottleneck case for the Balkan for the first 48 hours following an interruption.

Country abbreviations: RU=Russia; UA=Ukraine.

In sum, I have shown that Europe is today not vulnerable to coercion of single countries, including Russia. However, some regions – the Baltic countries and the Balkan – are very vulnerable to coercion by Russia, due to their isolation from the larger European gas network. Successfully coordinated action by all pipeline exporters or all gas exporters globally during peak demand would entail European vulnerability. Europe is practically invulnerable during average demand, as the buffers can cover any import disturbance, including a global embargo.

9 Results: vulnerability to critical infrastructure failure

In this chapter, I present the results of the assessment of European vulnerability to critical infrastructure failures. In the following section, I show the results of the chokepoint diversity analysis. This is followed by the results of the buffers/interruptions analysis (section 9.2), showing how many failed chokepoints the systems can buffer without suffering outages, and the disruption assessment (section 9.3), showing the size and duration of possible outages caused by failed chokepoints.

9.1 Chokepoint diversity

The results of the diversity analysis show that all scenarios and the Today benchmark are highly diversified with respect to their chokepoint structure, see Table 21. Desertec is much more diversified than both GEA and Today – the difference is up to two orders of magnitude – whereas GEA is similarly diversified as Today's system. The different cases indicated in the table are described in section 7.5 and the chokepoint structure tables in the Appendix.

Table 21: Results of the chokepoint diversity analysis (Herfindahl-Hirschmann index) for Desertec, GEA and the Today benchmark.

	Desertec	GEA	Today
Min.-diversification	$1.4*10^{-3}$	$6.4*10^{-2}$	
Base	$6.6*10^{-4}$	$2.1*10^{-2}$	$2.8*10^{-2}$
Max.-diversification	$3.3*10^{-4}$	$6.6*10^{-3}$	

These results originate in the high number of chokepoints in all scenarios, and defy the presence of very large chokepoints in GEA and Today (the 5 largest chokepoints in the GEA and Today base cases hold 25% and 30% of the total supply capacity, respectively). Desertec lacks these concentration points, it has a highly uniform distribution of capacities among the chokepoints and has a lower share of total supply coming from the chokepoints, which explains its very high diversity. This diversity result strongly shows that, from a chokepoint perspective, all scenarios and Today are secure due to their high diversities, and that Desertec is the most secure.

9.2 Buffers/interruptions

The results of the buffers/interruptions analysis contradicts those of diversity analysis: in this perspective, Desertec is much less secure than both GEA and the Today benchmark, as the Desertec system is not able to buffer as many failed chokepoints as the other systems (see Table 22; the variation cases are described in section 7.5). The electricity system of Desertec is designed to withstand the failure of one component, but not necessarily two (in the max. case, the import links are smaller, so that 2 lines fall under the normal n-1 paradigm, which is defined to hold other units than HVDC links). Hence, 2-3 disabled chokepoints could cause a blackout in Desertec. The gas systems of GEA and Today can buffer the simultaneous failure of, depending on the case, 5-80 chokepoints. These systems can only be disrupted during peak demand: during average demand (or with double response capacities), the GEA and Today systems cannot be disrupted by failing chokepoints. If only half of the storage capacity is present in the Today benchmark, already the undisturbed gas supply cannot be satisfied: this case is thus unfeasible.

Table 22: Results of the buffers/interruptions analysis for Desertec, GEA and the Today benchmark: minimum number of chokepoints that must fail simultaneously to disrupt the electricity (Desertec) or gas (GEA, Today) supply system.

	Desertec			GEA			Today
	Max.	Base	Min.	Max.	Base	Min.	
Peak demand	3	2	2	80	28	7	5
Average demand	3	2	2	n.a.	n.a.	n.a.	n.a.
Half response	3	2	2	40	13	5	---
Double response	3	2	2	n.a.	n.a.	n.a.	n.a.

The difference between GEA and Today on the one hand and Desertec on the other is a qualitative difference between the two types of systems: due to the storability of gas and the requirement to exactly balance electricity demand and supply at every instant, every electricity system is much more brittle than a gas system containing storages. Only the introduction of a higher operation security standard for electricity, replacing the n-1 principle with, say, n-5 or n-10 operating principles would change this: such extremely high security precautions would however be very expensive and seem utterly improbable and unrealistic. This result is thus robust, as it rests of the physical properties of different systems: the gas systems of Today and GEA are considerably more resilient, and thus secure, to chokepoint failure than the electricity system of Desertec.

9.3 Disruption assessment

The disruption assessment partially confirms the diversity analysis result, and shows that the vulnerability is low in all scenarios. It however also partially contradicts the diversity assessment, similarly to the buffers/interruptions results, and shows that within this low vulnerability, Desertec is more vulnerable than GEA and Today.

9.3.1 Desertec

The Desertec base case is not very vulnerable to CI failure. However, all failure cases, including the 3-fail case, cause outages but these can in most cases be rapidly removed. Only the case in which all chokepoints fail causes irremediable blackouts, whereas the 3- and 5-failure cases cause blackouts of up to 2% (14 GW) of peakload for up to two hours. The 10-failure case causes roughly twice as large blackouts that are remedied within 4 hours, see Figure 36.

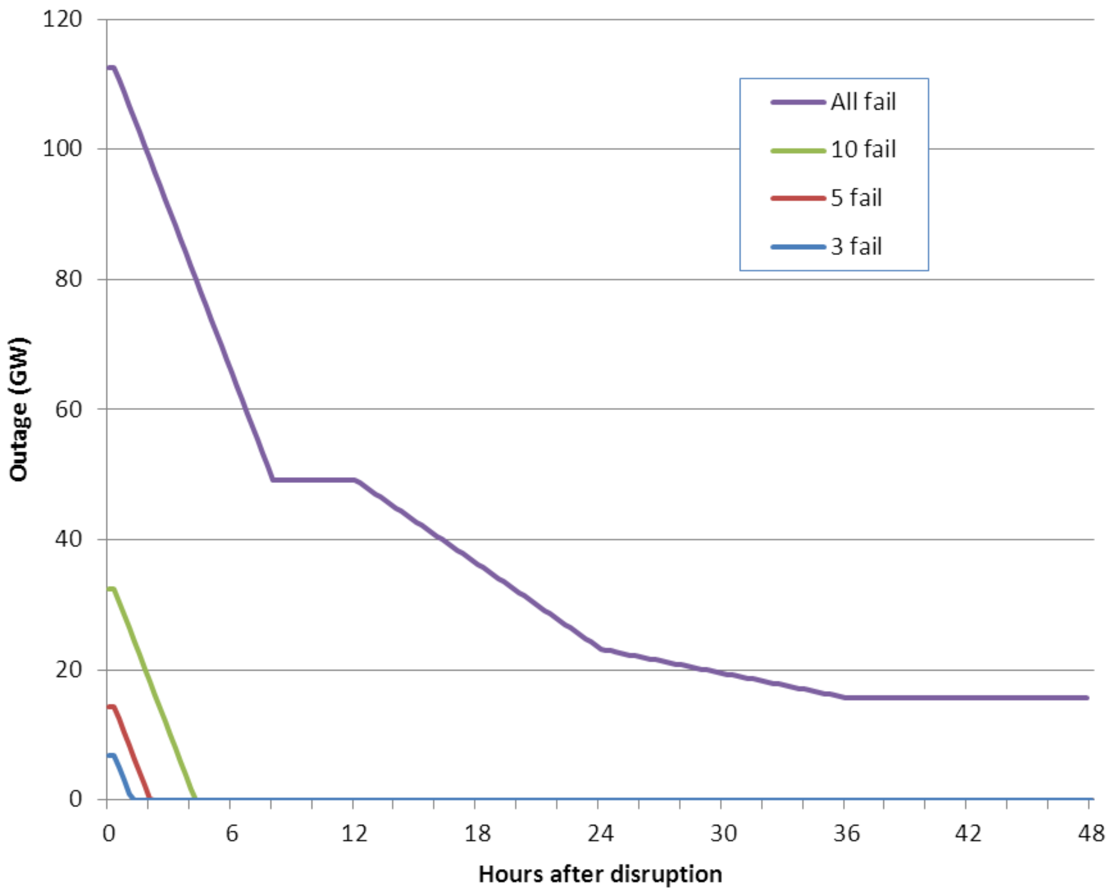


Figure 36: Blackout magnitudes for the first 48 hours following the simultaneous failure of the 3, 5 and 10 largest and all 33 chokepoints in the Desertec base case. The peakload is 605 GW.

This result is only partially sensitive to changes in demand, see Figure 37. If the interruption happens during average load times, the initial outage is lower and the blackouts can be removed faster than in the base case. Importantly, even the blackouts following the failure of all chokepoints can be remedied, within 15 hours.

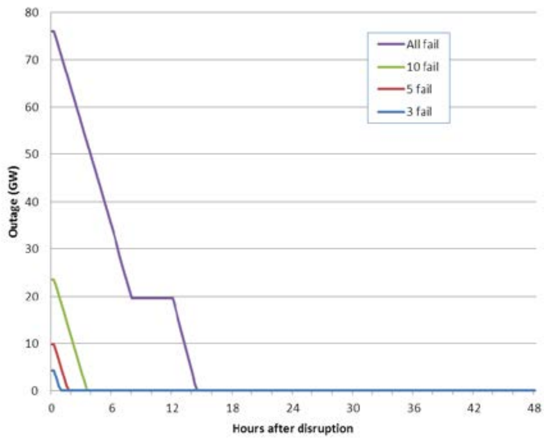


Figure 37: Blackout magnitudes for the first 36 hours following the simultaneous failure of the 3, 5 and 10 largest and all 33 chokepoints in the Desertec average load case. The average load is 463 GW.

Doubling the size of each chokepoint (the min.-diversification case) strongly increases the outage size (except the all fail-cases) and, especially in the 10-failure case, the blackout duration compared to the base case, see Figure 38. Halving the size of the chokepoints (the max.-diversification case), strongly reduces the size of the blackouts in following the disabling of 10 or less chokepoints. This indicates that bundling chokepoints into larger units increases the the vulnerabilty in terms of blackout size, whereas reducing the chokepoint size and spreading the imports over more units strongly reduces vulnerability both concerning blackout size and duration.

The all-fail interruption cases in both variations are almost identical to the base case; the slighly higher long-term blackout in the min.-cases originate in the lower spare capacity available[35]. An important difference between the results displayed in Figure 38, a difference that cannot be seen in the graph, is that the all-failure/min.-diversification case consists of 17 units whereas the all-failure/max.-diversification case has 66 units: hence, the simultaneous disabling of all units is much less probable in the latter than in the first case.

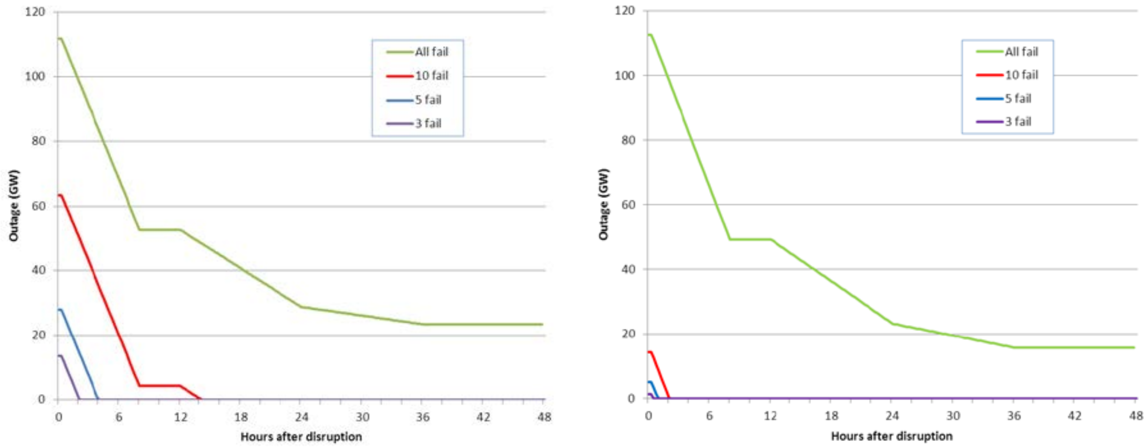


Figure 38: Blackout magnitudes for the first 48 hours following the simultaneous failure of the 3, 5 and 10 largest and all 17 and 66 chokepoints, respectively, in the Desertec min.- (left) and max.-diversification cases (right).

Doubling the response capacities does not affect the initial size of the blackout, which remains identical to the base case, but the duration is strongly reduced, to around 1-2 hours in the 3-10 chokepoint failure cases (see Figure 39). The blackout following an all-fail event can be removed within 7 hours.

[35] In order to keep the large HVDC links with the n-1 principle, I doubled the primary control capacity in the min.-diversification case, and subtracted this capacity from the spare capacity, see section 7.5.1.

The half responses case, in contrast, sees much longer outages than in the base case (see Figure 39). The blackouts in the all-failure/half-responses case are dramatic: these remain at over 60 GW, or about 10% of the European peakload, after all responses have been activated.

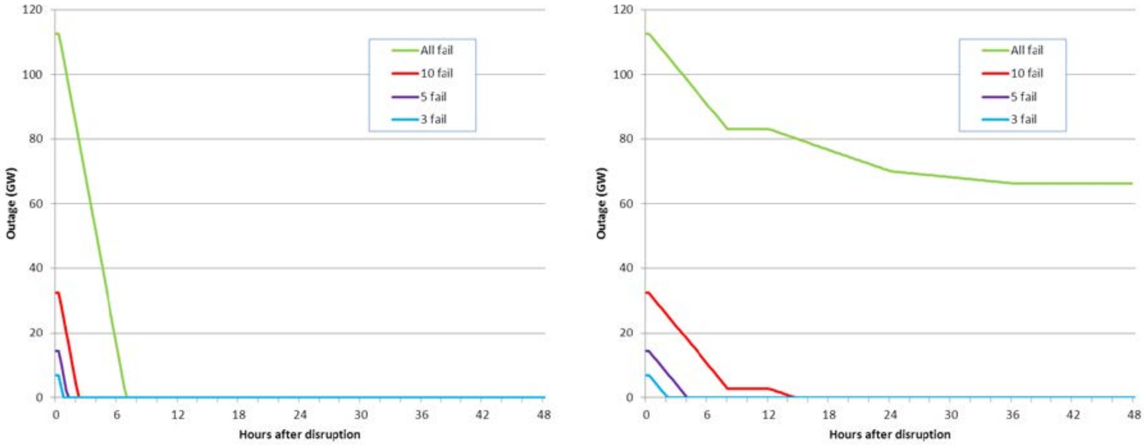


Figure 39: Blackout magnitudes for the first 48 hours following the simultaneous failure of the 3, 5 and 10 largest and all 33 chokepoints in the Desertec double (left) and the half (right) response cases.

The results are sensitive to the assumption that the European electricity system is completely unified. The Polish bottleneck case, with its very high import dependency (43% of demand), shows a higher vulnerability to chokepoint interruptions than Europe as a whole, see Figure 40. Here, already the failure of two chokepoints cause blackouts, but these can be rapidly removed. However, the failure of all four chokepoints entering Poland causes large and irremediable blackouts, remaining at over 5 GW, or 18% of peakload, until the imports through the chokepoints are resumed, despite full responses and full reliance on intra-European imports.

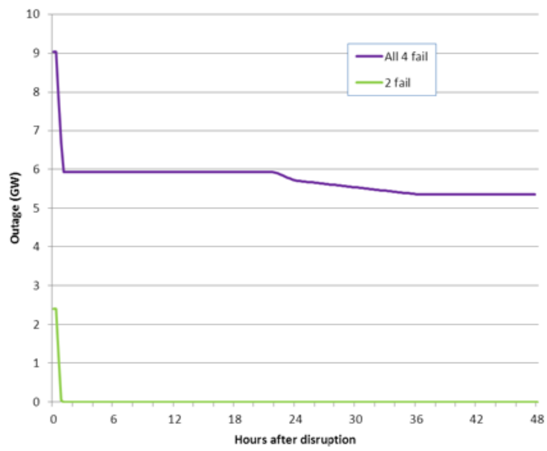


Figure 40: Blackout magnitude for the first 48 hours following the simultaneous failure of the 2 largest and all 4 import lines during peakload (29 GW) in the Desertec bottleneck case for Poland.

The bottleneck regions Iberian Peninsula and Balkan are less vulnerable than Europe as a whole, see Figure 41. This is to some extent unexpected: the Iberian low vulnerability largely originates in its low import dependency (12%), but the Balkan imports more than Europe as a whole (19%, compared to 17% for Europe). This can be explained by the Balkan's ability to utilise both the domestic capacities and the bottleneck interconnectors to the rest of Europe: although this is a limited connection, it suffices to reduce the region's vulnerability.

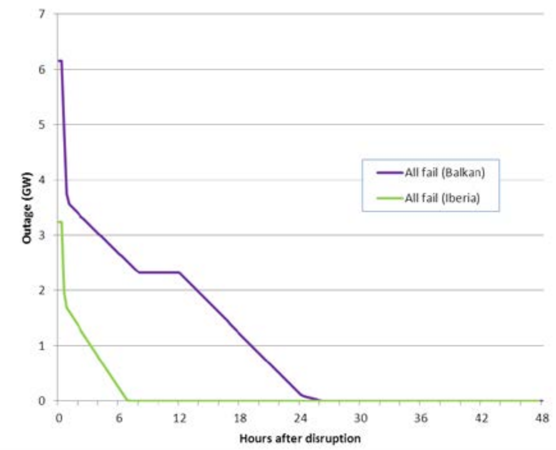


Figure 41: Blackout magnitude for the first 48 hours following the simultaneous failure of the 2 lines arriving in the Iberian Peninsula and the 3 lines arriving in the Balkan during peakload (59 and 45 GW, respectively) in the Desertec bottleneck case for these regions.

In sum, I have shown that Europe is only somewhat vulnerable to chokepoint failure in the Desertec scenario. Low-number failures cause small and short blackouts, and high-number failures cause large outages lasting for a few hours. Extreme failures of all or almost all chokepoints could cause lasting blackouts during peakload times, but such events are highly improbable, although not impossible. The transmission bottleneck between the bulk of Europe and Poland, with its high import dependence, is a main vulnerability in Desertec.

9.3.2 GEA

In the GEA base case, Europe is not vulnerable to chokepoint failure. Almost all failure cases during peak demand and all cases during average demand do not disrupt supply, as the failures are fully buffered by storage-draw. The exception is the most extreme case, when all 83 units fail simultaneously during peak demand, see Figure 42: these large outages cannot be removed, but remain until the supply through the disabled chokepoints is resumed.

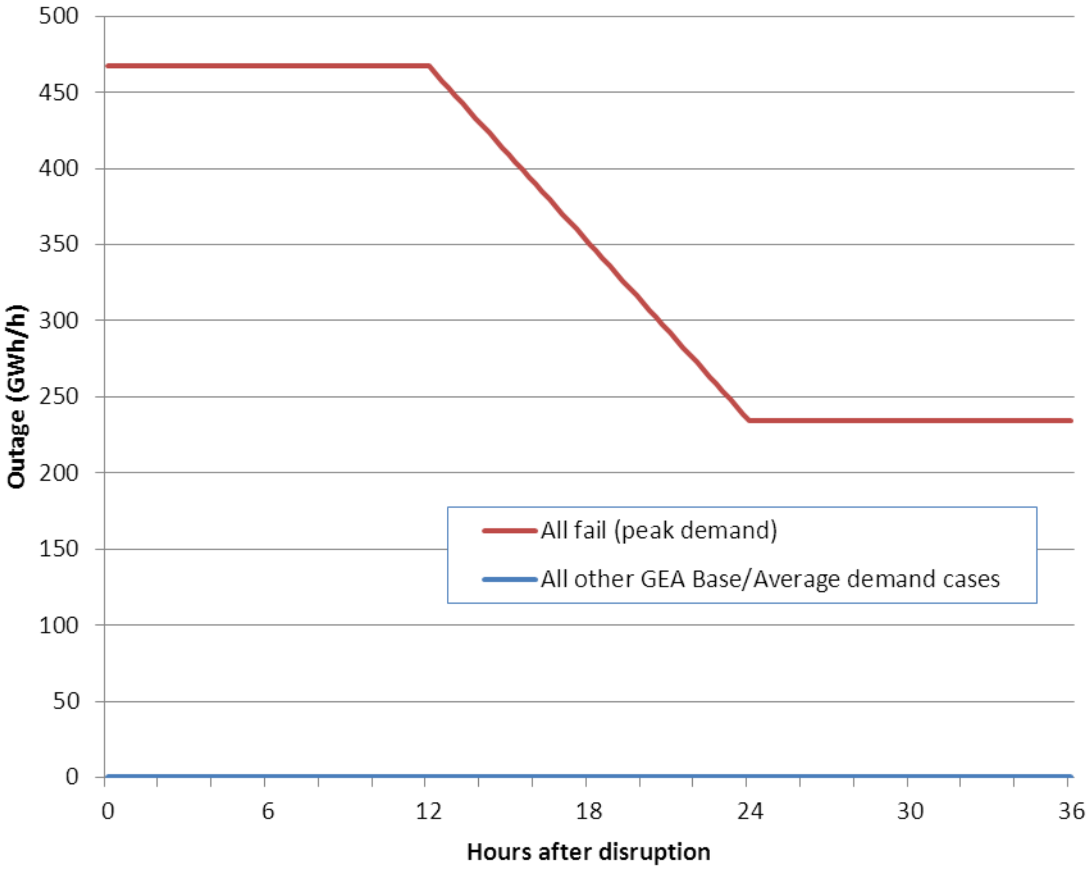


Figure 42: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3, 5 and 10 largest and all 83 chokepoints in the GEA base and average demand cases. The peak demand is 1768 GWh/h, the average demand is 1028 GWh/h.

In the min.- and max.-diversification variations, European outages happen only when all chokepoints are disabled (as in the base case) and in the 10-failure/min.-diversification case during peakload (which loses over 80% of the import capacity). The outages can only almost be removed, so that miniscule outages remain after all responses have been activated, see Figure 43.

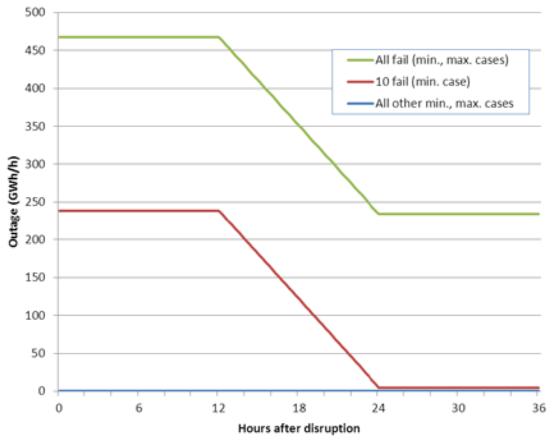


Figure 43: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3, 5 and 10 largest and all 15 and 121, respectively, chokepoints in the GEA min.- and max.-diversification cases.

The availability of storages and, to a smaller degree, fuel-switching capacity strongly influences the results (Figure 44). Halving the response capacities compared to the base case more than doubles the outage during peak demand, as a higher share of storage is needed to satisfy demand before the interruption. Halving responses also means that outages, including irremediable ones, occur also in the 5- and 10-failure cases. Doubling the storage size, in contrast, prevents outages even in the most extreme cases during peak demand, highlighting the importance of gas storages to gas security.

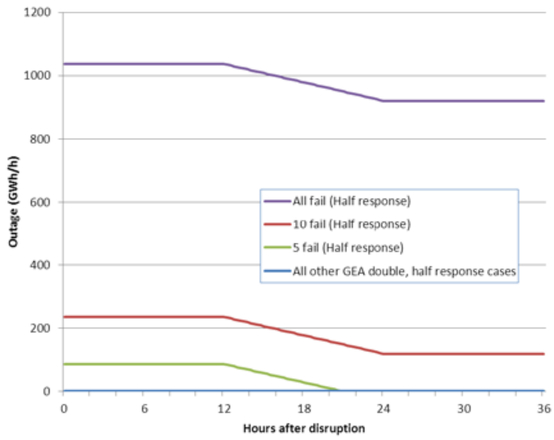


Figure 44: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3, 5 and 10 largest and all 83 chokepoints in the GEA half and double response cases.

The bottlenecks cause significant problems, indicating that – at least in the Balkan and Baltic cases – the integration into the overall European gas system is an important issue to increase the European gas security. The Iberian bottleneck case has very high LNG and storage capacities, so that not even a failure of all chokepoints during peak demand would immediately disrupt supply.

The Balkan suffers substantial and irremediable outages if all (10), 5 or even only 3 import routes are disrupted during peak demand, see Figure 45. Thus, the Balkan is considerably more vulnerable than Europe as a whole.

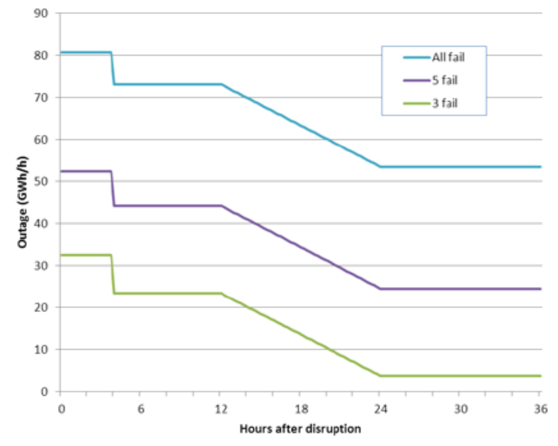


Figure 45: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3 and 5 largest and all 10 chokepoints during peak demand (136 GWh/h) in the GEA bottleneck case for the Balkan.

In the Baltic, the presence of large storages and some LNG import capacity mitigates the outage size and duration for all but the all-failure case. The initial outage in the 5-failure case is high, but temporally limited (see Figure 46), whereas the 3-failure case goes without outages. Hence, despite its isolation from the main part of the European system, the Baltic region is only slightly more vulnerable than Europe as a whole.

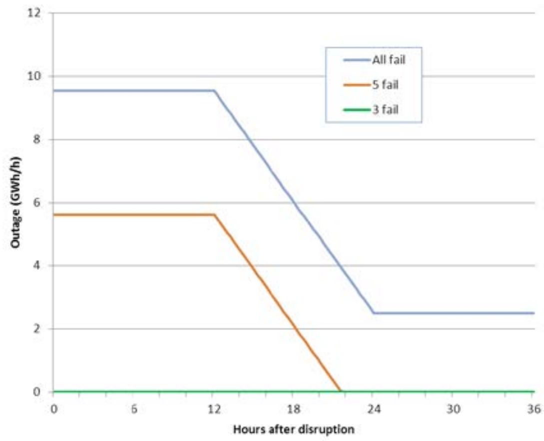


Figure 46: Gas outage magnitudes for the first 36 hours following the simultaneous failure of 3, 5 and all 6 chokepoints during peak demand (36 GWh/h) in the GEA bottleneck case for the Baltic region.

In sum, I have shown that Europe is not vulnerable to chokepoint failure in GEA. Almost all cases go without supply disruptions, as the storages can buffer most failure events; during average demand, the storages can buffer even the simultaneous failure of all chokepoints. Europe experiences outages only if all chokepoints fail during peak demand, which is very improbable. The main vulnerability is the intra-European bottlenecks to peripheral regions, especially to the Balkan, which have low storages and low chokepoint diversification.

9.3.3 Today

The Today benchmark shows that the present European gas system is slightly vulnerable to failures in the import chokepoints. The simultaneous failure of 5 or more chokepoints during peak demand would cause outages, and 10 or more disabled chokepoints would cause lasting outages, see Figure 47. Europe is invulnerable at average demand times: the domestic production capacity and the storages are sufficient to cover even the total loss of imports during average demand.

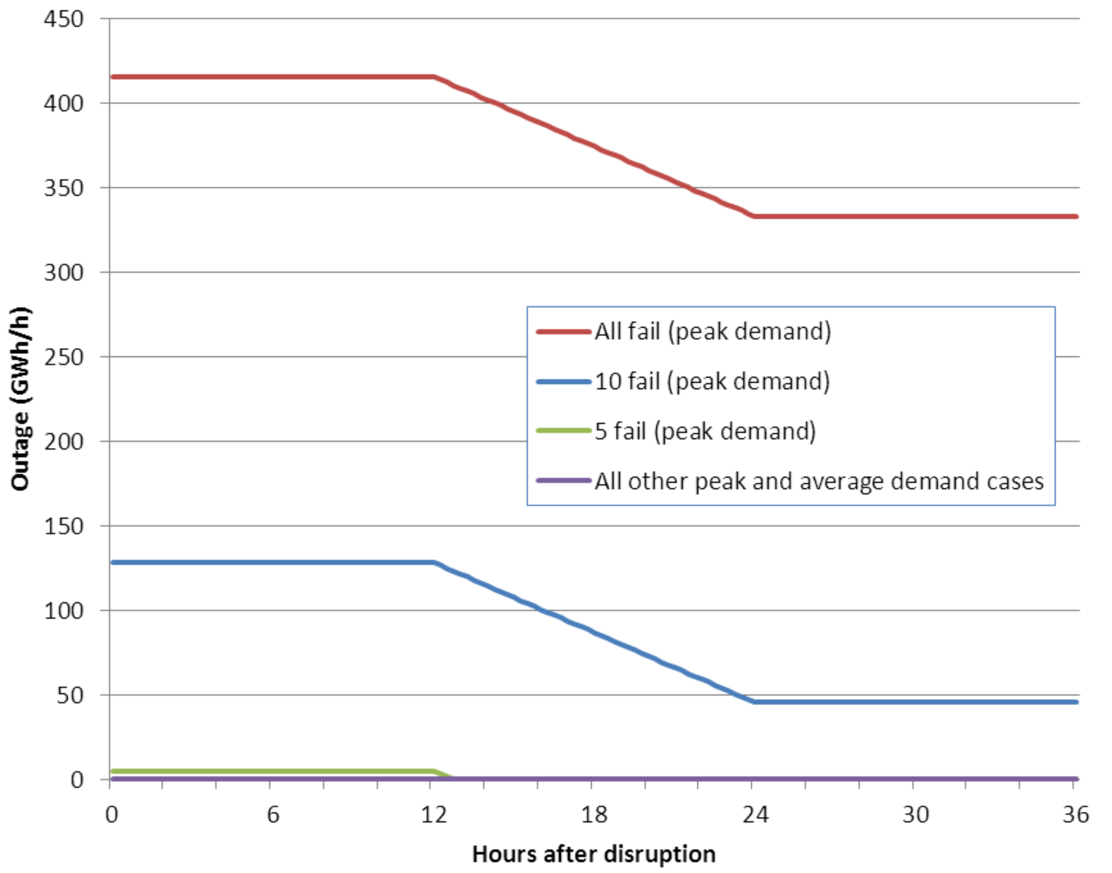


Figure 47: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3, 5 and 10 largest and all 38 chokepoints, in the Today benchmark base case (peak demand) and average demand case. The peak demand is 1632 GWh/h, the average demand is 696 GWh/h.

The assumption that the European gas system is unified proves to be an important assumption: the most vulnerable regions in Europe are much more vulnerable than Europe as a whole. This is in particular the case for the Baltic countries (incl. Finland), see Figure 48: already the failure on the largest chokepoint causes irremediable outages, mainly due to the low storage capacity. The failure of all 3 chokepoints supplying this region during peak demand would cause disastrous outages, even after all responses (storage and demand-reduction) have been activated, revealing a very high vulnerability.

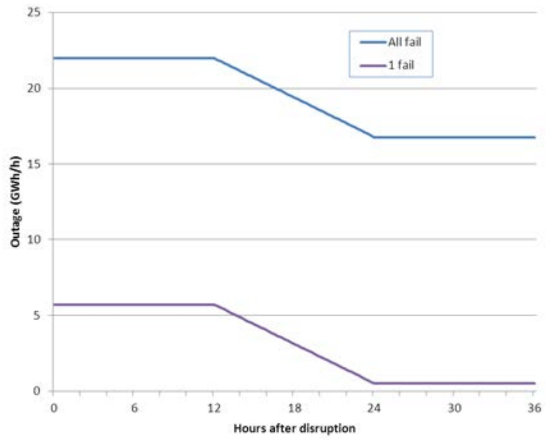


Figure 48: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the largest and all 3 chokepoints entering the Baltic region during peak demand (32 GWh/h) in the Today benchmark bottleneck case for the Baltic.

The Balkan is similarly vulnerable as the Baltic. Disabling the two or more of the 4 chokepoints ending in the Balkan causes large and irremediable outages of 18-27% of peak demand (see Figure 49). This is caused by a lack of storages and the strong limitations on emergency deliveries from rest-Europe imposed by the west-east transmission bottlenecks.

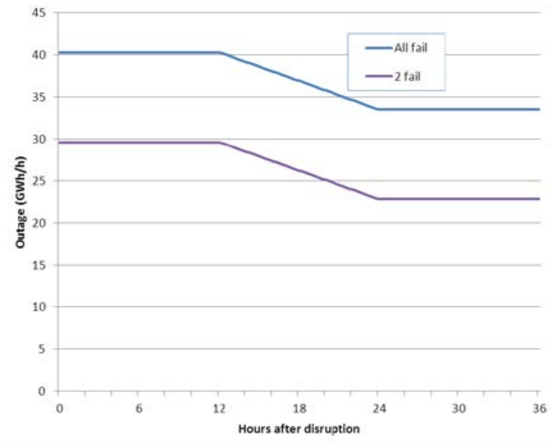


Figure 49: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the two largest and all 4 chokepoints entering the Balkan region during peak demand (128 GWh/h) in the Today benchmark bottleneck case for the Balkan.

Also the Iberian Peninsula is slightly more vulnerable than Europe as a whole, see Figure 50. Disrupting 5 or more chokepoints entering Spain or Portugal during peak demand causes significant and irremediable outages.

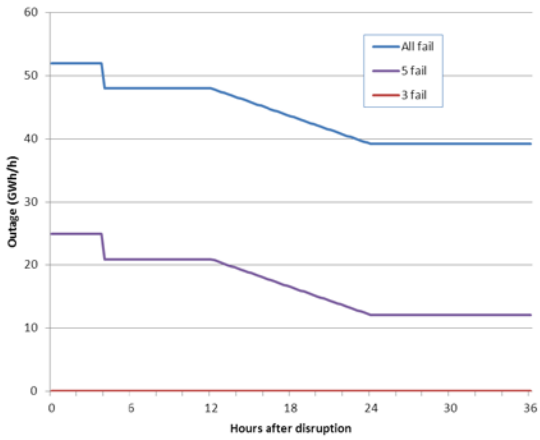


Figure 50: Gas outage magnitudes for the first 36 hours following the simultaneous failure of the 3 and 5 largest and all 9 chokepoints entering the Iberian Peninsula region during peak demand (136 GWh/h) in the Today benchmark bottleneck case for Iberia.

In sum, I have shown that Europe is currently slightly vulnerable to chokepoint failure. Almost all cases (5 or less chokepoint failures) go without supply disruptions, as the storages can buffer most failure events; during average demand, the storages can buffer even the simultaneous failure of all chokepoints. Europe experiences lasting outages if 10 or more chokepoints fail during peak demand, which is improbable but possible. The main vulnerability is the intra-European bottlenecks to peripheral regions, especially to the Baltic and Balkan, which have low storages and very low chokepoint diversification.

10 Discussion: energy security assessments

My overarching objective in this dissertation is to investigate how a Supergrid future with renewable electricity imports from the MENA would affect European energy security. In this chapter, I synthesise, discuss and explain the results of the two previous chapters, thereby answering the second and third research questions concerning the European vulnerability to coercion by exporter countries and to critical infrastructure failure. I discuss these **findings** separately for vulnerability to coercion (section 10.1) and vulnerability to critical infrastructure failures (section 10.2).

Following the discussion of the findings, I also discuss some **epistemological and methodological aspects**. This discussion concerns both the methodological/epistemological aims of this dissertation and to the robustness of the data and models used to produce the results. This includes a discussion of the validity of the power balance/disruption assessment model and the robustness of the input data (section 10.3), as well as a discussion of the reasons for the partly dissonant results in the diversity assessments and the new methods I have developed in this dissertation (section 10.4). In sections 10.5 and 10.6, I discuss the usefulness of energy coercion to exporters and the attractiveness of critical energy infrastructure targets to terrorists. In these two last sections, I also discuss how the presence of alternative objectives of coercing states and terrorists would affect the conclusions, as well as a discussion of limitations of the new vulnerability assessment methodologies.

10.1 Findings: vulnerability to coercion

The vulnerability assessment results I presented in chapter 8 show that Europe is not vulnerable to energy coercion by the exporter countries in any of the scenarios or the Today benchmark. The two methodological approaches I applied – the mainstream diversity index and the new power balance methodology – agree on this conclusion, but give contradictory results concerning the ranking of the scenarios and the benchmark. I discuss this dissonance in detail in section 10.4.

The exporter diversity analysis shows that the supplier diversity is high for Desertec and Today, but clearly lower for GEA. The difference between the scenarios is large: the Desertec scores are 1-2 orders of magnitude better than the GEA scores, whereas the Today score is between GEA and Desertec. This indicates that the Desertec exporter countries, as well as those Today, have no power and Europe is not vulnerable to coercion. In GEA, however, the diversity analysis shows that some exporters may have power, even more power than the exporters in the current European gas system, so that GEA could introduce a vulnerability to coercion.

The power balance assessment confirms that Europe is not vulnerable to power from single exporter or transit countries in any scenario or Today: no single country can inflict high and lasting costs on Europe by cutting supplies, but the exporters would inflict high and sustained costs on themselves. This assessment approach however rejects the scenario ranking of the diversity analysis, by showing that Desertec – although its vulnerability is low – is more vulnerable than GEA and Today.

In Desertec, every export interruption, also those of single export countries, is potentially large enough to overcome the buffers and cause outages. As the electricity system buffers are designed to withstand technical failures in single units, losing a few GW capacity, the import losses – which are between 10 and 32 GW – exceed the buffers in all cases. All import interruptions may therefore cause blackouts and, for the duration of these, high costs in Europe. Nevertheless, the blackouts can be eliminated after a few hours in all single-country cases, showing that the European vulnerability to coercion in Desertec is low, but it is not zero. In GEA and Today, in contrast, single country export cuts do not cause outages, and hence no costs for Europe, as the European storages suffice to buffer all such disturbances. In these cases, only the exporters themselves experience costs, showing that they do not have any power over Europe. In GEA and Today, a full Russian embargo during European peak demand could cause very small and short outages, but the costs for Russia itself would be much higher and – above all – sustained, so that Russia has an unfavourable power situation in these cases.

These differences between the scenarios are emphasised in the cases with disturbances during average demand. Single-country export cuts cause blackouts in Desertec also during average load, although they are smaller and can be remedied faster than during peakload. In both GEA and Today, however, the gas storages are larger than the average demand, so that gas outages should not occur even during a full global embargo.

Hence, the costs inflicted on Europe are high but short-lived (Desertec) or negligible (GEA, Today), whereas the costs inflicted by the single exporters on themselves are generally high and, above all, constant. After the European outages are removed (should such appear), the exporter costs are always higher than the European costs, so that the power balance rapidly tips in favour of Europe, especially in the gas-importing scenarios. This shows that GEA and Today are practically invulnerable to single-country coercion, as the exporters inflict costs on themselves but not on Europe. Desertec, in contrast, is weakly vulnerable, as also single-country cuts cause short blackouts and costs that are temporarily higher than the costs of the exporter. This is caused by a technical difference between the systems: whereas gas storages can buffer most disturbances and fully avoid end-user outages in GEA and Today, the electricity system of Desertec cannot buffer the lost imported capacity, but it is capable of recovering fast from blackouts if they happen.

Although Europe is not vulnerable to coercion, certain regions within Europe – the Balkan (GEA, Today), the Baltic (Today) and Poland (Desertec) – are. These regions are today separated from the rest of Europe through transmission bottlenecks, have high import dependencies coupled with low response capacities. Export cuts from one or few countries could cause very large (proportional to the regional demand) and sustained outages, and thus high and sustained costs. This vulnerability is exacerbated by the export countries' low dependence on the markets of these regions: the exporter costs are very low compared to the costs of these importer regions. As the European – especially the European Commission's – perception of energy security refers to the stability of supply in all of Europe, including its most vulnerable parts, this regional vulnerability to coercion poses a vulnerability for Europe as a whole, unless the bottlenecks are removed (see chapter 4).

All scenarios and Today are vulnerable to full embargoes of all exporters during peak demand: such extreme events would cause high and lasting costs in Europe, at a level much higher than the costs experienced by the exporters. Also here, there is a clear ranking: GEA is the least vulnerable, seeing the lowest costs for Europe, followed by Today (about three times the lasting GEA cost, mainly because of the lower GDP) and Desertec (about four times the GEA cost). The costs in Desertec are higher than those in GEA, because the VOLL of electricity is higher. Also in this case, therefore, the ranking and differences in vulnerability between the scenarios primarily originate in the different natures of gas and electricity systems.

However, such massive events are improbable. It is highly unlikely that all suppliers see a reason to 'punish' Europe at the same time, and as coordination – in particular avoiding free-riders – is increasingly difficult with increasing number of participating countries. The probability that a strong reason appears for many countries to join an embargo is low in all scenarios, especially in GEA and Today, as the gas exporter countries are diverse in terms of politics and culture. In Desertec, this appears slightly more likely, as all exporters within one geographical and cultural area. For example, a conflict between Europe and the Arab world (or, for example, European backing for an Israeli military conflict; see Locklider 1988) could trigger an export cut from all Arab exporters in Desertec, but a strong reason for all former Soviet and MENA countries to join a common embargo is harder to conceive of. A full-scale coercion event with the participation of all exporters during European peakload/peak demand should, for all scenarios, therefore be seen as an extreme case with very low, but not zero, probability of happening.

My results and conclusions therefore cast doubt on the prevailing sense of threat in the energy security literature: at least the two types of scenarios I have assessed here are not highly vulnerable to energy coercion, due to two main factors. First, the large European interconnected energy systems are highly resilient, because of the way they are operated and the significant capacity margins put in place for reasons other than to protect Europe from coercion of external suppliers. Second, because of this resilience, the exporters are generally more dependent on the energy export revenues than Europe is on the energy imports.

10.2 Findings: vulnerability to critical infrastructure failure

The results I presented in chapter 9 show that the European vulnerability to critical infrastructure failure is low in all scenarios and the Today benchmark. The different methodologies – the mainstream diversity index and the new, resilience-based methodologies – agree on this low-vulnerability conclusion, but they produce in part contradicting results concerning the ranking of scenarios. I discuss this dissonance in detail in section 10.4.

The chokepoint diversity analysis gives very low concentration scores in all cases, although the scores for Desertec are 1-2 orders of magnitude better than GEA and Today. This indicates that the vulnerability to chokepoint failure is very low in all scenarios and Today, but it is even lower in Desertec than in GEA and Today.

The buffers/interruptions analysis, however, rejects this ranking and shows that Desertec is more vulnerable than Today and much more vulnerable than GEA: already 2 chokepoint failures can cause blackouts in Desertec, whereas Today and GEA can withstand many more failures (in the base cases: 5 and 28, respectively) without suffering outages. The GEA scenarios and Today are thus practically invulnerable except to very extreme events, and can even buffer the failure of all chokepoints during average demand without experiencing outages.

The critical infrastructure disruption assessment confirms that Desertec is more vulnerable than GEA and Today, but also shows that it is not dramatically more vulnerable. Although small-number chokepoint failures can cause blackouts in Desertec during both average load and peakload, these blackouts are limited in size and can be remedied fast. The gas-import system of GEA is practically invulnerable to all events except failure of all (or almost all) chokepoints during peak demand, or very large-scale failures combined with large unavailability of storages. The same applies for Today, which however also sees lasting outages following the failure of 10 or more chokepoints during peak demand.

These differences in vulnerability originate in the same technical differences between gas and electricity systems as mentioned for the coercion vulnerability assessments above: electricity systems are more brittle than gas systems, and they do not have the option of large-scale storage buffers. As limited blackouts are the possible consequence of non-extreme chokepoint failure in Desertec, but not in GEA and hardly in Today, all scenarios and Today have a low vulnerability to chokepoint failure, but Desertec is slightly more vulnerable than the other cases.

Europe as a whole has a low vulnerability to chokepoint failure in all scenarios and Today. However, certain regions presently separated from the main European systems by intra-European bottlenecks – Poland (Desertec), the Baltic and the Balkan (GEA, Today) – experience outages also following 1-3 chokepoint failures. In these regions, very large – up to 20% of peak demand – and lasting outages are the likely consequence of failures of low-number (3-5) chokepoints during peak demand. Although multi-failure events are not every-day events, they are possible outcomes of especially natural events or terrorist attacks. These regions are vulnerable to chokepoint failure. Therefore, the internal European transmission bottlenecks, effectively reducing the response capacities of exposed regions, pose a European vulnerability to import chokepoint failure.

If all, or almost all, chokepoints are simultaneously disabled, the likely effect in all scenarios and Today is lasting outages, but only if this happens during peak demand. During average demand, or if less than all (or almost all) chokepoints are disabled, outages can either be completely avoided (GEA, Today) or remedied within a few hours (Desertec). In all scenarios, the probability of such complete failure happening is miniscule: it is all but impossible that one extreme natural event simultaneously disables chokepoints spread out over several thousand kilometres. Unless a common control system is introduced for all chokepoints, a technical failure simultaneously disabling all 16-121 chokepoints in the different scenario cases is close to impossible. Concerning terrorism, it is possible to disable that many units, but it is very difficult and not many, if any, terrorist groups are capable of such multi-target, simultaneous attacks. Although it sounds cynical, the comparison to traditional terrorist targets indicates that terrorists aiming to create fear in a wider population are unlikely to target energy chokepoints, but rather softer and higher-impact targets, like humans. In addition, attacks against the electricity chokepoints must be simultaneous – at least within a few minutes – so that the system does not have time to find a new n-1 secure state. As the effects of even successful attacks are in most cases not devastating (or even noticeable on a supply level) for Europe, the chokepoints of all scenarios and Today, especially the gas chokepoints, are unattractive terrorist targets (see also section 10.6 for further discussion of terrorist target attractiveness).

My results therefore reject the prevailing notion in the literature that energy infrastructure is highly vulnerable to terrorism. They however confirm the low-vulnerability conclusions of Smith Stegen *et al.* (2012) and Toft *et al.* (2010), although my conclusion is based on slightly different arguments. They found that the low vulnerability is due to the lack of symbolism in CI systems and the non-discriminate effects of energy outages. I, in contrast, found the low vulnerability is rooted in the low impacts of practically all events and the difficulty to carry out high-number simultaneous attacks. Nevertheless, the arguments of Smith Stegen *et al.* (2012) and Toft *et al.* (2010) may hold in the future as well, but one cannot know today; if they hold, the low-vulnerability conclusion here would be further strengthened.

10.3 Model validity and data robustness

The conclusions that no scenario is vulnerable to coercion and chokepoint failure are very strong, especially considering the uncertain input data. This, together with the partial contradiction between the new methods I developed here and the mainstream diversity indices, raises an important question: are the power balance and CI vulnerability results the product of bad data, or of a bad representation of reality in the new model?

It is difficult to validate a model for the vulnerability to energy coercion or large-scale import chokepoint failure, as such events are very rare. The analysis of how the threats unfold and how the vital energy systems are resilient and react to disturbance (see chapter 7 and the Appendix) underlying the model make the model conceptually valid. For Europe, there is probably only one case that offers the possibility of empirical validation: the 2009 Russian-Ukrainian gas crisis, during which all Russian gas transited through Ukraine was stopped. This event was not directed at Europe, but it had serious knock-on effects in Europe: although the overall European response mechanisms would have been sufficient to satisfy total demand, the small regional storage capacities in the Balkan and the severe transmission bottlenecks to the rest of Europe greatly limited the Balkan's ability to react to the disturbances so that gas outages occurred there (EC 2009b; Pirani *et al.* 2009).

I have reproduced this result here, in the Balkan bottleneck case of the Today benchmark (see Figure 30 and Figure 35): stopping all Russian gas supplies transiting Ukraine causes no outages in a unified European system but, due to the bottlenecks, the Balkan sees large outages. Robust data on exactly how large the outages were in 2009 and how much they cost is not available, but existing descriptions of events are very similar to what is found here (Kovacevic 2009). My results also suggest that tighter intra-European system integration would have greatly reduced, and probably completely avoided, supply disruptions in South-

Eastern Europe in 2009, a conclusion that also others have arrived at (e.g. EC 2009b). Although it would be interesting, in future research, to apply the model to historical (non-European) coercion events and further empirically validate it, I view these results as confirmation that the model I have developed is valid.

This leaves the question of data uncertainty. In the discussion below, I show that uncertain data is not the reason for the low-vulnerability conclusion or the differences between scenarios. The data is uncertain, but it is certain enough to support the conclusion. I find three main reasons for this, related to three different data issues.

First, the results of the power balance and CI vulnerability assessments, as well as the buffers/interruptions analysis, hinge on the data concerning emergency response mechanisms, the data for which is uncertain. If these assumptions are too optimistic, the results would lose greatly in credibility because the low-vulnerability result could be an underestimation of the actual vulnerability. When constructing the data not directly available from the scenarios, I took great care not to overestimate the responses (see the Appendix, sections 13.1.4 and 13.2.4), and to test the assumptions in a sensitivity analysis based on what is possible rather than what is probable, using knowledge that is at least qualitatively knowable (see section 7.5). For example, the minimum bound for gas storages in GEA – the half-responses case – implies that a large share of the presently existing storages will close, which is highly unlikely in a scenario with strongly increasing gas demand. Similarly, the minimum bound for the Desertec responses is half of those in the present electricity system (relative to peakload), which is an extraordinarily cautious assumption for a scenario with greatly increased intermittent generation. Furthermore, I can safely expect that electricity will remain grid-bound, that gas will be imported through some combination of pipelines and LNG also in the future, and that electricity lines, pipelines and LNG terminals cannot be arbitrarily large or small. As I have shown in sections 8.2 and 9.3, the extremely pessimistic variations of the already conservative assumptions concerning responses and supply structures have numerical impacts on the results, but they do not change the conclusion. The conclusion that all scenarios and Today have low vulnerabilities to both coercion and chokepoint failure is robust, as the response capacities are definitely not overestimated.

The responses could however be underestimated, which could be a problem for the comparison across scenarios. For Desertec, I took the overall available capacity from the scenario itself. Therefore, the only assumptions I made was the allocation of the generation capacity to the differently quick and durable control and spare capacities, as well as the demand-reduction capacities. The sensitivity analysis furthermore shows that the impact of increasing responses is small: in the double responses case, the blackouts have the same initial size as the base case, but are slightly shorter. The potential error from underestimating the Desertec responses is thus small, and certainly non-pivotal: only the introduction of at least an n-5 (or, in the GEA base case, n-28!) security paradigm for electricity would reduce the Desertec vulnerability to levels similar to GEA and Today – and this is extremely unlikely, if at all technically possible. For GEA, I made assumptions concerning storages and demand-response, and the sensitivity analysis shows that if they are double the size as in the base case, GEA is completely invulnerable to all interruptions. Hence, if I have underestimated the GEA responses, the low-vulnerability conclusion would be even stronger, and GEA's ranking above Desertec would be even clearer.

Therefore, although the responses assumptions are in part uncertain, they are certain enough: they are definitely not overestimations and they are not sufficiently serious underestimations to affect the conclusions.

Second, the results (except the average demand variations) describe disturbances during peak demand, during which Europe is in some extreme cases vulnerable to coercion or chokepoint failure. During average demand, the vulnerability is much lower (Desertec) or practically eliminated (GEA, Today) – and average demand times are much more frequent and longer lasting than peak times. Electricity peakload happens a few times a year (one hour in early evening on a weekday in winter), and is in Desertec 30% higher than average load. During large parts of the year, the loads are much lower than peakload: presently, for example, the difference between the January and July daily peaks in the ENTSO-E area is more than 100 GW, or 18% of peakload. This is roughly the same size as the entire Desertec import capacity. The daily peak/off-peak swing is of a similar magnitude, so that the difference between the winter peak and the summer minimum is around 300 GW, or over 50% of the peakload (ENTSO-E 2011c, 2012a). Hence, peakload is infrequent and very short, with important implications: the lasting blackouts in the Desertec all-failure/full embargo base case are 16 GW, but the day-night swing in winter is more than 100 GW. Any outages caused by import interruptions or chokepoint failures would thus probably disappear when the night comes (after up to 16 hours). However, and this is a reason for the constant demand assumption, blackouts may reappear when the load increases again in the morning. Further, it is possible that loads are shifted by blackouts, as consumers catch up on production, heating, etc., thus increasing demand above 'normal' levels after the blackout is lifted. Hence, through the constant-demand assumption, I may have slightly overestimated the vulnerability in the all-fail interruption cases (coercion and chokepoint vulnerability) in Desertec, although it is not possible to know how much. I have not overestimated the smaller interruptions, as these blackouts do not last long enough for night to come and reduce demand.

Gas peak demand, in contrast, is in Europe defined as 30 days of exceptionally high demand, with a probability of happening once in 20 years (Gas security Regulation 2010, Art. 8; ENTSO-G 2011b). This is thus much less frequent than peakload, but it lasts longer (up to a month, compared one hour). Furthermore, the peak/average swing is higher than for electricity: currently, the peak demand is 250% of average demand, whereas I estimated the GEA peak/average swing to be 170% (see Appendix, sections 13.2.1 and 13.3.1). Particularly important here, however, is the predictability of peak gas demand, which strongly depends on the time of year. A malevolent actor could thus plan her actions to coincide with a prolonged period of peak demand, which happens in cold winters, thereby maximising the European vulnerability and her own power (coercion) or impact (terrorists). Hence, a chokepoint failure or export cut during peak demand in GEA or Today could cause outages like those depicted in the graphs above: it is not an underestimation, as it describes the worst case, but also not an obvious overestimation of the potential impacts.

Third, the conclusion that within the overall low vulnerability, GEA is even less vulnerable than Desertec rests on the physical properties of gas and electricity systems. I did not test these properties in the sensitivity analysis, because they are extremely unlikely to change. Electricity systems must, also in the future, be exactly balanced at every instant, so that a disturbance exceeding the pre-defined buffers is likely to immediately cause the system to fail – a blackout. Gas, in contrast, is much less brittle: the pressure in the pipelines may vary without the system failing, and gas can be stored in large amounts and released when needed. Thus, gas system operators have some operation margin and, especially, they have time to activate emergency responses so that a disturbance can be counteracted without customers even noticing. This will not change over time: gas will be gas and electricity will be electricity, also in 2050, and each will be associated with its own set of vulnerabilities.

However, in particular one game-changer can be seen at the horizon: the successful development of economically feasible large-scale electricity storages would, possibly greatly, reduce the European vulnerability to both assessed threats in Desertec. I did not assess the possibility of electricity storage here, as such technologies are far from technical and economic maturity today. Nevertheless, electricity storage is a focus of current European energy research, especially as a means to facilitate grid integration of renewables, and a successful development of large-scale electricity storages by 2050 appears at least possible. Storages, especially rapid-response ones such as batteries, would increase the European short-term response capacity, potentially allowing it to buffer disturbances (both coercion and chokepoint failure) for a short period of time (at least minutes, probably more). During this time, back-up generation can go online and replace the storage-draw until the disturbance is over, thus preventing blackouts. The effect of storages would be much smaller for exporting countries contemplating to engage in coercive action: it would probably not be possible to rapidly store more than a few hours' worth of electricity, and there would be no one to sell it to after the interruption. Therefore, by far most of the renewable electricity production for exports would have to be stopped for the duration of an interruption, and the exporter costs would be roughly as described in section 8.2.1, even if large-scale electricity storages become available in the future.

In the coercion vulnerability assessment, another important difference between the scenarios is caused by the higher costs for supply outages in Desertec, originating in the much higher VOLL compared to gas. The higher electricity VOLL will likely remain much higher than the gas VOLL in future, for two reasons. First, whereas a blackout stops essentially all economic and much societal activity, large parts of society are not immediately affected by a gas outage. This is unlikely to change fundamentally: many vital systems like computers, the financial system and various information and communication technologies will not be directly fuelled by gas in the future, but by electricity. Second, gas operators have time to choose which sectors to disconnect first following an interruption, and can thus protect more sensitive or valuable customers. Electricity system operators cannot, as electricity disconnections are automatic and instant in order to protect the physical equipment. Hence, the costs for gas outages can, at least in part, be controlled and minimised, whereas blackouts strike an area and everything – including sensitive and expensive customers – within it. Also this system difference is very unlikely to change in the future.

In sum, as mentioned above, the data I used for the power balance and disruption assessment model is uncertain, but it is certain enough to support the conclusion that Europe is not particularly vulnerable to coercion or chokepoint failure in any of the scenarios or Today.

10.4 The dissonance between the diversity analysis and the vulnerability assessments

The diversity indices on the one hand and the power balance and disruption assessment analyses on the other show in part different results. Both approaches agree that the vulnerability in all scenarios is low, but although the Desertec scenario has much better diversity scores than GEA and Today, the power balance and disruption assessments clearly show that GEA and Today are less vulnerable than Desertec. This is surprising: the more diverse Desertec scenario should be expected to be less vulnerable than GEA and Today.

Uncertainties in the input data are not the reason for this discrepancy, as shown above. In addition, all assessment perspectives use the same data regarding chokepoint and supplier country structure. Instead, I find the reason in the epistemological and methodological differences between the approaches.

Diversity indices, as applied in the literature and as I have used here, assess the diversification of a system as a proxy for energy security, with respect to chokepoints or suppliers. As I have criticised above (see section 6.3), the diversity indices are highly generic and thus directly applicable to essentially every scenario, but at the price of de-contextualisation. Pure diversity indices includes only very limited knowledge about the functioning of threats (i.e. market concentration as the causal threat in coercion) and measure dependence on in general, aggregated terms (e.g. using yearly import dependence as input). In addition, they include the resilience of a system only in a very indirect way, as high diversity also means that a high share of the options is likely to remain functional after an event. Diversity indices do not include knowledge of how systems function, especially not the very important resilience aspect of system flexibility, such as buffers and other emergency response mechanisms.

Hence, the diversity analyses above show that Desertec is less exposed to export interruptions and chokepoint failures than GEA and Today, and indicate that it is more resilient as more supply options are likely to remain intact after an event. However, I do not need a diversity index or other data manipulation method to see that the scenarios have different threat exposures: the largest exporter in Desertec (Algeria) supplies 5% of the European electricity demand whereas the largest exporter in GEA (Russia) supplies 56% of the gas demand (33% via pipeline, 23% as LNG), and 50% of the imported gas in Today. Similarly, the largest chokepoint in Desertec is 3.8 GW whereas it is 130 GW (3116 GWh/d) in GEA and Today. Still, these very large differences in threat exposure make the conclusion that Desertec is more vulnerable than GEA and Today appear all the more surprising.

The reason for the diverging results lies in the difference between the de-contextualised nature of diversity indices and the contextualised metrics I have developed here. In this respect, there are three main differences between my metrics and the diversity indices.

First, systems are to varying degrees flexible and they react to disturbances in different ways, but this is ignored by diversity indices. Including flexibility as the key part of resilience in the assessment metrics, as I have done here, is especially important when comparing different types of systems, as these have different characteristics and thus different ways to respond to disturbances (e.g. gas can be stored but electricity cannot). As I have shown above, the diversity in GEA and Today is much lower than in Desertec, but as electricity systems must be exactly balanced at every instant, which is fundamentally different from gas systems, and as gas systems have much higher buffers, the vulnerability in Desertec is higher. Ignoring this, like the diversity indices do, is therefore a critical omission: if one wants to assess vulnerability, system functionality, flexibility and resilience are critical issues that must be explicitly included in the metric. My metrics do precisely this.

Second, my vulnerability assessment methods take the contextualisation further by looking at the temporal development of the systems' emergency responses *during the emergency event*. This is an innovation and an important conceptual contribution to the energy security assessment and metrics literature, which usually uses aggregated metrics (such as yearly import dependency, etc.) but does not look at dependence during the event in a dynamic and event-specific way. The general dependence in, say, the course of a year is not so important for understanding whether Europe is vulnerable to coercion, but the knowledge of whether an embargo is likely to cause high costs in Europe during the event is. The metrics I have developed do precisely this, and also describe whether the emergency responses of a system are sufficient to avoid outages or, if outages emerge, restore system functionality and minimise their size and duration. In the Desertec scenario, for example, outages emerge following most events, showing that there are vulnerabilities in this system, but as the outages can be rapidly removed, the vulnerabilities are small.

Third, my metrics contextualise the assessment further by including knowledge about why and how the events happen: if a threat is very unlikely, that particular vulnerability may be less serious. For example, it can be practically ruled out that one natural event disables chokepoints in Estonia, Belgium, Greece and Portugal at the same time, as no natural event is that large. Therefore, if a system can withstand all but such extreme and extremely improbable threats, as is the case in GEA, the chokepoint diversity is irrelevant – that system is not vulnerable to natural events.

Human-caused, malevolent events, in contrast, do not have a meaningful probability. In this, I add knowledge about the probability – in a qualitative manner – that a human threat materialises in a certain way by looking at what terrorists or coercing states are able to do, what they do and want to achieve. Again, to find out whether the specific event (coercion, attack) are useful and attractive tools for the perpetrator and a serious threat to the victim, it is important to look at the consequences and what happens *during the event* with disaggregated, context-specific metrics. I argue that if the direct impacts in Europe are small, if the costs to the terrorist or exporter herself are large, or if it is difficult to successfully carry out and coordinate the action, such action is unattractive to the perpetrator, and hence improbable (see also sections 10.5 and 10.6).

It is therefore not surprising that the diversity assessment produces results that differ from the other vulnerability metrics: whereas my new metrics measure vulnerability, including both threat exposure and all aspects of resilience in a disaggregated, contextualised and event-specific way, the diversity indices only measure threat exposure in an aggregated fashion and, indirectly, a part of the resilience. The fact that not all data is known with high certainty and that it is impossible to foresee and fully contextualise all ‘soft’ factors, like the conflicts between states in 2050, does not mean that diversity analysis is, in Stirling’s words, ‘all we can do’, nor does it devaluate a more contextualised assessment. We do not know everything, but we know much more than nothing, both regarding how systems function and about why and how energy security threats may materialise. There is thus good reason to expect that the model and the metrics I have developed here, which are conceptually validated by the theoretical and methodological deliberations in chapter 7 and empirically validated by the Balkan bottleneck case in the Today benchmark (section 8.2.3), describes actual vulnerabilities better than a diversity index. Going beyond diversity by adding knowledge about system functionality, resilience and flexibility as well as some considerations concerning attractiveness and probability of threats may not only be beneficial because it is more specific, it may also be necessary as a diversity index alone is not a suitable proxy for vulnerability.

10.5 Irrationality, indirect costs and usefulness of the ‘energy weapon’

In the power balance assessments, I consider the immediate costs for exporter and importer during a coercion event and use these as a measure for power of rationally acting states in an interdependent relationship. This is an innovation in the energy security assessment research. However, the methods I have developed here have some important limitations, as they do not consider irrational actions and indirect costs. Further, they do not answer the question of who will win the coercion event and whether the ‘energy weapon’ is at all a useful political tool for exporters. I discuss these issues and limitations below.

The present study is embedded in a rational choice setting: a rational exporter would only pursue coercive action if she can inflict serious damages on the importer without harming herself too much, and thus act from a power position. However, also irrational action – meaning that a state acts without having power over the opponent – or imperfectly informed export cuts may happen. From history, at least the Libyan-Swiss incident (2008) and the Iraqi 2001 oil embargo are examples of such irrational events. In both these cases, the governments probably knew, or should have known, that the impacts on the importers would be miniscule and their own costs would be high. It is possible that such export cuts happen in the future as well, but the effects of an irrational cut on Europe would be identical to or smaller than the already small or negligible impacts of the single-country interruptions shown above. A rational exporter is the worst possible case from a European perspective, so that I evaluate the threat from irrationally acting states implicitly in the power balance assessment. In the scenarios I have assessed here, therefore, Europe is not vulnerable to coercion from irrational or rational exporters.

The direct power balances are important, as the importer is unlikely to yield in an energy coercion standoff unless the exporter is able to inflict high and sustained costs on the importer by cutting exports. However, also indirect costs may play a role, in particular when looking at the attractiveness of such action for the exporter and at the likelihood of one side winning the conflict. These indirect costs are prominently reputational costs of the exporter: an export interruption is a strong display of a country's unreliability as a supplier. This could discourage other countries from buying energy from it, and it may trigger a shift in the importing countries' energy strategies away from the dependence on the unreliable partner.

An example can be seen in the 1973 oil crisis. Whereas the exporters were initially at least partially successful, as prices increased greatly and triggered a more Israel-critical rhetoric of some Western (Locklider 1988), from a Western perspective this event above all demonstrated the unreliability of the Arab oil exporters. These increased price and unreliability of the exporters caused the West (here: the IEA countries) to massively shift away from OPEC oil, for example by expanding nuclear power and exploring the North Sea for domestic oil. In the twelve years following the oil crisis, the IEA countries cut their oil imports from OPEC almost by half. This reduction, in turn, contributed to the oil price crash in the 1980s (López-Bassols 2007). Hence, the Arab OPEC countries were partially successful in achieving their short-term goals (in terms of a price increase), but the long-term effects appear highly detrimental.

Such reputational, indirect costs cannot be quantified *ex ante*, and only with great difficulty *ex post*. However, although maintaining a good reputation can be expected to be a motivation for complying with existing deals and treaties, it is not clear exactly how strong this motivation really is: history suggests that at least on occasion, reputational issues do not hinder states from breaking deals and treaties (Keohane 2005). For the purposes here, it is important to note that reputational costs in energy coercion events apply only to the exporter, and thus they reduce the incentives for exporters to engage in coercive behaviour. As I have not considered indirect costs here, I may have overestimated the importer vulnerability: although the European vulnerability, based only on direct costs, is low in all scenarios, the real-world vulnerability, accounting for expected long-term costs, may be even lower.

Another aspect of indirect costs not included in the assessment here is the exporters' expected benefits of engaging in coercive action. These benefits may play a role in the power balance, for two reasons. First, the benefits are what the exporter wants to achieve, and hence they are the reason for triggering the event. Second, the expected exporter benefits translate – with some proportionality factor – into expected costs for the importer, should she accept the exporter's demands. Hence, these expected costs are also the reason why the importer does not accept the exporter's demands. These costs and benefits are important when assessing who is likely to 'win' the standoff: high expected benefits may increase the exporter's stamina and willingness to accept short-term damages (which are the ones I assessed here). This would probably also equal high expected costs for the importer, similarly increasing her willingness to accept short-term damages.

If these costs/benefits are economic, they could in principle be included in the power balance calculations, but if they are of a political nature (like national or personal pride, revenge, etc.) their 'value' is qualitative and context-dependent so that the 'value' of the same demand may differ between the importer and exporter perspectives. As I, in the new assessment method, look at who depends on whom during the coercion event, I do account for differences in value of the embargoed good in the exporter (energy price, generating income) and importer (costs of potential outages) perspectives, but I do not account for the 'value' of the demands. Speculatively, it is possible that such 'qualitative' demands may increase an actor's willingness to accept damage, possibly even beyond what a rational assessment of the power balance would show is likely (see Keohane and Nye 2001; Wagner 1988). This could be an explanation of why the Libyan-Swiss oil dispute or the 2001 Iraqi embargo broke out: hurt personal pride and the desire to set an example and try to 'punish' their opponents (Switzerland, the world) may have overridden 'rational' knowledge of what would happen. It would therefore be interesting to, in further research, find ways to incorporate indirect costs and the impact of the reason of the event on the actors' willingness to accept damage and achieve more insights on the prospects of winning an energy coercion events. Nevertheless, the argument that an actor without short-term power, the issue I have assessed here, is very likely to fail her objective in a coercion event remains valid.

If an actor without short-term power is unlikely to be successful in a coercion standoff, one could then ask the reciprocal question: if she has power, is the 'energy weapon' a useful political tool? As I mentioned in section 7.1.1, the translation from bargaining power (the short-term power assessed here) to outcome power (the ability to push through one's demands) is often less than perfect. For example, Russia was successful in increasing the Ukrainian gas price following the 2009 gas dispute, although the underlying quarrel is still (December 2012) ongoing. The 1956 Suez oil crisis can probably also be seen as successful, as the US-supported Saudi Arabian oil embargo against the UK and France was a contributing factor to their military withdrawal from Egypt. In contrast, the countries causing the 1973 oil crisis succeeded in increasing the price, but the crisis had little or no effect on its immediate trigger, the US support for Israel in the Yom Kippur war. The Six-day war oil embargo in 1967 failed to achieve any of its targets as surge production of other producers covered the shortfall and no supply shortages arose (see also Table 10). History thus suggests that the energy weapon is a rather blunt political instrument that has been useful on some occasions, but the chances of success – i.e. that the exporter's political objectives are achieved – are highly uncertain, even if the exporter has power (see Smith Stegen 2011, also Larsson 2006). This is similar to the observations from the sanctions literature, showing that implemented sanctions have relatively low chances of success, at least compared to threatened but not imposed sanctions (Drezner 2001, 2003; Hovi *et al.* 2005, see below). The combination of these mixed experiences and the outlook of potentially large negative long-term effects of cutting exports (see above) add to the disincentives of exporters to engage in coercive action.

The usefulness of energy export interruptions in the particular scenarios analysed here is, as discussed above, very limited, because no supplier has power. However, in Desertec, the power balance assessment shows a high but short-lived cost spike during the first few hours after an interruption, also in the smaller cut cases. This spike rapidly sums up to 500 million € (base case, Moroccan or Algerian cut), or even 3 billion € (min.-case, Maghreb), but after that they only increase slowly. I do not interpret this as a serious vulnerability, but as one that is non-negligible as the absolute costs are very high. Two remarks can be made concerning this. First, such short blackouts are an unsuited tool for exporters to put European governments under pressure: before even a very fast European decision to accept the exporter's demands can be made, the blackout has probably already been remedied, rendering the decision unnecessary. Second, although an actual export cut is an ineffective political tool, the threat of an export cut may be better suited: the importer is aware of the extreme short-term costs, and may be willing to enter negotiations about minor exporter demands to avoid this initial shock. Both actors have an incentive to reach an agreement without supplies being cut, as both sides are likely to suffer losses – albeit perhaps asymmetrically distributed – during implemented sanctions (see section 7.1.1). This distinction between initial short-term and longer-term lasting costs is a reflection of Keohane and Nye's sensitivity and vulnerability level (see section 7.1.1): power can primarily be drawn from imbalances in vulnerability interdependence, but sensitivity interdependence can be a power resource if the sensitivity is very large.

Coercion threats may, if the power asymmetry is in favour of the exporter, materialise in the form of sudden, dramatic events, but also as low-intense 'bullying'. Such bullying may come in the shape of repeated small price increases or minor political demands, and constraints on both foreign and domestic policy (see also section 4.4.2). Such low-intense and unspectacular usage of asymmetrical interdependence can be observed in energy relationships around the world. For example, Belarus depends on Russian oil, gas and, in part, electricity. In recent years, and despite the close ties between the countries, this highly asymmetrical interdependence was repeatedly used by Russia – generally without actually cutting supplies to Belarus – to make Belarusian political decision more agreeable, in particular by increasing Russian control over the Belarusian energy sector (e.g. France24 2011; Gutterman 2011; Reuters 2011). In the scenarios I analysed here, however, Europe is not vulnerable to power by any single country, and is thus not vulnerable to bullying or to spectacular cuts. The exporters cannot credibly threaten to suddenly stop supplies and inflict damages on Europe, as these damages would be too short-term (Desertec) or miniscule (GEA). Furthermore, Europe in all scenarios and Today has the medium-term option to produce electricity domestically at only slightly higher costs (Desertec) and longer-term option to import gas or electricity from other suppliers (in all scenarios). Following any hostile action, Europe could thus simply phase out the bullying exporter, who therefore would have nothing to gain from such action, but much to lose.

10.6 Attractiveness and alternative objectives for terrorist target selection

The low-vulnerability conclusion concerning terrorist attacks rests on three pillars: small-number attacks will have no (GEA, Today) or small (Desertec) impacts; it is difficult to carry out the multi-target attacks needed to disrupt supply in Europe; and the impacts of even successful multi-target attacks are probably small. However, whereas it is indeed difficult to cause large and lasting outages, doing so may not be the terrorists' objective. Possibly, they may also find that a small outage is spectacular, or perhaps they do not target Europe, but the owner of the infrastructure or the exporting state. Further, whether an attack is 'successful' – and hence whether such action is attractive to attackers – may depend not only on how large its effects are, but also on how the targeted audience reacts. I discuss these points and their impact on the conclusions below.

Some historical cases of terrorist attacks have not caused any supply effects, but may qualify as spectacular anyways. The Al-Qaeda suicide attack on the oil tanker *Limburg* (e.g. BBC News 2002) is an example: this attack received massive media coverage, signalling to the public that terrorism is a grave threat to the oil supply, although the Limburg attack had no supply effects and the ship was not sunk. Small-number attacks on Desertec's HVDC lines would not cause spectacular blackouts, but they could – especially if they cause at least some blackouts and happen repeatedly – rouse great attention. Depending on the reaction in the public and in media, also events with small or even non-occurring blackouts, terrorist attacks could trigger a shift in European energy policy away from 'unstable' imports. If the terrorist group aims to deflect a particular development, such as increased electricity exports from MENA to Europe, such attacks could be attractive to terrorists, although the attacks do not cause serious blackouts. It would however not be an immediate energy security problem for Europe: as shown in section 4.4, energy security in the assessed context concerns the continuity of supply to European consumers (which are not, or only minimally, affected by small-number attacks) and the stability of prices (which are not greatly affected if the market functions well and prices remain cost-based).

Furthermore, if a terrorist group is capable of causing spectacular damages in Europe, one could then ask whether terrorism is a useful tool to achieve political concessions? The simple answer is, as indicated in section 7.2.1: probably not. If terrorists aim is to achieve political concessions from Europe – e.g. releasing prisoners, stopping its support for Israel, ending a war, etc. – their chances of success look very bleak, as Europe is unlikely to concede to such demands. Targeted countries usually infer the aims of terrorists, in particular when civilian targets are attacked, instead of sticking to what the terrorists actually demand. This inferred aim, commonly 'to destroy of our society' or a similar maximalist aim, is unacceptable to governments (Abrahms 2006). As modern societies depend on stable energy supplies, it appears likely that an attack debilitating the European electricity and/or gas system may be interpreted exactly that way – as an attack on 'our way of life' – so that conceding is virtually impossible.

Governments have strong incentives to remain unyielding and not negotiate with terrorists, both as a strict no-concessions strategy reduces the attractiveness of future terrorist acts and as civil society may not accept 'weakness' of the government. For example, there were large protests in Spain in 2005/2006 against the government's renewed negotiations with ETA, in particular in the light of the al Qaeda bombings in Madrid in 2004 (Alonso 2013). Furthermore, terrorist attacks are not necessarily bad for the public perception of the government, as long as it takes a stance against the attackers. For example, the public support for US President Bush reached an all-time high after September 11th – in late September 2001, 90% of US citizens approved of his work, which is the highest approval rating of any President since 1937[36] (Roper Center 2013). In a way, highly spectacular attacks may be counter-productive and prohibit the terrorists from achieving their demands: if the impacts of an attack are truly devastating, the target public may view a government negotiating with the attackers weak and ready to give up 'our way of life'. As I mentioned in section 7.2.1, less

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[36] Bush's approval rating dropped to 19% in 2008, which was the lowest rating of any President since 1937, in part because of the Iraq war and the war on terrorism (Pew 2013; Roper Center 2013).

than 10% of the world’s major terrorist groups have been successful in achieving significant political concessions (Abrahms 2006): this very meagre track-record should act to diminish the already low attractiveness of attacks against European energy infrastructure.

Still, terrorists may perceive a success perspective of 10% as better than peaceful protest or doing nothing. In addition, many terrorist groups overestimate their ability coerce a change in (Abrahms 2006), so that terrorists may decide to strike anyways, despite the probably unspectacular impacts and low chance of political success. In this dissertation, I have shown that if they do, the characteristics of the meshed and diversified systems – which have these characteristics for other reasons than protection against terrorism – make the electricity and gas systems highly resilient, so that terrorism is not a great vulnerability to European energy security.

It is furthermore conceivable that terrorists do not target European audiences, but rather the exporting states. Some countries in the scenarios rely on revenues from energy exports to Europe for a few percent of their GDP. This is for example the case for Iraq in GEA (up to 1.5% of GDP) or Jordan and Morocco in Desertec (up to 3.7% of GDP). These countries may suffer significant impacts of terrorist attacks, as they export their energy through one (Iraq), 3 (Jordan, plus 3 transit lines passing through) or 6 (Morocco) chokepoints. Even targeting only one or two of these could cause significant immediate costs for these countries (see ‘exporter costs’ in the figures in sections 8.2.1-8.2.3), making it a potentially attractive terrorist target and, indeed, an energy security issue for export revenue-dependent countries. As I elaborated above, such events could force Europe to source its energy from elsewhere, exacerbating these exporters’ vulnerability, but Europe itself would not be vulnerable.

For the owner of an infrastructure asset, the destruction of only one critical component may be devastating, and thus such attacks may be attractive for terrorists aiming to harm the owner. Some units – like compressor stations or transformers – are bulky, expensive and difficult to repair or replace quickly, meaning that the income from the infrastructure may be lost for a long time. It cannot be ruled out that such events could even cause operators to go bankrupt. Just like in the previous point, however, this is not an immediate European energy security problem, but a problem for infrastructure owners: all single attacks, and most low-number attacks, would go largely or completely unnoticed for consumers in all scenarios I assessed here.

11 Conclusions

In this dissertation, I have shown that energy security in the European policy context is a narrow and concrete concept, addressing the European vital electricity and gas systems, a small number of threats and aiming to avoid two concrete types of disruptions. By developing and applying new methods to assess the two shock-threats that can be meaningfully assessed in scenarios, I have shown that the vulnerability to coercion and critical infrastructure chokepoint failures in the Desertec Supergrid scenario is low, but it is even lower in the gas-import scenarios I assessed.

In addition to these findings, my work with this dissertation has also generated a number of methodological and epistemological insights of interest to both the Supergrid and the energy security research fields. In the following, I present detailed answers to the research questions, and some epistemological and methodological findings, also including limitations of the present work and outlooks for further research.

11.1 Part 1: energy security definition in the European perspective

Regarding the **empirical answers** to the first research question - What is energy security in a European perspective? – I have shown that energy security in a European policy context concerns the **national and European electricity and gas systems**. Sub-national electricity systems and global gas systems are minor foci. Other energy systems, such as the oil supply system, are not focal points of European energy security policy measures. The potential **disruptions** to avoid are end-use outages, such as blackouts, or unpredictable price volatility resulting from a small number of threats, which can be both shocks and stresses. These

threats are the shock-threats of coercion and power asymmetries in international energy trade, physical import interruptions (especially gas), and infrastructure failures, as well as the stress-treats of emerging capacity gaps (due to underinvestment, aging of components or nuclear phase-out), fossil fuel resource depletion and limited access to global energy resources. I could not identify other 'new dimensions' as suggested in the literature, in particular environmental (e.g. greenhouse gas emissions) and social (e.g. high, unaffordable prices) concerns, as an integral part of energy security in European policy. Such issues are related to energy security, as they affect the same vital energy systems, but they do not immediately threaten to disrupt a vital energy system. These 'new dimensions' are thus not energy security dimensions, but refer to other policy areas.

This European policy-perspective definition of energy security is narrower than some definitions found in the literature, and it is much more concrete. The reason for this is that my method of basing a contextualised definition on empirically observed energy security policy measures filters out threats of secondary importance and indirect threats, as actual policy measures only address immediate, concrete threats. I have here shown that the sets of energy security concerns in the three European cases are both narrow and similar, but with some case-specific distinct aspects, indicating that energy security is not a broad universal concept but a well-defined and context-dependent one.

Turning to the **methodological and epistemological aspects** of the first research question, I generated a number of important contributions and insights during the work with this thesis. The energy security definition approach I developed here is epistemologically and methodologically different from most approaches in the literature, as I induce the definition based on empirically observed policy concerns in specific context, instead of deducing it from abstract deliberations or expert interviews concerning what energy security could be in a general sense. This new approach has the benefit of focusing the definition on the core issues, while acknowledging the political and context-dependent nature of energy security. A generic, abstract deduction of the energy security concept, as found in the literature, produces a definition that may be valid for all contexts, but at the price of de-contextualisation and of being excessively broad. The methodology I developed here, in contrast, is based on an observed, and hence context-dependent and narrower, set of concerns specific to each case. My approach of asking three fundamental energy security questions has two main advantages compared to those in the literature. First, it has a built-in mechanism to separate core energy security concerns from secondary and indirect ones, as the core concerns are the most likely to be allocated scarce policy attention and resources. Second, it is a tool to structure the identified threats with respect to the vital energy systems they affect and the type of disruptions energy security policy aims to avoid. This methodology thus offers a way to explain why certain concerns are a part of energy security in a particular context whereas others are not, as a useful and necessary first step towards assessing it for that particular case.

Nevertheless, this method also has **limitations**. First, a definition method based on observed policy concerns runs the risk of missing issues that are in fact critical but are currently falsely ignored by policy, thus excluding important issues from a definition. The non-diversity of the policy measures identified in this dissertation can thus correctly reflect a very limited set of serious threats to European energy security. However, it can also be the result of a too narrow policy view in Europe, or by jurisdictions simply mimicking each other, without detailed considerations of the appropriateness of the adopted policies. In addition, serious problems may be ignored by policy, not because they are not important but because there is no good available solution, or because there are strong interests against a certain policy. My method cannot account for such effects. Further research is needed to explain the low diversity of policy measures and to find out whether such falsely ignored issues exist in a particular case, as the methods here cannot identify such problems. A possible way to identify whether policy falsely ignores important issues could be a combination of the bottom-up method developed here, defining energy security in a contextualised way based on observed policy concerns, and a top-down approach, deducing a definition based on general normative deliberations of what energy security should be. Any threats identified in the top-down but not in the bottom-up approach would then need to be further investigated to find the reason why it is ignored by policy – whether it is falsely or rightly ignored.

In addition, the method developed here presumes that energy security is a context-dependent concept. This implies that the results are not easily generalisable across countries or times, as highlighted by the absence of coercion concerns in the Swedish case above. Nevertheless, energy security policy is likely to follow a certain logic that does not change quickly, and some aspects of the contextualised definition may be generalisable across countries. Further research is needed to see which energy security components are in focus in most countries, and which ones are different, and whether they have changed over time. The methodology itself is certainly applicable to all contexts, so that it can be used for further case studies both of EU and non-EU countries, also including energy exporting countries, also in a historical setting. Doing this would be very interesting in order to see to which degree energy security is a generic and to which degree a context-dependent concept.

The results of the definition part has two **implications for the vulnerability assessment**. First, when European policy refers to energy security, it almost always refers to the supply and/or demand of electricity or gas. These vital energy systems have primarily European system boundaries, but also a national perspective is present, as is an international perspective if energy is imported. Second, the stress-threats which European energy security policy is concerned with cannot be meaningfully assessed in scenarios. These threats either make a scenario impossible to realise (e.g. depletion), are not possible to assess for the future (e.g. unreliability following aging infrastructure), or affect all scenarios in the same way by giving them insufficient capacities (e.g. underinvestment). Hence, in the scenarios here, I can only meaningfully assess the European vulnerability to the shock-treats of coercion and power asymmetries as well as infrastructure chokepoint failures.

11.2 Part 2: energy security assessments

In the second part of the dissertation, I developed and applied methods to assess the vulnerability of the European vital gas and electricity systems to the two shock-threats of coercion and critical infrastructure failure. I did this quantitative assessment for the Supergrid electricity imports of the Desertec scenario and for gas-import-dependent business-as-usual and decarbonisation scenarios from the Global energy assessment (GEA), while using the current gas import situation as a benchmark (Today).

Research question 2: How serious is the European vulnerability to energy coercion by the exporters in a Supergrid future compared to other scenarios?

I have shown that Europe is not vulnerable to coercion by its external energy suppliers in the Desertec Supergrid scenario and, even less, in GEA and Today. The power balance is not favourable to the exporters as their costs of coercing are high, whereas the European costs are low as the European supplier structures are highly diversified, especially in Desertec, and as the buffers and emergency response mechanisms are high, especially in GEA.

In all scenarios and Today, no single exporter or transit country is capable of causing large and lasting outages in Europe, so that they are not able to inflict sustained and high costs on Europe. This shows that no single country has power over Europe: the European vulnerability to single-country coercion is very low. However, whereas Desertec sees costly but short-lived blackouts following the single-country interruptions, single-country export cuts cause no mentionable outages in GEA and Today. Therefore, the vulnerability to coercion in Desertec is low, but it is higher than the almost completely invulnerable GEA scenarios and Today benchmark.

In addition, the exporter costs relative to GDP are generally higher than the European costs – in some cases even during the European outages – indicating that the exporters may have more to lose than the importer. The exporter costs, both absolute and relative to GDP, are always higher than the European costs after the outages have been removed, which – if outages appear at all – generally happens within a few hours. This casts serious doubt on the credibility of the threat of an export interruption and further reduces the already low European vulnerability. In all single country cases in all scenarios and Today, Europe can wait the exporter out, and the exporter does not have power.

In all assessed scenarios and in the present system, Europe is vulnerable to coercion only under two specific circumstances. First, some parts of Europe – especially the Balkan (GEA, and Today) and Poland (Desertec) – are currently separated from the rest of Europe through the presence of intra-European transmission bottlenecks. These bottlenecks effectively reduce the response capacity in these peripheral and highly import-dependent regions by prohibiting them to access the full European responses, thus leaving them only with their own limited emergency capacities in case the import lines ending there are interrupted. Import cuts to these regions could cause large outages that remain until the imports are resumed, resulting in high and lasting costs at a much higher level than experienced by the exporters. As long as such bottlenecks are present in the European system, parts of Europe may thus be vulnerable to coercion. As European energy security policy refers to prevent outages anywhere in Europe, these bottlenecks pose a vulnerability to the energy security of Europe. Removing these bottlenecks is, as I have shown previously in this dissertation, a priority of current European energy security policy, and this problem may – although it is serious today – be reduced or removed in the future.

Second, if all (or almost all) gas or electricity exporter countries join an export embargo against Europe during peak demand, they may cause very large and lasting outages and thus high and sustained costs in Europe, while the exporters themselves experience much lower costs. In this case, the exporters together may have power over Europe during peak demand, especially if the European buffers and responses are low. Due to the very high costs of blackouts compared to those of gas outages, the costs arising in Desertec are higher than those in GEA and Today, again reflecting a slightly higher vulnerability in Desertec. At off-peak times and with base case buffers or higher, also all countries together do not have power over Europe, as outages can be completely avoided (GEA, Today) or quickly removed (Desertec). During off-peak times, the European costs are thus low (or even zero), whereas the exporter costs are high and constant, at around one or a few percent of hourly GDP. With base case buffers and during almost all times of the year (i.e. outside the peak demand times) the exporters do not have power in any of the scenarios or Today, and hence Europe is not vulnerable to coercion.

Such multiple-country interruption events are rare, but they have happened in the past. History however also shows that the required coordination between numerous countries is very difficult. Free-riders are a problem in such constellations, but also conflicting objectives: it is highly improbable that all or almost all exporting countries will simultaneously see a legitimate reason to pursue aggressive action against Europe. Hence, the threat of a very large coercion event exists but it is very small, because it is highly unlikely to happen and to be successfully coordinated.

In conclusion, I have shown that Desertec has a low vulnerability to coercion, although this vulnerability is not zero as also single-country export cuts may cause short-lived blackouts and temporary but high costs. The electricity imports of Desertec are thus slightly more vulnerable to coercion than the almost invulnerable gas imports of GEA and Today, which experience non-negligible costs only following extreme export cuts. Overall, Europe is not vulnerable to coercion and exporter power originating in energy trade in any of the scenarios or in the present system. There are three main reasons for this:

- The economic impacts in Europe of all but the most extreme events are small and short-lived (if they happen at all) – the European vulnerability to coercion is thus low.
- The power balance is not favourable for the exporters, as their costs for cutting exports are higher than the European costs at all times without outages in Europe – the exporters thus have no sustained power over Europe.
- The type of event in which the exporters have power over Europe, when they all join in a total embargo, is very unlikely due to the low likelihood of a reason for a multi-country embargo and the difficulties to successfully coordinate such action.

Research question 3: How serious is the European vulnerability to critical infrastructure failures, caused by terrorists, natural events, or technical failures, in a Supergrid future compared to other scenarios?

I have shown that the vulnerability to critical infrastructure chokepoint failures is low in Desertec, GEA and Today, as all scenarios have a diversified chokepoint structure and large emergency response mechanisms; GEA and Today furthermore have very large buffers. No scenario is vulnerable to forceful attacks, technical failure or extreme natural events, as almost all chokepoint failure events cause no or only small and short outages. Only extreme disturbances can cause large outages: this would however require a very large number of simultaneously disabled chokepoints, which is very unlikely to happen.

Desertec has a low vulnerability to chokepoint failure, but it is more vulnerable than GEA and Today. In Desertec, already two simultaneous chokepoint failures could cause small and short-lived blackouts, lasting up to a few hours. In the gas systems of GEA and Today, in contrast, only extreme failure cases cause any outages at all: in the base cases, these systems can withstand 5 (Today) or 28 (GEA) simultaneously disabled chokepoints during peak demand without experiencing outages. During average demand, the Today and GEA systems can buffer even the failure of all chokepoints without suffering outages. Sustained and large outages are the potential impact only following a large number of chokepoint failures during peak demand in all scenarios and Today, and such massive failures are very unlikely. Hence, the vulnerability is low in all scenarios and Today.

Technical components generally break down independently of each other. Hence, a large number of simultaneous failures would be an extreme statistical deviation, and only a common failure source – for example a single computer system controlling many or all parts of the infrastructure system – could reasonably be the cause of this.

Natural events may cause multiple failures in chokepoints located close together, but it is unlikely that such events cause a very large share of chokepoints to fail. In Desertec, the chokepoints are spread along the southern and eastern Mediterranean coasts, several thousand kilometres apart, and in the GEA and Today, the chokepoints are spread along all European coasts and along its eastern and southern borders. Weather systems, earthquakes and other natural phenomena are not that large, so the probability of a natural event simultaneously disabling all or almost all chokepoints is virtually zero.

Deliberate attacks are a possible cause of such high-number failures, but also these are very unlikely, as critical infrastructure is an unattractive target for attackers. A small number of attacks are unattractive because the potential impact is small. A large number of simultaneous attacks are unattractive because they are very difficult to carry out and as the impacts even of successful attacks are uncertain and generally low. Even if such multiple attacks are successfully carried out, it is still unlikely that the impacts in Europe are spectacular, as attacks during average demand and/or if the response capacities are high cause no or only limited outages. Only spectacular outages hold potential to cause large economic damage and to create fear, which is necessary for terrorists to have at least a small chance to achieve their political targets. In comparison with other terrorist targets – especially human targets – the impacts and fear-creation of an attack against energy infrastructure are small, and energy targets are, in comparison, very expensive to the attacker. Thus, the European vulnerability to terrorist attacks is low.

In conclusion, the European vulnerability to critical infrastructure chokepoint failure is low in all scenarios and Today, but it is lowest in GEA. GEA and Today are practically invulnerable, especially during average demand, and only see outages during peak demand following extreme failures. The low vulnerability to critical infrastructure failure in all scenarios and Today has three main reasons:

- The outages following all but the most extreme failure events are likely to be small and short-lived (Desertec) or not happening at all (GEA, Today).
- Natural and technical extreme events causing a high number of simultaneous chokepoint failures are extremely unlikely, because of the nature of such events.
- Terrorist attacks causing a high number of chokepoint failures are very unlikely, as they are very difficult to carry out, as the impacts are uncertain and probably small, and the chances of political success are minimal: the infrastructure chokepoints are thus unattractive terrorist targets.

I also generated a number of **methodological and epistemological insights** during the work with the energy security assessments. The new approaches, drawing especially on critical infrastructure research, international relations theory and terrorism research, are a contribution to the methodological development of the energy security research field, in two main respects.

First, my methods focus on what happens *during an event*, including the full resilience of systems. By focusing on the impacts of coercion and critical infrastructure failure events, I can show not only whether a system is exposed to a threat, but also describe how much strain the system can withstand and the magnitude of any resulting outages. I describe the impacts by their size (e.g. natural events, terrorism) or by the costs to both exporter and importer (e.g. coercion), and the development of these impacts over time during the emergency event.

Second, the new methods can also indicate whether an event is attractive to perpetrators of such events. For coercion events, I focus on both importer and exporter while looking at who depends on who how much during the coercion event by showing the power balance and its development over time. If the exporter has power, she may be able to coerce the importer into accepting political or economic demands. For terrorist attacks against chokepoints, I focus on whether it is possible for terrorists to cause significant outages with a reasonable-scale effort, as the available tool for them to coerce the target audience into conceding to political demands. If it is very difficult to carry out such spectacular attacks, or if the chances of significant outages are low or uncertain, attacks against the energy system are unattractive to terrorists and, in turn, improbable. Such threats do not pose a great vulnerability to the importing region. Similarly, considering the chokepoint structure informs the vulnerability assessment concerning natural threats: if the chokepoints are numerous and far apart, the system relying on these chokepoints is unlikely to be vulnerable to a single extreme natural event.

The diversity index analyses and the results of the new methods I have developed here produce in part **dissonant results**, especially with respect to the ranking of scenarios. My new methods show that Desertec is weakly vulnerable to both coercion and critical infrastructure failure, whereas the other scenarios are almost completely invulnerable. This is surprising, as the diversity of Desertec is much higher than that of the other scenarios and Today. This dissonance is caused by a substantive difference between the methods. Diversity indices, one of the most used energy security assessment methods in the literature, do not adequately reflect the vulnerability of a system to a particular threat, as they ignore the context of the threat and is an aggregated measure of the threat exposure, only indirectly taking a part of the resilience of a system into account.

My new assessment methods, in contrast, focus on what happens during the event and assess all aspects of vulnerability: both the threat, including knowledge about why and how each specific threat unfolds, and the system resilience and flexibility to respond to an interruption. As noted by Bhattacharyya (2009; see section 6.1.1), an import-dependent system may be secure if it is highly diversified. However, as I have shown here, also a non-diversified, highly import-dependent system may be secure if the buffers or emergency responses are high. In addition, I further refine the assessment of human-caused threats, such as coercion and terrorist attacks, by including knowledge about the behaviour and objectives of the perpetrator: threats which are unattractive, because they are difficult to carry out or are unlikely to lead to the perpetrator achieving her political goals, are improbable to happen and thus pose a smaller vulnerability to the assessed system. The new metrics and the diversity indices thus assess different things, and only the new methods fully assess the vulnerability – including threat exposure and all aspects of resilience – of a system.

In this dissertation, I have demonstrated that it is possible and meaningful to contextualise an energy security assessment with detailed data concerning system buffers and responses, as well as including knowledge about how threats develop and what malevolent actors do and want to achieve. I have also shown that such contextualisation may be necessary, as a diversity index – a highly generic and de-contextualised energy security metric – does not assess all aspects of the vulnerability of a particular vital energy system so that diversity index results may even be misleading.

Despite the strengths of these contributions, the new methods also have some **limitations**, and raise some questions for **further research**.

First, the results show that Desertec is not vulnerable to coercion or chokepoint failure, but it is slightly more vulnerable than two pathways of the GEA and the current system. However, this does not necessarily mean that all Supergrid scenarios have low vulnerabilities – Desertec is not the only imaginable Supergrid scenario. Further, numerous other alternative, non-Supergrid futures are possible, and these may be more or less vulnerable than those I assessed here. Hence, in future research, it would be interesting to apply the methods developed here to assess more scenarios, both Supergrid scenarios and alternative ones.

Second, the power balance assessment in this dissertation shows who is likely to have power in a coercion event. This however does not show who will 'win' the stand-off: having power is a necessary, but not sufficient, condition to be successful in a coercion event. In future research, it would be interesting to take the power balance assessment further by including the indirect costs of coercion and a more detailed view on the trigger for the event – the demands the exporter wants to push through. The nature of the demand may influence the actors' willingness to accept damage, and hence affect the point at which the importer accepts or the exporter abandons her demand. Further research, including a detailed investigation of past, successful (for the exporter) coercion events, could thus build on the methods and results here and find ways to incorporate indirect costs and the willingness to accept damage in an assessment of vulnerability to coercion.

Related to this, a very interesting area of further research would be the application of the power balance method to historical coercion events (e.g. the Russian-Ukrainian/Belarusian gas crises, taking the Russian, Ukrainian and Belarusian perspectives). Doing this could further empirically validate the model I developed here.

Third, in the present dissertation, the coercing actors were 'the state', but in reality, state- or private-owned companies could be sender and/or target in a coercion event, and these may have different interests than the state. If the actor structure is different, the power balance may play out differently, as it is not made up by national income and national losses, but of lost profits and sunk costs of the companies on both sides of the conflict. An analysis of historical events, for example the Russian-Ukrainian gas crises, in which companies appear to have played important roles, would be interesting for this.

Fourth, terrorists do not necessarily aim to cause outages and damages in Europe, as I assumed here, but may for example aim to harm the exporting state or the exporting company. They may also aim to deflect a particular development, and pointed attacks at an early stage of the construction of new energy trade structures may be a way to achieve this. I did not investigate in detail how such alternative objectives would influence the attractiveness of energy system targets, but an analysis of the impacts and importance of alternative terrorist objectives could build on the methodological approach and the results developed in this dissertation and take it further.

Fifth, similarly to the coercion vulnerability analysis, I here assess only whether terrorists are likely to be able to cause large outages through reasonable-cost attack modes, but I did not assess whether they are likely to achieve their political aims. I argue that if terrorists cannot cause large outages, they are unlikely to cause fear and thus unlikely to achieve their aims, but – also as the results here show that large outages are improbable – I did not answer whether large outages could be a suitable terrorist tool. A historical study of terrorist attacks against the energy system would be highly interesting to find out more about terrorist energy targets and the usefulness of terrorist attacks.

My overarching research objective in this dissertation was to investigate how a Supergrid with significant renewable electricity imports from the Middle East and North Africa would affect European energy security. As I have shown above, the conclusion is that the European energy security would not be seriously threatened in a Supergrid future such as described in the Desertec scenario. The vulnerabilities associated with the Desertec Supergrid are low, as the impacts of almost all events are small and as the extreme events are very unlikely to materialise. These small vulnerabilities originate in the physical properties of electricity, especially the need for exact balancing of supply and demand at every instant, as highlighted by the even lower vulnerabilities identified for alternative gas import-dependent scenarios.

This conclusion indicates that the big challenge for realising a Supergrid vision like Desertec is to actually make it happen, to find ways for countries within and outside Europe to cooperate, to finance power stations in the deserts, and to find ways to enable long transmission lines crossing multiple borders. From a European energy security perspective, however, no serious vulnerabilities concerning coercion and critical infrastructure chokepoint failure stand in the way of the realisation of a Supergrid.

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13 Appendix: data for the vulnerability assessments

In the following sections, I describe the data needed for the vulnerability assessments. For Desertec and GEA, I always use data for the year 2050, whereas the Today benchmark refers to the situation in 2009-2012 (I always indicate the exact year).

13.1 Desertec

13.1.1 Demand

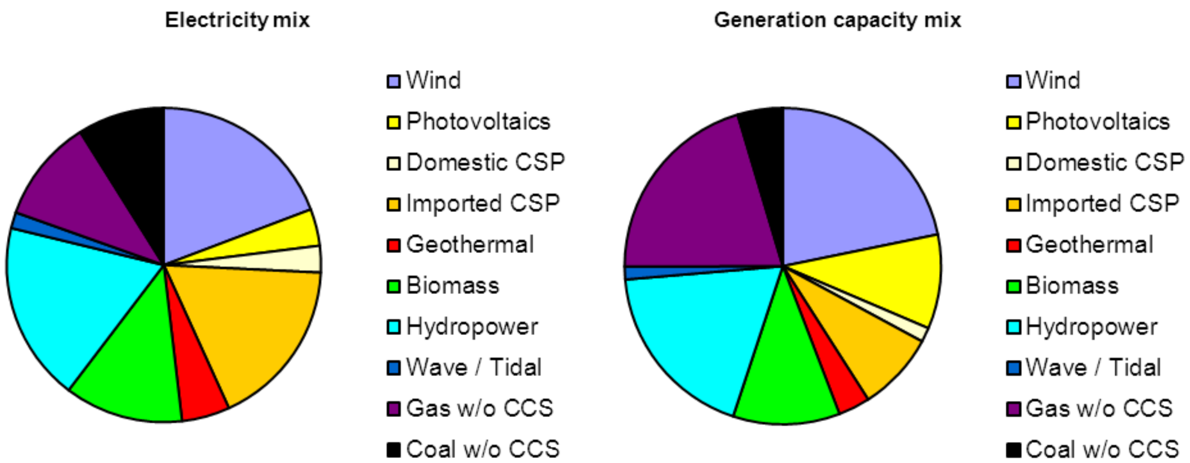
The Desertec scenario focuses on the electricity supply, and does not describe any other energy sector. The electricity demand in Desertec depends on three factors: socio-economic development, population growth and efficiency gains. The population figures are based on UN projections, whereas the socio-economic factors and the correlation between economic and electricity demand growth and efficiency increases are based on historical data.

In Europe, the demand-side development is much like a business-as-usual scenario: there are no paradigm shifts in on the demand side, such as introduction of electro-mobility or electric heating. The population in most European countries decreases, but the decrease is outweighed by an increase in especially Turkey, so that the total population is almost constant until 2050. The European GDP grows at 2%/a on average, with higher growth in the south-eastern parts than in the north-west. Thus, the European economy more than doubles in four decades (see also Table A 4, below), but increased end-use efficiency buffers the electricity demand increase: the demand increases only by about 20%, from 3390 TWh/a in 2000 to 4060 TWh/a in 2050. Hence, the average demand is 463 GW. The peak demand in 2050 increases to 605 GW, up from 521 GW in 2000 (DLR 2006).

13.1.2 Supply

Desertec foresees a radical change in the electricity supply structure, driven by sustainability criteria, in particular climate protection. The greenhouse gas emissions of the European electricity sector in 2050 are 76% lower than in 2000. This is comparable to the current, but still non-binding, European emission reduction targets for 2050, which are 80% for all greenhouse gases compared to 1990, but lower than the 93-99% electricity sector decarbonisation envisaged by the European Commission for 2050 (EC 2011d).

The electricity mix in 2050 consists of 80% renewables, which emit about 20% of the CO_2 from the electricity sector. Wind, hydro and biomass power are the main pillars of the domestic supply, and generate about 50% of the electricity. The total electricity demand is 4060 TWh/a and the installed capacity is 1285 GW. The characteristic element of Desertec – the imports of solar power from MENA – covers 17%, or 703 TWh/a, of the European demand in 2050, and amounts to 117 GW, see Figure A 1.



Sources: DLR (2006); Trieb *et al.* (2012).

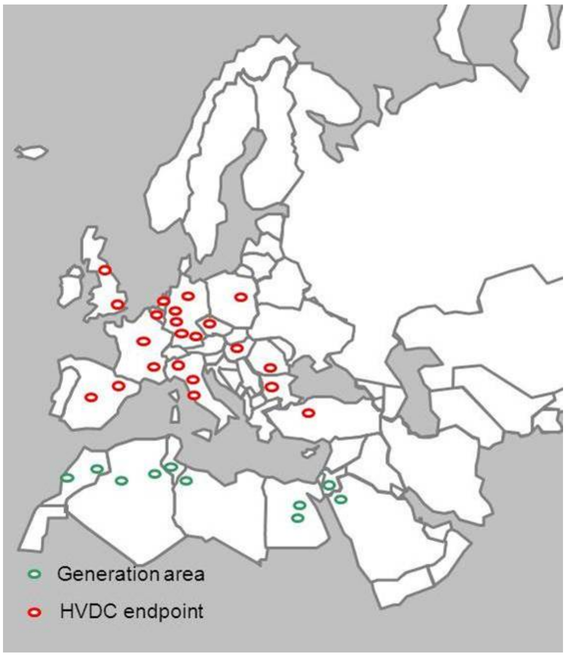
Figure A 1: Electricity mix (left) and generation capacity mix (right) in Desertec for the year 2050.

As wind and photovoltaic (PV) generation are intermittent and supply-controlled, they do not replace firm capacity but they lower the fuel consumption and the operation time of other power plants. The load factors in Desertec reveal that the demand-controlled wind and PV capacities are operated at, or near, maximum utilisation (with 32% and 14% load factors, respectively). Gas power, in contrast, has a load factor of only 19%, indicating that it is used primarily as peaking plants and as back-up capacity during low-sun or low-wind times.

13.1.3 Electricity import sources and infrastructure

Most of the electricity – 83% – in Desertec is generated domestically, whereas 17% are imported dispatchable CSP electricity from MENA (DLR 2006). These imports are handled by 33 single HVDC lines, originating in 10 generation areas in the 5 North African countries and one area in Jordan and Saudi Arabia, respectively (Trieb *et al.* 2012). The HVDC lines end near 22 different European load centres (see Figure A 2), where the imported electricity feeds into the European domestic HVAC system[37].

[37] The overall data for Desertec is described in DLR (2006), whereas the source countries and infrastructure used is specified in Trieb *et al.* (2012). There are small (~1% capacity and generation) deviations in the data between the two sources. Here, I use the general data from DLR (2006), but replace the CSP import data with the data from Trieb *et al.* (2012) to create an internally consistent scenario.



Source: based on Trieb *et al.* (2012).

Figure A 2: Generation areas and HVDC feed-in points to the HVAC system in Desertec.

The HVDC lines are of 4 GW each at the starting point, but as they are of different lengths and operate at different loads, their losses – and thus their net import capacity – are different (see Table A 1 and Table A 2). On average, the losses are 11% of the generated CSP electricity, ranging from 6% (Morocco-Spain, 960 km) to 17% (Egypt-Poland, 3800 km). I use this import infrastructure and import origin structure for the CI vulnerability and vulnerability to coercion assessments as the base case for Desertec. I test the impacts of different source country and infrastructure assumptions in the sensitivity analysis (see section 7.5).

Table A 1: Gross generation capacity and the arriving imports from each source country (and generation area) in Desertec. Rounded.

Source country (generation area)	Gross generation capacity (GW)	Generation load factor	Average losses	Arriving imports (TWh/a)
(Morocco 1)	16	65%	13%	79
(Morocco 2)	20	70%	10%	110
Morocco	36	67%	11%	189
(Algeria 1)	20	75%	11%	117
(Algeria 2)	16	70%	10%	88
Algeria	36	73%	10%	206
Tunisia	12	68%	9%	64
Libya	12	68%	10%	64
(Egypt 1)	4	64%	16%	19
(Egypt 2)	8	73%	15%	44
Egypt	12	70%	15%	63
Jordan	12	59%	13%	53
Saudi Arabia	12	71%	13%	64
Total	**132**	**69%**	**11%**	**703**

Source: Trieb *et al.* (2012).

Table A 2: The net capacity at the feed-in point in Europe and arriving CSP imports in Europe for the 33 import HVDC lines in Desertec. Rounded.

From	Transit	To	Length (km)	Net import capacity (GW)	Arriving imports (TWh/a)
Morocco 1	--	**Germany**, Karlsruhe	2917	3.44	23
Morocco 2	--	**Germany**, Jülich	2455	3.55	25
Tunisia	--	**Germany**, Mainz	2160	3.59	24
Algeria 1	--	**Germany**, Hannover	2851	3.46	24
Algeria 2	--	**Germany**, Munich	1998	3.62	25
Morocco 1	--	**France**, Paris	2306	3.55	19
Morocco 2	--	**France**, Paris	1939	3.61	20
Tunisia	--	**France**, Paris	2195	3.58	21
Algeria 1	--	**France**, Lyon	1847	3.63	25
Algeria 2	--	**France**, Lyon	2208	3.57	25
Morocco 1	--	**UK**, London	2643	3.50	19
Morocco 2	--	**UK**, London	2304	3.56	22
Algeria 1	--	**UK**, Newcastle	2748	3.48	24

From	Transit	To	Length (km)	Net import capacity (GW)	Arriving imports (TWh/a)
Morocco 2	--	**Spain**, Madrid	964	3.78	21
Algeria 1	--	**Spain**, Zaragoza	1178	3.75	24
Algeria 2	--	**Italy**, Milano	1587	3.69	20
Tunisia	--	**Italy**, Firenze	1432	3.72	19
Libya	--	**Italy**, Rome	1761	3.66	21
Egypt 1	--	**Poland**, Warsaw	3525	3.37	19
Jordan	Syria	**Poland**, Warsaw	3500	3.34	18
Egypt 2	--	**Poland**, Warsaw	3817	3.32	22
Saudi Arabia	Jordan, Syria	**Poland**, Warsaw	3586	3.32	24
Jordan	Syria	**Turkey**, Ankara	2255	3.55	19
Saudi Arabia	Jordan, Syria	**Turkey**, Ankara	2310	3.54	20
Saudi Arabia	Jordan, Syria	**Turkey**, Ankara	2310	3.54	21
Algeria 1	--	**Czech Republic**, Prague	2230	3.58	20
Libya	--	**Czech Republic**, Prague	2154	3.59	19
Morocco 1	--	**Belgium**, Brussels	2612	3.49	19
Morocco 2	--	**The Netherlands**, Apeldoorn	2462	3.52	22
Jordan	Syria	**Romania**, Bucharest	2502	3.51	16
Algeria 2	--	**Romania**, Bucharest	2918	3.46	19
Egypt 2	--	**Bulgaria**, Sofia	2849	3.49	22
Libya	--	**Hungary**, Budapest	2254	3.60	25
Total			**78,777**	**116.9**	**703**

Source: Trieb *et al.* (2012).

Of the 83% domestically generated electricity, 63% are European domestic renewables and 20% are generated by coal or gas power plants. Desertec foresees 31% import dependency for the electricity sector by 2050, of which 17% are imported CSP electricity (DLR 2006). Thus, 14% of the coal and gas power are generated with imported fuels and 6% are domestic primary fossil energy. The scenario does not describe how this amount is split between the two sources is unknown, as are the countries of origin and the import modes. Here, I assume that the gas and coal supply for electricity generation in Desertec are perfectly secure.

13.1.4 Electricity emergency response capacities

The electricity system has a range of pre-defined emergency response mechanisms, some of which start immediately and automatically and some measures that can be started manually with some lead-time. I describe and quantify these responses below; the response capacities, their timing and priority are summarised in Table A 3 at the end of this section.

The size of these measures and the way they are operated in the future cannot be known with precision, and I must assume or estimate them. The guiding principle for this is to keep them constant relative to peakload at today's levels and to let them operate within the same time intervals as existing emergency responses do. I test this principle in the sensitivity analysis (see section 7.5). In all cases, I choose a conservative – i.e. towards the less secure side of an uncertainty range – quantification in order to avoid an underestimation of the vulnerability. Furthermore, I assume that the no-cascading principle in place today, prescribing that blackouts cannot cascade out of the affected grid area, remains in the future as well (ENTSO-E 2009a, c).

For the vulnerability assessments, I assume that the n-1 principle remains the most important operation rule of European electricity grids in 2050, just as it is today. This principle means that the system must be able to absorb a failure, for whatever reason, of any given component without suffering system failure and blackouts (ENTSO-E 2009a, c). The size of the capacities controlling the n-1 principle thus determines the size of the immediate buffers. In Europe, this buffer is the primary control.

The primary control in the largest European system – the continental ENTSO-E grid – is currently 3 GW, or 0.7% of the current peakload. Keeping this share constant corresponds to a Desertec primary control capacity of 4.3 GW. No single unit can be larger than the primary control, and if larger units are to be integrated, the primary control must be increased to keep the system n-1 secure. The primary control starts automatically and reaches full capacity within 30 seconds. This capacity can be maintained for at least 15 minutes (Büchner *et al.* 2006; ENTSO-E 2009c; TenneT 2009; UCTE 2008a).

The main emergency response mechanisms, besides the primary control buffer, are the secondary and tertiary control capacities, which are present to counter disturbances of all causes. There are no numbers for the European secondary and tertiary control, as these are nationally determined. Here, I use the figures for the largest European control block, Germany. The German secondary control ranges around 4% of peakload, whereas the tertiary control is around 4.2% (Regelleistung.net 2012). For Desertec, this corresponds to 24.2 and 25.4 GW secondary and tertiary control, respectively. This is a very conservative estimate: a scenario with high shares of fluctuating renewables, such as Desertec, will likely have higher control capacities than today's more predictable system based on dispatchable sources (ECF 2010; Pierre *et al.* 2011), but it is not clear how much higher. Hence, I use the constant-to-peakload assumption here, and test this assumption in the sensitivity analysis (see section 7.5). The secondary control starts automatically with the aim to free primary control, which returns back to idle when secondary control comes online. The tertiary control starts manually to add capacity to the system or to free secondary control, which then returns to idle if possible. The secondary control starts automatically and reaches full capacity within 5 minutes, and parts of it can operate indefinitely (which then reduces the capacity available to counter further disturbances, should these occur). Here, I assume that half of the secondary control must return to idle after 30 minutes to maintain stability in the operating parts of the grid, whereas the other half is operated for as long as required. The tertiary control has to reach full capacity within 15 minutes, and can operate for as long as it is needed. I here assume that 2/3 of the tertiary control can be operated indefinitely, whereas the rest goes back to idle after 24 hours to maintain stability in the operating parts of the grid (Regelleistung.net 2012; ENTSO-E 2009b; Büchner *et al.* 2006; Swedish national grid 2010).

In addition, there is some unutilised, but active generation capacity. Whereas wind and PV are non-dispatchable, and hence not predictably available in emergencies, I assume that unutilised nuclear and fossil-fuelled power stations are fully dispatchable, as is 60% of the hydro power capacity. Of the 1285 GW capacity in Desertec, 775 GW are dispatchable. A part of the unutilised capacity is offline due to maintenance: I assume that each power station is down for maintenance one month per year. Subtracting this 1/12 share as unavailable leaves 710 GW dispatchable and available capacity in Europe, which can in principle be brought online at any given time. Subtracting the peakload (605 GW) and the capacities already reserved for control gives 51.7 GW (8.6% of peakload) of dispatchable available spare capacity present in Desertec[38] during peakload. During average load, the spare capacity increases by 141.5 GW (the difference between peak and average load) to 193.2 GW. Much of this spare capacity is present in power stations that are currently not generating electricity and thus need some time to start operating. I therefore assume that the spare capacities start operating after 12 hours, reaching full capacity only after 36 hours, and that they can be operated indefinitely. Also this

[38] To be compared with the 2008/2009 continental ENTSO-E buffer to peakload of at least 80 GW, corresponding to 13.4% of peakload; this buffer is expected to increase to 128 GW (15.7%) by 2015 (UCTE 2008b).

is highly conservative, as some unutilised power stations can, and may even be obliged to, react within one hour (Bundeskartellamt 2011).

Adding to these spare capacities are the inactive, or mothballed, capacities, which can be brought online with a longer lead-time. These capacities are considerable: the Platts database, for example, registers 22.8 GW of mothballed capacities in Europe, excluding Turkey (Platts 2008). However, the data concerning these capacities is very uncertain. Importantly, it is not clear how much of the mothballed capacities are present already in the capacity figures for Europe, nor is it known which share of the registered mothballed power stations are indeed capable of producing electricity – most mothballed power stations are 50-60 years old, but some are approaching 90 years of age and their reliability appears questionable. Therefore, and because such capacities are not mentioned in Desertec, I assume that the available mothballed capacity is zero.

In the cases when less than all exporting countries participate in a coercion event, or when less than all export infrastructures is disabled, it may be possible to increase imports from other sources or via alternative routes, up to 100% of the undisrupted import capacity. The size of this thus response depends on the interruption case (see section 7.5). From an operational standpoint, this possibility is essentially identical to accessing domestic unutilised capacity, and I assume that its operating time interval is the same as the domestic spare capacities, as are the costs (see section 13.1.5).

As a last measure, the demand can be reduced. This is done when strained situations can be anticipated a few hours in advance, and is triggered by price spikes, behavioural changes (e.g. media campaigns), and by rationing measures and interruptible contracts. Typically, these savings are limited to about 5% of demand for a few hours or days. In single cases, savings of up to 15-20% for a sustained period of time (weeks-months) have been recorded on a national scale, e.g. during the 2001 drought in Brazil and in Japan following the 2011 earthquake (Meier 2005; Pasquier 2011). Here, I conservatively assume that 5% of demand can be reduced on short notice, equal to 30.2 GW during peakload and 23.2 GW during average load. As parts of the demand-constraint potential is used as negative secondary/tertiary control (Swedish national grid 2010), I assume that the demand-constraint operates as tertiary control.

Re-igniting a system after a blackout is a non-trivial task, and one that takes time. How much time depends on where the blackout happened, what types of generation and loads are available in the area, and other case-specific factors. Thus, the re-ignition time cannot be known in advance. Historically, however, even the largest blackouts caused by errors in the transmission system could be remedied fast, generally within a few hours[39] (Eaton 2010; UCTE 2007). Here, I parameterise the difficulties to re-ignite the grid by letting the secondary and tertiary control linearly increase to their maximum capacity with an 8-hour delay; the secondary control fully replaces the primary control when this goes back to idle after 15 minutes. In addition, I assume that blackouts do not reappear once the entire system has been restarted (i.e. after the blackout size has reached zero). Equally, I assume that blackouts do not increase in size over time, but either remain constant or decrease after the initial blackout.

Bipolar HVDC systems – the by far most common HVDC configuration – show a high redundancy, for two reasons. First, if one pole fails, the second can carry more than half the load of the entire line in monopole mode, with the back current via the ground return path. Second, the maximum thermal load of an HVDC line is generally about twice the nominal allowed load, which allows for emergency re-routing of electricity if one line goes down and

[39] Very long blackouts are generally not very large (in terms of lost capacity), as long blackouts are almost always caused by failures in the medium- and low-voltage grids (CEER 2008).

another, more or less parallel, line is present (Rudervall *et al.* 2000; Siemens 2011; Czisch 2005; Trieb *et al.* 2009; DLR 2006). This redundancy is an important feature of an HVDC system, as it makes it more robust against technical failure, but is not compatible with the worst-case approach in this paper: as both poles are generally on the same pylon, both poles are likely to be disabled by a natural event or a terrorist attack. Further, it seems unlikely that two HVDC lines are built in parallel, so for consistency, I assume that no other line can immediately take the load of a failed HVDC link, which is a highly conservative assumption.

I summarise the size and operation intervals of the response mechanisms in Desertec in Table A 3. The priority refers to the order in which the responses start: priority 1 (primary control) starts first, if this is insufficient, priority 2 (secondary control) starts, and so on.

Table A 3: Summary of the European response capacities in Desertec.

	Capacity (GW) during peakload (average load, if different)	Operation time interval	Priority
Primary control	4.3	**0-15 min;** 100% reached after 30 sec.; after 15 min. back to idle	1
Secondary control	24.2	**1/2: 0-30 min;** 100% reached after 5 min.; after 30 min. back to idle **1/2: 0-∞;** 100% reached after 5 min.	2
Tertiary control	25.4	**1/3: 15 min.-24 h;** 100% reached immediately; after 24 h back to idle **2/3: 15 min.-24 h;** 100% reached immediately	3
Spare capacity	51.7 (av. load: 193.2)	**12 h-∞;** 100% reached after 36 h	4
Surge imports	0 (av. load: up to 100% of non-disrupted cap.)	As spare capacity	5
Demand-response	30.2 (av. load: 23.2)	As tertiary control	6

13.1.5 Costs

The costs arising for the exporter during a coercion event are proportional to the amount and the price of the non-delivered electricity. This price, just like all other prices, cannot be predicted well for the future, but costs can, with at least some precision. Therefore, based on the notion that prices are unbiased and cost-based (see sections 4.4.2 and 2.3), I here assume that the price for the lost electricity exports is the generation cost for the CSP electricity. In Desertec, this cost is 5 €c/kWh at the point of delivery, i.e. including the levelised generation costs (4 €c/kWh) and the levelised HVDC transmission costs (1 €c/kWh) crossing the Mediterranean (DLR 2006). These costs has also been confirmed by more recent research (e.g. Williges *et al.* 2010). I set the transit fee, when applicable, to 20% of the price, i.e. 1 €c/kWh.

The costs of back-up generation are higher than the costs of normal electricity. The costs of the control capacities primarily consist of a payment for available capacity, with only a minor part being paid on a kWh-basis. Thus, it is not possible to say what the control capacities cost per kWh, as this depends on how much it is used. As a general rule of thumb, however, control capacity adds on average 1-3 €c/kWh to fluctuating electricity (Wenzel 2007). This is also roughly the cost of new gas power (Garz *et al.* 2009), which makes 1-3 €c/kWh a reasonable estimate of both future control capacity and spare capacity costs: gas power is the most flexible electricity generation technology, and the one with the lowest capital costs, making it a likely technology for low-load factor operation (Bundeskartellamt 2011). Here, therefore, I assume that the control and spare capacities cost 6.5 €c/kWh, which is 2.5 €c/kWh higher than the generation costs of the import solar power and 1.5 €c/kWh higher than the total import cost.

In contrast, I assume that demand-response measures are free of cost, as these measures are usually 'paid for' by lower prices to interruptible customers during normal system operation. Electricity savings in households of the magnitude I consider here (≤5%) are also likely to happen be without cost – if anything, the households save costs. Nevertheless, due to the inconvenience, I assume that demand-response is only used as the last measure to avoid blackouts.

The costs of blackouts, or the value of lost load (VOLL), are difficult to quantify, as they depend on where and when a blackout happens, how long it lasts, etc. (de Nooij *et al.* 2009). For example, a blackout at night is less costly than during the day. The costs also vary across sectors, with the mining and energy sectors seeing a very low, or even negative, VOLL and the government seeing very high costs of up to 34 €/kWh. Although the VOLL is uncertain, it is always much higher than the value of the non-delivered electricity: average estimates generally range between 6-9 €/kWh, or about a factor 120-180 higher than average wholesale electricity prices (Bliem 2005; de Nooij *et al.* 2007; de Nooij *et al.* 2009; Zachariadis and Poullikkas 2012). It is impossible to know which sectors are most affected by a sudden blackout in the future and exactly at which time the blackout happens. I here assume that the blackout happens suddenly across an area proportional to the blackout size, affecting all customers equally. Hence, I use an average VOLL across all sectors, at a fixed 8 €/kWh not delivered.

In the power balance assessments, I present the costs for exporter and importer as absolute costs (€) and as share of GDP. For this, I extrapolate the GDP from 2010 to 2050, using an average growth rate of 4.5% (MENA) and 2% (Europe), see Table A 4. This data is roughly consistent with the macroeconomic data underlying Desertec (and it is roughly consistent with the GEA as well, see section 13.2.5), but it is not identical so that I use the same GDP data for all scenarios.

Table A 4: GDP (billion €) for all relevant countries and regions in Desertec.

	GDP 2010	GDP 2050
Europe	13.889	30.667
Balkan	499	1101
Iberian peninsula	1259	2779
Poland	361	797
Morocco	70	410
Algeria	122	710
Tunisia	34	198
Libya	55	322
Egypt	166	963
Jordan	21	123
Saudi Arabia	334	1945
Syria (transit country)	46	268
Total MENA exporters	803	4670

Source: based on UN (2011).

13.2 Global energy assessment

13.2.1 Demand

In the GEA_MESSAGE_Mix decarbonisation pathway, economic development, population growth and demand-side efficiency measures are the primary drivers of electricity and energy demand. The average economic growth in all GEA scenarios is around 2%/a up to 2050, with lower growth in the richest countries and higher in poorer ones. The European GDP more than doubles between today and 2050. In the MENA and the FSU, the GDP growth is even stronger, so that these regions narrow the economic gap to Europe, although without reaching the same per-capita income (see Table A 11, below). The population growth follows the UN's projection, and increases to 9 billion globally around 2050. Overall, the basic socio-economic assumptions are therefore conceptually very similar to the same demand-drivers in Desertec. Nonetheless, the demand differs strongly.

The GEA electricity demand more than doubles, from 3100 TWh/a today to 7520 TWh/a in 2050. The share of electricity in the final energy demand increases from 19% today to 43% in 2050. This is driven by a doubling of electricity demand in industry (+1500 TWh/a) and transport (+1200 TWh/a), whereas the residential/commercial demand increases by only 694 TWh/a, or 40%. This is a difference between GEA and Desertec: whereas the GEA industry demand keeps pace with economic growth (both roughly doubling by 2050) and a noticeable-scale expansion of electro-mobility takes place, Desertec does not foresee electrification of transport or increased demand in industry.

The European gas consumption increases by 60% (3400 TWh/a[40]) from today and reaches 9000 TWh/a by 2050 (which equals an average consumption of 24,675 GWh/d). This increase is driven in particular by a strong increase gas power generation, from 740 TWh/a to 2558 TWh/a. Assuming a constant efficiency of 50%, the European gas power plant fleet consumption is 5100 TWh/a, or almost 60% of the total gas consumption; this is more than the entire EU27 gas consumption in 2009 (Eurostat 2011).

The data produced by GEA are only yearly numbers, which means that there are no figures for peak demand or the variability of demand throughout the year. The variability in gas demand is considerable: currently, the average EU27 demand is 15,250 GWh/d, and the peak demand (1-in-20 weather conditions) is 35,500 GWh/d – about 250% of average demand –

[40] I have used the conversion factor 1 bcm=11.1 TWh for all unit conversions.

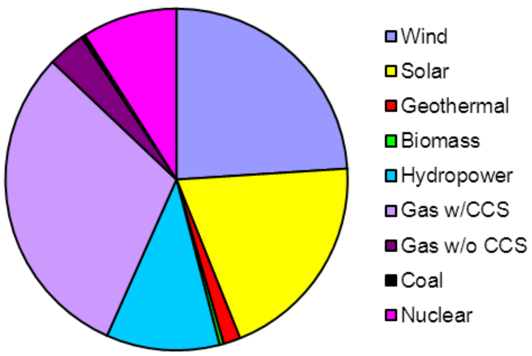
caused mainly by extreme heat demand during cold phases (ENTSO-G 2011b; Eurostat 2011, 2012). In the GEA, the gas demand in the residential/commercial sector – most of which is heating – is reduced by 85% compared to today, whereas the electricity sector demand increases strongly. This would indicate that the summer-winter swing will be much lower in 2050 than today. This is supported by the European network of transmission system operators for gas (ENTSO-G) forecasts as well: the projections for the medium-term gas system expansion build on the expectation that peak demand grows by 8%/a whereas the average demand grows by 11%/a (ENTSO-G 2011b). Extrapolating these numbers to 2050 makes no sense, as the average demand will then be higher than peak demand. Instead, I assume – analogue to the explanation of today's summer/winter demand swing (see section 13.3.1) – that the final gas demand in the heating sector (buildings/commercial) increases five-fold during peak times compared to average[41], and that the peakload gas power generation is twice the average. This gives a peak gas demand of 42,456 GWh/d, compared to the 24,675 GWh/d average demand. With these assumptions, the peak demand is 172% of the average, which is a conservative – probably too high – estimate of the 2050 peak gas demand in GEA.

13.2.2 Supply

The GEA foresees a radical change of both the electricity sector and the primary energy supply. The electricity sector is almost fully decarbonised by 2050, driven by a strong shift to

[41] The monthly final gas consumption fluctuates from >80% of yearly average in summer to <140% in winter (Eurostat 2012, monthly gas demand table). Assuming that the transport and industrial sectors have constant demand (and thus that the buildings sector (27% of final gas demand) is responsible for the entire demand increase in winter), the building gas demand increases by up to a factor 5 in winter compared to average demand.

gas power with CCS and renewables. Fluctuating renewables (wind 24%, solar[42] 20%) and gas (34%, of which 31% with CCS) dominate the electricity supply, see Figure A 3. This means that the GEA electricity supply is almost entirely carbon-neutral in 2050. The total electricity consumption is 7520 TWh/a, but GEA does not publish electricity generation capacity data; assuming that the operation mode of gas power is similar to Desertec (primarily to cover peakload and back-up at low wind/solar generation times), applying the same load factor (19%) would imply that GEA has about 1540 GW gas power capacity installed.



Source: Johansson *et al.* (2012).

Figure A 3: Electricity mix in GEA for the year 2050.

All of the renewable electricity is generated domestically, but only 16% – 1422 TWh/a – of the total gas demand are produced in Europe, whereas 84% (7585 TWh/a) are imported (see section 13.2.3). I assume that the domestic production capacity (3895 GWh/d) remains fully utilised (today, the average yearly utilisation is 96%, see BP 2011; ENTSO-G 2011b; Eurostat

[42] GEA does not explicitly state which type of solar power it considers, but PV is the most common solar generation technology, and the one that is best suited for large-scale generation in Europe. Here, I assume that all solar power in GEA is PV.

2011). This means that Europe cannot increase the domestic production in case of disturbances.

13.2.3 Gas import sources and infrastructure

GEA, just like the overwhelming majority of scenarios, does not describe the exact routes and modes of energy imports. However, it does describe the origin of energy imports, which is allocated among 11 world regions. This means that the sources are broadly known, and combined with knowledge about the locations of energy resources, I can break this regional allocation down to country level with some precision. I therefore cannot take the specifications of import sources at a country-level, import routes and modes directly from GEA, but I base the data sets for the assessment on the data produced by GEA.

In GEA, the gas trade is strongly dominated by Europe as importer (Europe imports 77% of all traded gas), and by MENA and FSU as exporters (90% of all exported gas). Given their geographic proximity, I here assume that all European gas imports originate in these two regions.

The precise structure of the gas import system in 2050 cannot be known, but one can know that it will consist of some combination of pipelines and LNG. Given the long lead times and the bulky investments, which lead to a very strong path dependency, a good first estimate is that the gas supply system of the future is already being defined today (SRU 2011). I therefore assume that the gas in GEA is imported through the import infrastructure already in place, in construction or in planning[43]. I test this assumption in the sensitivity analysis, see section 7.5.

It can be expected that the gas is first of all imported through pipelines, as these are cheaper than LNG over medium distances (a few thousand kilometres). Pipelines are however very bulky investments and require high utilisation to be profitable. The existing and planned import pipelines, which form part of the base case for the GEA, are shown in Table A 5.

Here, I assume an 80% yearly average utilisation of the pipelines – which is very high compared to the 51% pipeline utilisation today (BP 2011; ENTSO-G 2011a), but nonetheless reasonable, given the bulkiness of pipeline investments. Therefore, the pipeline gas imports from FSU are 3163 TWh/a and from MENA 1077 TWh/a. The remainder – 3345 TWh/a – is imported as LNG (see below).

[43] This requires choices to be made: very many pipelines are proposed, but only few are built. Here, I list only pipelines that are currently seen as realistic, in this or a similar shape, in the ongoing European debate. This leads to a conservative estimate of future pipeline capacities. Hence, some proposed projects, such as the Trans-Caspian, Trans-Anatolian and Persian pipelines (all of which could eventually feed into Nabucco, or be competitors of Nabucco, or of each other), White Stream and the Azerbaijan-Georgia-Romania interconnector, are not listed as planned. Here, I assume that Nabucco is fed with Iraqi gas; this is a speculative assumption, but for the assessments here, it is of little relevance whether it is Iraqi, Turkmen, or Kazakh (as there are no other gas imports from these countries), whereas the power balance would tilt slightly in favour of the exporters if the gas was sourced in Iran, Azerbaijan or Russia.

Table A 5: Existing and planned (italic) import gas pipelines or pipeline entry points. Rounded.

Origin	Transit	Entry	Pipeline/entry point	Capacity (GWh/d)
Algeria	Morocco	**Spain**	Maghreb-Europe	355
Algeria	--	**Spain**	Medgaz	260
Algeria	Tunisia	**Italy**	Transmed	1088
Libya	--	**Italy**	Greenstream	376
Russia	--	**Finland**	Imatra	225
Russia	--	**Latvia/Estonia**	Korneti/Irboska	166
Russia	Belarus	**Latvia**	Kotlovka	281
Russia	Belarus	**Poland**	Tietierowka	7
Russia	Belarus	**Poland**	Kondratki	1026
Russia	Belarus	**Poland**	Wysokoje	167
Russia	Ukraine	**Poland**	Drozdowicze	173
Russia	Ukraine	**Slovakia**	Velké Kapušany	3116
Russia	Ukraine	**Hungary**	Beregdaróc	750
Russia	Ukraine	**Romania**	Mediesu Aurit	117
Russia	Ukraine	**Romania**	Isaccea	250
Russia	--	**Turkey**	Bluestream	495
Azerbaijan	Georgia	**Turkey**	South Caucasus	619
Iran	--	**Turkey**	Tabriz-Ankara	433
Russia	--	**Germany**	Nordstream	1673
Algeria	--	***Italy***	*Galsi*	*241*
Iraq	--	***Turkey***	*Nabucco*	*936*
Russia	--	***Bulgaria***	*South Stream*	*1768*
Total				**14,520**

Sources: ENTSO-G (2011a, b), pipeline websites.

In the long run, some countries may start running out of recoverable gas resources, reducing the importance of factors like political relations: only countries with sufficient gas resources can export gas. For LNG, the transport of which is not distance-dependent, I expect and assume that resource endowment is the most important parameter determining the origin of the European long-term future gas supply. The proven reserves of MENA and the FSU are shown in Table A 6. For the export source country allocation, I exclude all countries with less than 3% of the regional reserves, unless it exports gas to Europe today (see BP 2011).

Table A 6: Proven natural gas reserves (rounded) for the Former Soviet Union (FSU) and Middle East/North Africa (MENA) regions. Rounded.

FSU	Reserves (TWh)	% of FSU reserves	MENA	Reserves (TWh)	% of MENA reserves
Azerbaijan	14,356	2.1%	**Algeria**	50,895	5.4%
Kazakhstan	20,855	3.1%	**Egypt**	24,973	2.6%
Russia	505,815	76.3%	**Libya**	17,504	1.8%
Turkmenistan	90,741	13.7%	**Bahrain**	2474	0.3%
Ukraine	10,566	1.6%	**Iran**	334,593	35.2%
Uzbekistan	17,624	2.7%	**Iraq**	35,795	3.8%
Other Eurasia	3203	0.5%	**Kuwait**	20,159	2.1%
			Oman	7797	0.8%
			Qatar	286,134	30.1%
			Saudi Arabia	90,573	9.5%
			Syria	2912	0.3%
			United Arab Emirates	68,145	7.2%
			Yemen	5520	0.6%
			Other Middle East	2470	0.3%
Total FSU	**663,158**		**Total MENA**	**949,945**	

Source: BP (2011).

I allocated the gas to the single export countries proportional to their share of the reserves in each region. In a first step, I assign the gas to each country's pipelines, with an 80% utilisation (as described above, Table A 5). In the second step, I allocate the remaining export gas to the exporting countries proportional to their share of proven reserves in each region, unless the pipeline exports already exceed a country's proportional share. This gas is delivered to Europe by LNG. I assume that the landlocked exporters Kazakhstan and Turkmenistan transit their gas to liquefaction terminals in friendly neighbouring countries at no risk. This gives the final allocation of gas export source countries in GEA, see Table A 7 and Figure A 4 (below). I test this country and import mode structure in the sensitivity analysis, see section 7.5.

Table A 7: Allocation of average gas imports and modes to Europe from the single FSU and MENA export countries.

	Imports (GWh/d)	Pipeline imports (GWh/d)	% of pipeline gas transited	LNG imports (GWh/d)
Azerbaijan	495	495	100% (Georgia)	0
Kazakhstan	234	0	--	234
Russia	13,858	8171	43% (Ukraine), 15% (Belarus)	5686
Turkmenistan	1020	0	--	1020
Algeria	1555	1555	18% (Morocco), 56% (Tunisia)	0
Libya	301	301	--	0
Egypt	68	0	--	68
Iran	1264	346	--	918
Iraq	749	749	--	0
Qatar	785	0	--	785
Saudi Arabia	248	0	--	248
United Arab Emirates	188	0	--	188
Yemen	16	0	--	16
Total	**20,780**	**11,618**		**9162**

Analogue to the pipeline structure assumption (see above), I assume that the LNG import structure in 2050 consists of currently existing and planned LNG terminals, see Table A 8. The resulting average utilisation of LNG terminals is 65%, compared to 47% today, see section 13.3.3.

Table A 8: Existing and in construction/planned (italic) LNG gasification terminals in Europe. Rounded.

Country	Terminal	Capacity (GWh/d)	Country	Terminal	Capacity (GWh/d)
Albania	Fiere	250	***Lithuania***	*Klaipeda*	*94*
Belgium	Zeebrugge I	475	***Poland***	*Swinoujscie*	*156*
Belgium	*Zeebrugge (exp.)*	*375*	***Poland***	*Swinoujscie (exp.)*	*234*
Croatia	*Adria LNG*	*468*	***Portugal***	*Sines*	*247*
Croatia	*Krk island*	*187*	***Romania***	*Constanta*	*94*
Cyprus	*Vassilikos*	*53*	**Spain**	Barcelona	533
Estonia	*Paldiski*	*94*	**Spain**	Huelva	410
France	Montoir	515	**Spain**	Cartagena	451
France	Fos Tonkin	219	***Spain***	*El Musel*	*219*
France	Fos Cavaou	515	**Spain**	Bilbao	328
France	Dunkerque	406	**Spain**	Sagunto	328
France	Fos-sur-Mer	250	***Spain***	*Tenerife*	*41*
Germany	*Wilhelmshafen*	*337*	***Spain***	*Gran Canaria*	*41*
Germany	*Wilhelmshafen*	*162*	***Spain***	Mugardos	228
Germany	*Rostock*	*156*	***Spain***	*Bilbao (exp.)*	*383*
Greece	Revithoussa	228	***Spain***	*Sagunto (exp.)*	*438*
Greece	*Palei Galini*	*69*	***Spain***	*El Musel (exp.)*	*328*
Ireland	*Shannon*	*337*	***Spain***	*Huelva (exp.)*	*492*
Italy	Panigaglia	250	***Sweden***	*Nynäshamn*	*n.k.*
Italy	P. Levante/Adriatic	236	***Sweden***	Oxelösund	n.k.
Italy	*Brindisi*	*250*	**Netherlands**	Gate	375
Italy	*Toscana Offshore*	*117*	***Netherlands***	*Gate (exp.)*	*500*
Italy	*Taranto*	*250*	**Turkey**	Marmara Ereglisi	194
Italy	*Porto Recanati*	*156*	**Turkey**	Aliaga	187
Italy	*Gioia Tauro*	*375*	**UK**	Isle of Grain	609
Italy	*Rada di Augusta*	*250*	**UK**	South Hook LNG	656
Italy	*Porto Empedocle*	*250*	**UK**	Teesside	128
Italy	*Rosignano*	*250*	**UK**	Dragon LNG	187
Italy	*Falconara*	*125*	***UK***	*Anglesey*	*406*
Italy	*Montefalcone*	*250*	***UK***	*Port Meridiam*	*250*
Italy	*Zaule*	*250*	***UK***	*Canvey Island*	*169*
Latvia	*Riga/Ventspils*	*156*			
			Total LNG capacity		**16,969**

Source: GIE (2011a, b)

Together, the pipeline and LNG import assumptions lead to the final gas import system in the GEA base case, see Figure A 4 and Figure A 5.

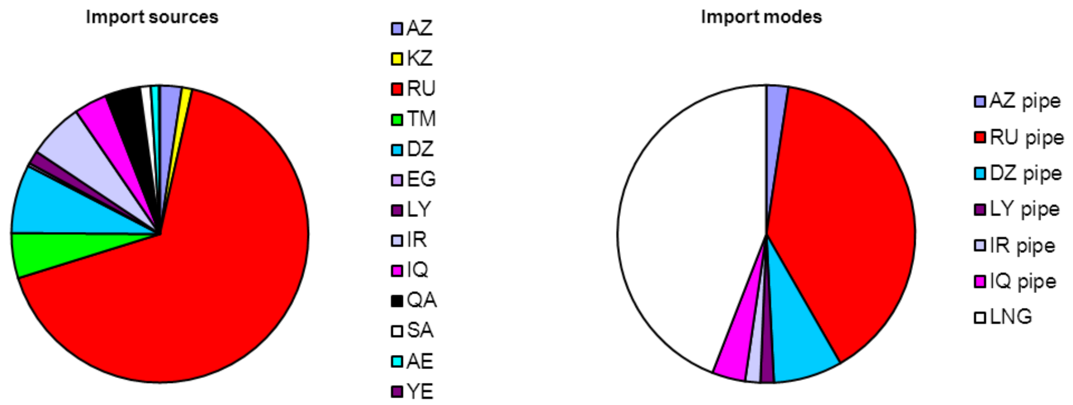
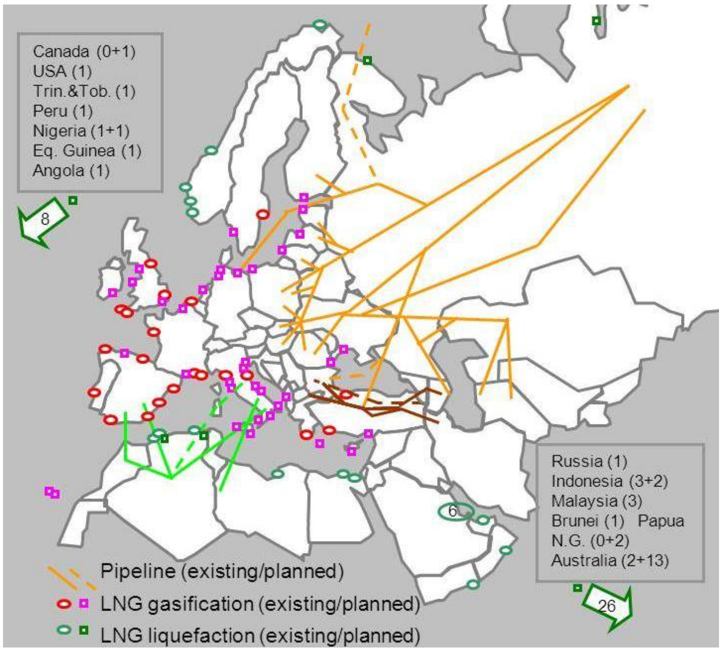


Figure A 4: Import sources and import modes for natural gas in GEA.

The European gas imports are 7580 TWh/a, of which 3450 TWh/a via pipelines. Country abbreviations: AZ=Azerbaijan; KZ=Kazakhstan; RU=Russia; TM=Turkmenistan; DZ=Algeria; EG=Egypt; LY= Libya; IR=Iran; IQ=Iraq; QA=Qatar; SA=Saudi Arabia; AE=United Arab Emirates; YE=Yemen.



Sources: based on ENTSO-G (2011a, b); GIE (2011a, b); Global LNG (2012).
Figure A 5: Existing and planned (as of autumn 2011) gas import pipelines and LNG gasification terminals in Europe, and existing and planned LNG liquefaction terminals in the world.

The final part of the gas import system is a large number of storages distributed across Europe (see Table A 9). These are mainly used to cover the peak demand in winter, but can also be used to bridge periods of import interruptions or chokepoint failures. The combined European gas storage capacity is large: the existing storages have a capacity of 1019 TWh, with another 720 TWh in planning. These storages have a cumulated maximum withdrawal capacity of 20,320 GWh/d (see Table A 14), and the planned (in autumn 2011) storages would add another 7024 GWh/d (GIE 2011c).

Table A 9: Existing and in construction/planned (autumn 2011) gas storages in Europe. Rounded.

	Number of storages	Capacity (TWh)	Max. withdraw. capacity (GWh/d)		Number of storages	Capacity (TWh)	Max. withdraw. capacity (GWh/d)
Albania	n.k	n.k	n.k	**Lithuania**	2	6	83
Austria	13	112	1425	**Luxemburg**	0	0	0
Bosnia	n.k	n.k	n.k	**Netherlands**	6	104	3024
Belgium	2	8	186	**Norway**	0	0	0
Bulgaria	1	5	37	**Montenegro**	0	0	0
Croatia	1	0	0	**Macedonia**	n.k.	n.k.	n.k.
Cyprus	n.k.	n.k.	n.k.	**Poland**	14	39	700
Czech Rep.	9	40	616	**Portugal**	4	3	78
Denmark	2	11	198	**Romania**	11	54	92
Estonia	0	0	0	**Serbia**	1	5	56
Finland	0	0	0	**Slovenia**	0	0	0
France	23	165	3667	**Slovak Rep.**	3	34	448
Germany	71	342	6455	**Sweden**	1	n.k.	7
Greece	0	0	0	**Spain**	25	112	3627
Hungary	5	68	877	**Switzerland**	0	0	0
Ireland	1	2	28	**Turkey**	5	n.k.	n.k.
Italy	29	309	3494	**UK**	32	283	1695
Latvia	2	37	553				
				Total	**279**	**1739**	**27,344**

Source: GIE (2011c).

In sum, the existing and planned storage withdrawal capacity (27,344 GWh/d) exceeds the total average imports foreseen by GEA for 2050. This is the case already today, see section 13.3.3, and thus appears to be a reasonable estimate. The average demand (24,675 GWh/d) is well below the import capacity (31,489 GWh/d) plus domestic production capacity (3895 GWh/d), but the peak demand of 42,456 GWh/d is higher than the supply capacities. To satisfy peak demand, storage draw is needed – just as it is today – and this is a primary reason for the construction of such significant storage capacities. The storage structure is tested in the sensitivity analysis (see section 7.5).

13.2.4 Gas emergency response mechanisms

The gas system has a range of pre-defined emergency response mechanisms that start immediately and automatically, and some measures that can be started manually. An overarching principle in the European gas transmission system is the n-1 principle, meaning that the system must be able to absorb the failure of any one unit without suffering final customer outages (Gas security Regulation 2010). I describe and quantify these responses below; the response capacities, their timing and priority are summarised in Table A 10 at the end of this section.

The buffers in the gas system are the storages. The storage capacities, which are used also for normal operations during peak times, are described above for GEA (section 13.2.3) and below for the Today benchmark (section 13.3.3). These are distributed across Europe, usually close to domestic transmission pipelines and/or close to demand-centres (ENTSO-G 2011a; GIE 2011c). Hence, I assume that the storages have no response time: emergency storage-draw, if available, starts immediately when the pressure starts dropping in the import pipelines.

Less immediate supply-side measures are surge production and surge gas from alternative import sources (Zeniewski and Bolado-Levin 2012). The domestic production is almost fully utilised and I do not consider domestic surge production here (see section 13.2.2). Instead, if there is capacity available in the non-disturbed import pipelines, the pipeline gas imports can be increased up to 100% (the precise size thus depends on the case, see section 7.5). The pipeline gas from Russia, assuming a gas speed of 30 km/h (Valentine 2005) and an average length of 2500 km from well to Europe, would require 80 hours from production site to Europe. Lochner and Dieckhöner (2012) even assume two weeks from well to central Europe in the case of emergency, including time to increase production, transport to Europe and through the European grid. However, storages along the pipelines, outside Europe, can be used to speed up the arrival or surge import gas. There is limited quantitative data on storages along the pipelines from MENA and in Russia, but there are at least 3 storages along the trunk lines in Belarus and the storage capacity along the trunk lines in Ukraine is large. These storages add 13% to the withdrawal and 21% to the European storage capacity (GIE 2011c). As the storages are close to the European borders, I assume, contrary to Lochner and Dieckhöner, that the non-disrupted pipelines react and boost transmission up to 100% as soon as the pipeline pressure drops. I assume that this gas reaches Europe 4 hours (given an average distance storage-border of 120 km) after the interruption and that this supply is maintained for as long as it takes. I make the same assumption for pipeline gas from other countries: the gas fields are located between 500 km (Azerbaijan, Iraq, Iran, Libya) and up to 2000 km (Algeria) from Europe, but the export pipelines have storages near the Mediterranean coast or the European border. Hence, surge pipeline gas supply via all undisturbed pipelines can be increased up to 100% immediately, and the gas reaches Europe after 4 hours. After the disturbance, surge foreign production is used to replenish all storages.

The existing and planned LNG gasification terminals have a storage capacity of 132 TWh (corresponding to 180 of the currently largest LNG tankers[44] (GIE 2011a, b), which enables them to maintain full capacity supply for some time (at least 100-200 hours, depending on the interruption case, see section 7.5). Also this was seen during both the 2009 and 2011 supply crises, during which LNG played an important role to stabilise the supply (Kovacevic 2009; Lochner and Dieckhöner 2012). As the LNG terminals are located in Europe, I assume that the LNG supply is constant (except, depending on the case, when LNG terminals are disabled): before the LNG storages are empty, new tankers will arrive in Europe.

On the demand side, fuel-switch and demand-constraint in industry and the electricity sector are the primary emergency measures. Demand-constraint outside these sectors is, at present, not accepted as an emergency measure in Europe (Gas security Regulation 2010; Zeniewski and Bolado-Levin 2012). Currently, around 40% of the operational gas power capacity in the EU27 can switch fuel (mainly to oil) during a gas supply crisis (Platts 2008). I assume that this share is maintained also for GEA. Thus, the GEA has 614 GW fuel-switch capable gas power, whereas the current fuel-switch capacity is 41 GW. Given the average load factors (see sections 13.2.2 and 13.3.2), average gas-savings from power plant fuel-switch of up to 5600 GWh/d (GEA) and 1990 GWh/d (Today) can be expected. I assume the same fuel-switch capability also for peak times in order to avoid an overestimation of this potential, and that these measures start after 12-24 hours. During a crisis, it is possible that gas power can be shut down, if other capacities are sufficient to satisfy electricity demand. In GEA, which has high shares of intermittent renewables, it is not possible to estimate this potential: it depends

[44] Most planned LNG terminals have not published data on their storages. I consider such terminals to have zero storage, and the number used here is probably a considerable underestimation.

on the solar and wind generation – and hence on the weather – at the time of the interruption. This is unknowable, and I therefore assume a highly conservative zero potential for gas power generation constraint. For consistency, I make the same assumption for the Today benchmark.

The industry demand-constraint is considerable, as some industries have interruptible contracts and many others can stop production for some time. There is no coherent European data on the size of this potential. I found sporadic reports from single countries of demand-reduction potentials of 5-15% of industry demand during this research, but with no information of how fast and how long, and under which conditions, these demand-reductions potentials may be utilised (EC 2009a, also Engerer *et al.* 2010). The share of industry with interruptible contracts is unknown, but its contribution to maintaining operations during the 2009 gas crisis was small. The industry demand-reduction was significant during this event, but it is unclear how much of this was 'negotiated' and how much was due to the simple fact that there was no gas to use (Kovacevic 2009). The latter type of managed outages (i.e. disconnection of customers), which was the by far most important demand-reduction measure in 2009, cannot be viewed as demand-constraint, but fulfils the definition of 'outage' in every respect. Thus, as there is no good data, I conservatively assume that the demand-constraint in industry is zero. Consequentially, I view all remaining shortages after all supply measures and fuel-switch in the electricity sector have been activated as outages.

I further assume that outages do not increase in size after the response mechanisms have started and the outages do no reappear once the supply to the entire system has been restarted. All response mechanisms are summarised in Table A 10. The priority numbering refers to the order in which the measures are activated to respond to a disturbance.

Table A 10: Summary of the European response capacities in GEA.

	Average demand available response (GWh/d)	Peak demand available response (GWh/d)	Operation time interval	Priority
Surge production	0	0	Cannot increase Assumed constant maximum output.	
Surge import				1
pipeline	Up to 100% of 14,520 (minus interruption)	0	**4 h-∞**; 100% after 4h	
LNG	Up to 100% of 16,969 (minus interruption)	0	**0-∞**; 100% immediately	
Storage-draw	27,344	Up to 27,344 (minus utilisation)	**0-∞**; 100% immediately	2
Electricity sector fuel-switch	5600	5600	**12 h-∞**; 100% after 24h	3

13.2.5 Costs

The costs arising for the exporter during a coercion event are the lost revenues, i.e. the amount of gas not delivered times its price. It is not possible to know what the gas price in 2050 will be. Over the last 4 years, the European gas import price[45] has fluctuated strongly, between 4700 and 8500 €/TJ, with an average of 6500 €/TJ (BAFA 2012). As the electricity costs I use for the Desertec coercion vulnerability assessment are based on technological learning and cost reductions, the gas price assumption should be conservative as well, in order to avoid biasing the scenario comparison in favour of electricity trade. Hence, I assume that the gas price in 2050 is 6500 €/TJ, or 23,400 €/GWh, which is the average import gas price for 2009-2012. Analogue to Desertec, I set the transit fee to 20% of the price, 4700 €/GWh.

[45] These figures are the German border prices.

Further, I assume that the costs for back-up gas are the same as the import gas price. The effective cost for European supply-surges and storage-draw is thus zero. For storage gas, this follows from the constancy of the gas price: the gas in the storages is the same gas that was bought at this price at an earlier time. The gas needed to replenish the storages after an interruption will also be bought at this, constant, price (and, for the coercion event assessment, from another supplier than the one cutting exports, see section 7.1.2). For the supply-surge measures, this price constancy follows from the assumption that gas is traded on a liquid and undistorted market (see section 7.4), in which the price increase during a disturbance is likely to be limited. The European import gas price even *decreased* in January 2009, despite the problems with the gas supply from Russia (BAFA 2012). Similarly, I assume that the fuel-switch (from gas to oil) in the electricity sector comes at no cost, as the gas and oil prices are strongly correlated.

The costs of gas outages are similarly difficult to determine as the costs of blackouts, as they, too, are context-dependent and vary between times, places and sectors. As gas outages are less frequent than blackouts, they have not been as extensively studied. The effects and costs of gas outages may also be correlated to blackouts, especially in isolated systems with a high share of gas power: for example, a recent study found that most of the costs caused by a potential gas outage in Ireland would accrue from blackouts (Leahy *et al.* 2010). The emergency measures in Europe foresee that industry and the electricity sector, as long as this does not cause blackouts, are the first to be disconnected, whereas the residential sector (heating) and government are protected customers (Zeniewski and Bolado-Levin 2012). The most relevant outage costs are thus those arising in the industry. These outage costs range between 0.27-1.2 €/kWh not delivered, with an expected cost of 0.55 €/kWh not delivered

(ILEX 2006a, b). Here, therefore, I use a constant gas outage cost of 0.55 €/kWh not delivered, or 550,000 €/GWh; this is about a factor 23 higher than the import gas price.

All cost results are given both in absolute terms (€) and relative to GDP. For GDP, I assume a constant growth of 2%/a in Europe and 4.5%/a for all other countries, see Table A 11. This data is roughly consistent with the macroeconomic data underlying GEA (and it is roughly consistent with the Desertec, see section 13.1.5), but it is not identical so that I use the same GDP data for all scenarios. The GDP numbers I use for MENA are lower than those used by GEA, but GEA assumes either a counterfactual or a wrong GDP (much too high) for 2005/2010. The growth rates I assume here and those used in GEA are practically identical.

Table A 11: GDP (billion €) for all relevant countries and regions in GEA (2050) and Today (2010).

	GDP 2010	GDP 2050
Europe	13.889	30.667
Balkan+Hungary	598	1320
Baltic+Finland	245	540
Iberian peninsula	1259	2779
Azerbaijan	40	232
Kazakhstan	113	657
Russia	1138	6621
Turkmenistan	18	103
Algeria	122	710
Libya	55	322
Egypt	166	963
Iran	297	1730
Iraq	22	126
Qatar	98	570
Saudi Arabia	334	1945
United Arab Emirates	229	1332
Yemen	49	284
Trinidad & Tobago	16	91
Nigeria	151	879

	GDP 2010	GDP 2050
Ukraine (transit country)	106	617
Belarus (transit country)	42	245
Morocco (transit country)	70	410
Tunisia (transit country)	34	198
Georgia (transit country)	9	52
All pipeline exporters	1674	9741
All exporters (pipeline + LNG)	2681	15.595

Source: based on UN (2011); IMF (2012).

13.3 Today benchmark

I compare the assessments of the Desertec and GEA scenarios to the situation today, as a benchmark. Structurally, the Today benchmark is similar to GEA – there are no electricity imports but significant gas imports, much of which is used for electricity generation. I identify the term Europe the same way as for GEA (see section 7.4). As this definition of Europe is not an economic or political entity today, not all data is available for all countries or for the same year. Therefore, the interpretation of 'today' is a generous one, and means a year between 2009 and 2012 (I always indicate the precise year). I expect the error from this to be miniscule.

13.3.1 Demand

The electricity demand in Europe in 2009 was 3725 TWh, whereof 3225 TWh in EU27, whereas the installed capacity was 905 GW (Eurostat 2010, 2011; EWEA 2011; TEIAS 2009). There is no data for the peakload of the entire area, but the ENTSO-E peakload in 2010 was 557 GW and the Turkish peakload projection (from 2009) indicates peakload of 33

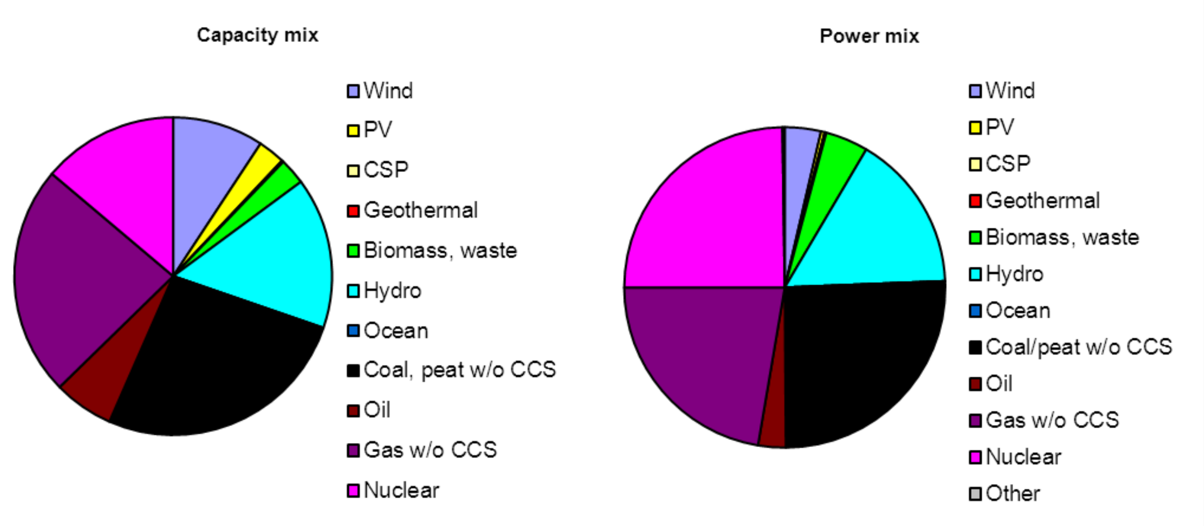
GW in 2010. Thus, the European peakload in 2010 was an estimated 590 GW, to be compared with the average 425 GW demand (ENTSO-E 2011c; TEIAS 2009).

The gas demand in the EU27 in 2010 was 5565 TWh/a (15,246 GWh/d), with a peak demand of 35,500 GWh/d (ENTSO-G 2011b). The 2010 demand in Norway, Switzerland and Turkey was 525 TWh/a (BP 2011), whereas the ex-Yugoslavian countries and Albania had a combined demand of 52 TWh/a in 2009 (IEA 2012b). The total European demand is thus around 6090 TWh/a (average demand of 16,685 GWh/d). There is no data for the peak gas demand in the non-EU countries. Assuming that the peak-to-average demand ratio is the same across the area as in the ENTSO-G area (2.32), the European peak demand is 39,175 GWh/d. Most of this increase is driven by heat demand in winter. This increase can be roughly explained by increasing the residential/commercial gas demand by a factor 5 and – as European electricity demand is higher in winter – doubling the gas power generation (Eurostat 2012).

The main consumers of this gas are the residential sector (primarily heating, accounting for 27% of total demand), electricity generation (19%, plus the electricity share of the CHP fleet, which consumes 14% of the gas), and industry (18%) (IEA 2012b).

13.3.2 Supply

The European electricity generation is strongly dominated by fossil and nuclear power, see Figure A 6. The European installed capacity in 2010 was 920 GW, of which 110 GW were fluctuating sources (wind and PV). I assume that these have zero capacity credit, that hydro is 60% dispatchable, and that each power station is down for maintenance during one month each year. This gives an estimate of 753 GW available, dispatchable generation capacity, and 162 GW of available spare capacity during peakload.



Sources: TEIAS (2009); EWEA (2011); IEA (2012a).

Figure A 6: Capacity (2009) and electricity mix (2010) for Europe in the Today benchmark.

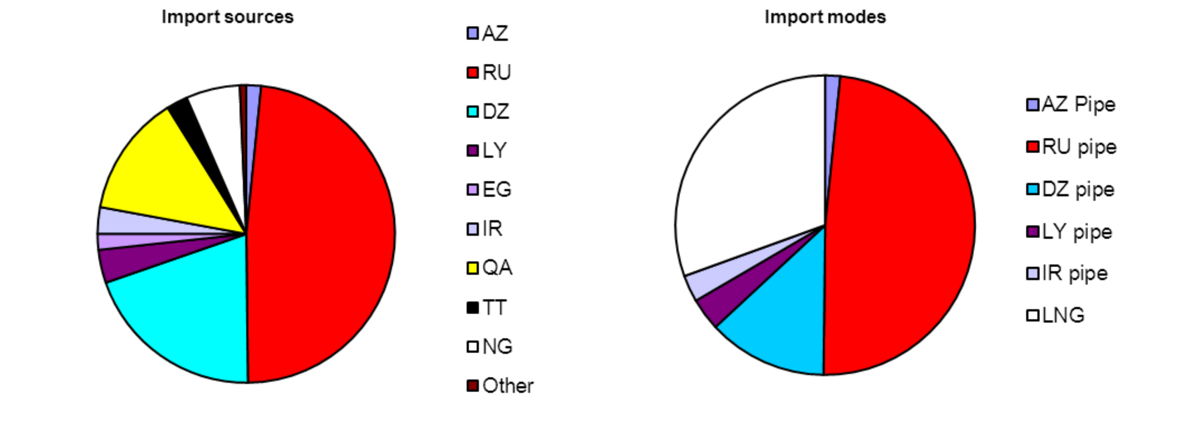
Europe today imports 50% of the 6090 TWh/a gas it consumes. The EU27 gas import dependency is about 60%, but the Norwegian production reduces overall European import dependency, whereas the Turkish import dependency slightly increases it. Essentially all Norwegian gas exports go to European countries (BP 2011).

The EU gas production capacity is currently 2020 TWh/a, and this is almost fully (96.5%) utilised to produce 1950 TWh/a (ENTSO-G 2011b). The Norwegian exports to the EU were 1160 TWh/a in both 2009 and 2010, compared to the Norwegian supply potential of 1220 TWh/a in 2010 (ENTSO-G 2011b). I found no data concerning the Turkish and Swiss gas production capacities, but given their low production, these capacities are small. Combined, the European production capacity is 3240 TWh/a, which is utilised to 96% to produce 3110

TWh/a of domestic natural gas. I thus assume that the domestic production cannot be increased during emergencies.

13.3.3 Gas import sources and infrastructure

The European gas imports in 2010 came from 14 supplier countries, but only 5 had a share exceeding 3% of all gas imports (Russia, Algeria, Qatar, Nigeria and Libya). Almost 50% of the imports come through pipelines from Russia, whereas about a third comes by LNG, see Figure A 7.

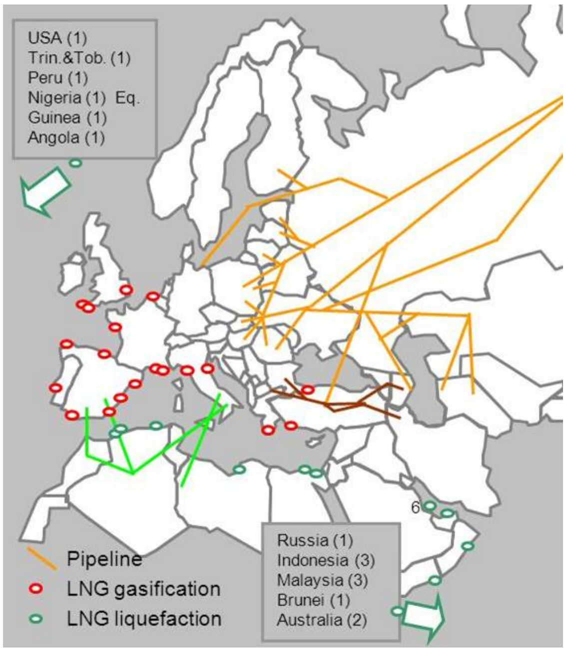


Source: BP (2011).

Figure A 7: Import sources and import modes for natural gas in the Today benchmark.

Country abbreviations: AZ=Azerbaijan; RU=Russia; DZ=Algeria; LY= Libya; EG=Egypt; IR=Iran; QA=Qatar; TT=Trinidad & Tobago; NG=Nigeria.

The gas for the European markets is currently imported through 19 pipeline entry points, and 19 LNG terminals, see Figure A 8.



Sources: base d on ENTSO-G (2011a); GIE (2011b); Global LNG (2012).

Figure A 8: Existing (autumn 2011) gas import pipelines and LNG gasification terminals in Europe, and existing LNG liquefaction terminals in the world.

The European pipeline import capacity in 2012 was 11,395 GWh/d, and the LNG capacity 6300 GWh/d, see Table A 12. The actual pipeline gas imports in 2010 were 2110 TWh, or on average 5800 GWh/d. Hence, the average pipeline utilisation was 51%, but there are considerable differences between pipelines: the Russian pipelines were 49% utilised, whereas the pipeline from Azerbaijan to Turkey was only used for 22% of its capacity and the one from Libya reached 83% utilisation.

Table A 12: Existing import gas pipelines or pipeline entry points (December 2012). Rounded.

From	Transit	To	Pipeline/entry point	Capacity (GWh/d)
Algeria	Morocco	**Spain**	Maghreb-Europe	355
Algeria		**Spain**	Medgaz	260
Algeria	Tunisia	**Italy**	Transmed	1088
Libya		**Italy**	Greenstream	349
Russia		**Finland**	Imatra	225
Russia		**Latvia**	Korneti	166
Russia	Belarus	**Lithuania**	Kotlovka	281
Russia	Belarus	**Poland**	Tietierowka	7
Russia	Belarus	**Poland**	Kondratki	1026
Russia	Belarus	**Poland**	Wysokoje	167
Russia	Ukraine	**Poland**	Drozdowicze	173
Russia	Ukraine	**Slovak Rep.**	Velké Kapušany	3116
Russia	Ukraine	**Hungary**	Beregdaróc	595
Russia	Ukraine	**Romania**	Mediesu Aurit	117
Russia	Ukraine	**Romania**	Isaccea	250
Russia		**Germany**	Nordstream	1673
Russia		**Turkey**	Bluestream	495
Azerbaijan	Georgia	**Turkey**	South Caucasus	619
Iran		**Turkey**	Tabriz-Ankara	433
Total				**11,395**

Sources: ENTSO-G (2011a), project websites.

The actual LNG imports were 950 TWh, or 2600 GWh/d, with an average utilisation of the regasification terminals of 41%, see Table A 13. The total imports of 3060 TWh/a (8400 GWh/d) are thus much lower than the technical import capacities of 17,700 GWh/d (BP 2011; ENTSO-G 2011a; GIE 2011b).

Table A 13: Existing LNG gasification terminals in Europe (December 2011). Rounded.

Country	LNG terminal	Capacity (GWh/d)
Belgium	Zeebrugge	475
UK	Teesside	128
UK	Isle of Grain	700
UK	Milford Haven/Dragon LNG/South hook	950
France	Montoir de Bretagne	370
France	Fos Tonkin/Fos Cavaou	410
Italy	Panigaglia	147
Italy	Cavarzere	291
Greece	Revythoussa	139
Spain	Barcelona	544
Spain	Sagunto	115
Spain	Cartagena	377
Spain	Huelva	377
Spain	Mugardos/El ferrol	115
Spain	Bilbao	228
Portugal	Sines	192
Turkey	Aliaga	187
Turkey	Marmara ereglisi	194
Netherlands	Gate LNG	375
Total		**6312**

Source: GIE (2011b).

Combined with the domestic production capacities, Europe can be supplied with up to 26,583 GWh/d of natural gas, which easily satisfies the average demand of 16,680 GWh/d but not the peak demand of 39,180 GWh/d. For this, Europe relies on stock-draw from a considerable and growing fleet of gas storages: the current (autumn 2011) storage capacity in Europe is 1376 TWh, with a maximum withdrawal capacity of 20,320 GWh/d (which is higher than the average demand, see Table A 14). These storages can also be activated to cover periods of short supply, for example caused by a disabled pipeline or political disputes.

Table A 14: Existing gas storages in Europe (autumn 2011). Rounded.

	Number of storages	Storage capacity (TWh)	Max. withdraw. capacity (GWh/d)		Number of storages	Storage capacity (TWh)	Max. withdraw. capacity (GWh/d)
Albania	n.k.	n.k.	n.k.	**Lithuania**	1	n.k.	n.k.
Austria	8	82	982	**Luxemburg**	0	0	0
Bosnia	n.k.	n.k.	n.k.	**Netherlands**	5	58	2391
Belgium	1	7	160	**Norway**	0	0	0
Bulgaria	1	5	37	**Montenegro**	0	0	0
Croatia	1	n.k.	n.k.	**Macedonia**	n.k.	n.k.	n.k.
Cyprus	n.k.	n.k.	n.k.	**Poland**	8	20	442
Czech Rep.	8	36	616	**Portugal**	2	2	n.k.
Denmark	2	11	198	**Romania**	8	30	25
Estonia	0	0	0	**Serbia**	0	0	0
Finland	0	0	0	**Slovenia**	0	n.k.	n.k.
France	16	141	3041	**Slovak Rep.**	2	32	415
Germany	47	225	4848	**Sweden**	1	n.k.	7
Greece	0	0	0	**Spain**	12	50	1989
Hungary	5	68	877	**Switzerland**	0	0	0
Ireland	1	2	28	**Turkey**	5	n.k.	n.k.
Italy	12	173	3050	**UK**	13	49	948
Latvia	1	26	266				
				Total	**176**	**1019**	**20,320**

Source: GIE (2011c).

13.3.4 Gas emergency response mechanisms

I determine the response capacities for gas emergencies in the benchmark the same way as for GEA. Thus, the response data is summarised in Table A 15, whereas my argumentation behind these numbers is found in section 13.2.4.

Table A 15: Summary of the European response capacities in the Today benchmark.

	Average demand available response (GWh/d)	Peak demand available response (GWh/d)	Operation time interval	Priority
Surge production	0	0	Cannot increase Assumed constant maximum output.	
Surge import				1
pipeline	Up to 100% of 11,395 GWh/d (minus interruption)	0	**4 h-∞**; 100% after 4h	
LNG	Up to 100% of 6312 GWh/d (minus interruption)	0	**0-∞**; 100% immediately	
Storage-draw	20,320	Up to 20,320 GWh/d (minus utilisation)	**0-∞**; 100% immediately	2
Electricity sector fuel-switch	1990	1990	**12 h-∞**; 100% after 24 h	3

13.3.5 Costs

The cost data I use for the coercion vulnerability assessment of the Today benchmark is identical to the cost data I use for GEA (section 13.2.5). The GDP data for the Today benchmark are included as 'GDP 2010' in Table A 11 (page 331).