Assessing the security of flexibility strategies for low carbon electricity systems.
A comparative analysis of back-up capacity, storage and interconnection strategies in electricity systems with a high variable renewable energy penetration.

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Abstract
The recent Global Energy Assessment (GEA 2012) highlights that securing the undisturbed provision of vital energy services, in particularly electricity, has been and will become one of the key strategic challenges for policy maker planning the transition towards LCES. However, systems transitioning to low carbon energy systems face increasing grid integration challenges from variable renewable energy sources (VRES). As such, grid flexibility and the security of flexible electricity provision are becoming of increasing interest to policy-makers. While flexibility has traditionally been in the hands of transmissions systems operators, with national-level policy-maker setting more and more ambitious targets, it is necessary to develop tools to make the planning of strategic flexibility sources accessible to policy-makers. This thesis takes a comparative case study approach to identify current trends and practises in the flexibility strategies of the countries with the highest VRES integration: Denmark, Germany, Portugal, Spain, Ireland and the UK. It finds that while traditional back-up capacity still dominates most flexibility strategies, other flexibility components such as electricity storage and particularly interconnection play a bigger role in the countries with the highest VRES share. Additionally, in placing flexibility services into an energy security context this thesis develops an indicator framework to assess comparative security of flexibility strategies. Initial findings from the framework reinforce the importance of diversifying sources of flexible electricity supply, as well as the necessity to ensure robustness and resilience of the domestic electricity system.

Keywords: flexibility, energy security, variable renewable energy integration, strategy
Executive summary

Transitioning towards low-carbon energy systems is arguably a critical step to timely mitigation of greenhouse gases (GHG), as it has been found to have the potential to transition faster than other economic sectors (Transportation, buildings etc.) by the IPCC (Stocker et al., 2013 2014). Most transition will entail integrating increasing renewable energy generation, with the IPCC (2015) stating that greater shares of renewables in the national and global energy mix are a recognized precondition for a sustainable energy future and the mitigation of ongoing anthropogenic climate change. As such, it is unsurprising that the International Energy Agencies’ (IEA) annual World Energy Outlook (2015) has identified a strong trend towards high renewable energy transition pathways. This trend goes in hand with an increased electrification of the overall energy system, in particular the transport sector (IEA 2015b). While dispatchable renewable energy sources (hydro power and geothermal power) are, much like traditional thermal or nuclear generators, constantly available, the power obtained from variable renewable energies is only intermittently available, depending on external and unpredictable factors, such as weather patterns (IEA–ETSAP and IRENA 2015).

Due to the limited geographical relevance of most dispatchable renewables, for most countries, a low carbon energy pathway will necessarily involve a high level of variable renewable energy integration in their overall electricity system. However, high variable renewable energy sources systems face significant grid integration and balancing problems (Endhofer 2011). Therefore, in order to avoid high curtailment rates and ensure that electricity demand is consistently met, countries need to develop their grid flexibility. The recent Global Energy Assessment (GEA 2012) highlights that securing the undisturbed provision of vital energy services, in particularly electricity, has been, and will increasingly become, one of the key strategic challenges for policy makers planning the transition towards low carbon energy systems. While the planning of grid flexibility mechanisms has traditionally been the sphere of electricity services providers, with the increased influence of policy makers on the target setting for low carbon energy systems, a basic understanding of flexibility mechanisms and their planning will need to become part of national policy maker’s toolkits (Cochran et al., 2014).

Finally, with the move away from fossil energy sources and towards high variable renewable energy sources systems, this thesis argues that security of flexibility, rather than security of fuel supply is likely to become one of the major energy security concerns of the 21st century energy system. As such, it seeks to deliver an accessible framework for assessing the security of flexibility strategies.

Therefore, this thesis has the following aims:

- **Aim 1**: to enhance policy makers’ strategic planning of flexibility strategies alongside variable renewable energy targets,
- **Aim 2**: to provide a framework to understand and assess flexibility strategies in an energy security context, in order to facilitate policy makers’ ability to protect the grid from failures caused by the integration of high levels of renewables.

1.1 Research questions

1. Why is flexibility an energy security concern?
2. How are countries with high variable renewable energy integration addressing their flexibility needs - i.e. what are current practises and trends in flexibility strategies?
3. How can countries ensure the security of their flexibility strategies?
   a. How can security of flexibility be assessed?
b. How secure are existing flexibility strategies?
c. What are policy recommendations for ensuring the security of flexibility?

1.2 Methods
This thesis bridges the disciplines of grid integration and energy security. It adopts a comparative case study approach to provide an overview of current trends and practices in the six countries with the highest variable renewable energy penetration: Denmark, Germany, Portugal, Spain, Ireland and the United Kingdom. It utilizes the flexibility chart method developed by Yasuda et al., (2013) to visualize and compare flexibility strategies. Additionally, an indicator framework is developed for assessing the comparative security of flexibility strategies of electricity systems with high variable renewable energy penetration. The framework assesses a flexibility strategy’s performance across the three perspectives of energy security: sovereignty, robustness and resilience, as developed by Cherp and Jewell (2011), and is outlined in Table 1.

Table 1. Indicators to assess the comparative security of electricity flexibility strategies (adapted from Jewell et al., 2014)

<table>
<thead>
<tr>
<th>Perspective of flexibility</th>
<th>Indicator</th>
<th>Vulnerability/ Failure addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td>Electricity trade intensity</td>
<td>Unavailability of flexibility through external electricity markets (Market failure)</td>
</tr>
<tr>
<td></td>
<td>Import dependency</td>
<td>See above</td>
</tr>
<tr>
<td></td>
<td>Export dependency</td>
<td>See above</td>
</tr>
<tr>
<td></td>
<td>Geographic diversity of interconnectors</td>
<td>Exposure to failure of any one external market</td>
</tr>
<tr>
<td>Robustness</td>
<td>Potential variable renewable energy sources share of peak load</td>
<td>Potential variability of electricity generation at peak load</td>
</tr>
<tr>
<td></td>
<td>Spare back-up capacity at historic peak demand</td>
<td>Unexpected increase of peak demand</td>
</tr>
<tr>
<td></td>
<td>Maximum potential flexibility capacity coverage</td>
<td>Failure of variable renewable energy sources to supply sufficient peak load</td>
</tr>
<tr>
<td>Resilience</td>
<td>Diversity of flexibility sources</td>
<td>Vulnerability to disruptions of any one flexibility component</td>
</tr>
</tbody>
</table>

1.3 Findings

Flexibility as an energy security issue
This thesis found that flexibility has become an energy security concern due to the transition to low carbon energy systems, dominated by variable renewable energy sources. Already, countries with a higher variable renewable energy sources potential are struggling to provide sufficient flexibility in order to prevent cost inefficient curtailment of installed variable renewable energy sources. As flexibility affects a high variable renewable energy sources dominated electricity system’s ability to provide vital energy services, in an increasingly electricity-based low carbon energy system, it should be considered a matter of concern from an energy security perspective. This finding in the literature was reinforced by the insights gained from attending the IRENA Innovation Week conference (IRENA 2016).

Current flexibility strategy practices
The examination and comparison of the six case study countries’ flexibility strategies, highlighted the following trends in how countries with high variable renewable energy integration are addressing their flexibility needs:
• Flexibility strategies continue to be dominated by reliance on back-up capacity, with most countries relying on either CHP or CCGT to provide flexibility.

• Storage is not yet a significant component of any country’s flexibility strategy, though this may change as more storage technologies reach technical maturity.

• Interconnection penetration is highest in the countries with the highest variable renewable energy sources penetration. This suggests that interconnection is likely to play an increasingly important role in flexibility strategies, as variable renewable energy sources levels rise.

• Finally, there is a trend to diversify the dominant flexibility components with rising variable renewable energy sources share, with both Germany and Denmark demonstrating a fairly balanced split between interconnection and back-up capacity penetration.

Increasing flexibility strategy security

This thesis cannot make any conclusive statements about the objective security of each country’s flexibility strategy, both due to a lack of sufficient sample countries to benchmark this indicator framework, but also because of the need to further refine the indicators chosen, which are discussed further in Chapter 6 of the thesis. However, it can provide the following general insights into how to increase comparative security of flexibility strategies:

1. Diversification, of both interconnection partners and installed flexibility sources, is key to increasing the ability of the system to deal with and recover from not only foreseeable, but especially unpredictable failures and shortages, both domestic and external in nature. As such, future flexibility strategies should take a systemic approach, incorporating all flexibility mechanisms that are relevant and realistic, from both a geographic and cost perspective.

2. Strategies focusing on sovereignty, will not ensure security unless they are also able to ensure a high level of robustness and resilience of the domestic system, as demonstrated by the UK. However, the same is not necessarily true in reverse, as even comparatively integrated systems, such as Portugal, can score highly if domestic resilience and robustness are ensured. As such, integration is not a significant security risk, as long as interconnections are diversified and internal flexibility mechanisms are designed to be robust and resilient.

1.4 Recommendations

Policy recommendations

1. Diversify both domestic flexibility resources, as well as sources of external flexible electricity (i.e. interconnections). Diversification is key to ensuring resilience of the system against both internal and external failure.

2. Consequently, take a systemic approach, incorporating all flexibility mechanisms that are relevant from both a geographic and cost perspective.

3. Irrespective of interconnection levels, ensure a high level of robustness and resilience of the domestic system, which is at the heart of securing flexibility supply. As such, focus on ensuring sufficient, diversified back-up capacity, as well as diverse storage solutions.

Further research recommendations

This thesis recommends that future research could both follow up on the research questions posed in this thesis, as well as pursue new research questions identified in this thesis, including:
• What are key determinants of a country’s flexibility strategy?
• How can the security of flexibility strategies be globally benchmarked?
• What are best practices and trends of emerging electricity systems transitioning to low carbon energy systems with high VRES penetration?

Following up on the research questions posed in this thesis, future research should include novel technologies, particularly in the field of energy storage, as well as demand-side management, wherever data availability allows, in order to provide a more comprehensive understanding of the full flexibility strategy. Additionally, it could augment the indicators considered in this thesis.

In identifying what key determinants of a country’s flexibility strategy, future research could consider adopting a time-series approach, in order to more thoroughly assess trends and developments, as well as include a quantitative assessment of correlations between electricity system characteristics (size of system, VRES integration level etc.) with the composition of a country’s flexibility strategy.

Benchmarking could be achieved by conducting a more comprehensive testing of indicator frameworks on a larger sample size of countries, in order to derive a more representative understanding of comparative security ranges and allow for benchmarking of secure, versus vulnerable strategies.

In identifying best practices and trends, either further along in the energy transition, or for emerging electricity systems transitioning to low carbon energy systems with high VRES penetration, future research should analyse a wider cross-section of countries, including developing electricity systems, once more countries reach higher VRES penetration and start documenting flexibility components in sufficient granularity.
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## Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>CCGT</td>
<td>Combined cycle gas turbines</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined heat and power plant</td>
</tr>
<tr>
<td>DE</td>
<td>Germany</td>
</tr>
<tr>
<td>DK</td>
<td>Denmark</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
</tr>
<tr>
<td>ES</td>
<td>Spain</td>
</tr>
<tr>
<td>GW</td>
<td>Gigawatt (=1000 MW)</td>
</tr>
<tr>
<td>IC</td>
<td>Interconnection</td>
</tr>
<tr>
<td>IE</td>
<td>Ireland</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>LCES</td>
<td>Low carbon energy systems</td>
</tr>
<tr>
<td>NG</td>
<td>Net generation</td>
</tr>
<tr>
<td>NGC</td>
<td>Net generating capacity</td>
</tr>
<tr>
<td>PT</td>
<td>Portugal</td>
</tr>
<tr>
<td>SWDI</td>
<td>Shannon-Wiener Diversity Index</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>VRES</td>
<td>Variable renewable energy sources (here: wind, solar PV)</td>
</tr>
<tr>
<td>VRES</td>
<td>Variable renewable energy sources</td>
</tr>
</tbody>
</table>
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2 Introduction

Anthropogenic climate change has been recognised by the IPCC as one of the main challenges of the 21st Century, affecting both humans and the biosphere (Stocker et al., 2013). Transitioning towards low-carbon energy systems is arguably the most important step to timely mitigation, as it has been found to have the potential to transition more quickly than other economic sectors (Transportation, buildings etc.) (IPCC, 2015).

In transitioning towards a low carbon energy system (hereafter LCES), countries can choose a mix of three low carbon energy technologies: nuclear energy, thermal energy (with or without biomass utilization) in combination with carbon capture and storage, and, finally, energy from renewable resources (IEA, 2015b). All of these come with challenges: nuclear energy faces not only security challenges, but entails an, as yet unsolved, waste storage problem; Similarly, carbon capture and storage solutions also face waste storage issues, and the technology itself is currently considered to have scaling-issues (IEA, 2015b; Denholm and Hand, 2011); Finally, energy from renewable sources face grid integration challenges, as outlined below.

Of the three pathways, transitions focusing on increasing renewable energy penetration are seen as the most likely strategy, with the IPCC (Edenhofer et al., 2011) stating that, greater shares of renewables in the national and global energy mix are a recognized precondition for a sustainable energy future and the mitigation of ongoing climate change. As such, it is unsurprising that the IEA’s annual World Energy Outlook (2015) has identified a strong trend towards high renewable energy transition pathways, with renewables projected to overtake coal as the dominant energy sources by the 2030s. This trend goes hand in hand with an increased electrification of the overall energy system, in particular the transport sector (IEA, 2015b). As such, the LCES of the future, is likely to be to a large extent an electricity-based system.

Renewable energy technologies for energy generation are categorised by the IEA–ETSAP and IRENA (2015) into dispatchable (hydro power, geothermal power, and biomass power) and non-dispatchable, or variable renewable energy sources (hereafter VRES) (wind power, solar photovoltaic, concentrating solar power and wave and tidal power). Dispatchability, is defined as “the source’s ability to be controlled in response to system requirements, such as variation in demand (i.e. at request of the power grid operator)”. Therefore, while dispatchable renewable energy sources are, much like traditional thermal or nuclear generators, constantly available, the power obtained from VRES is only intermittently available depending on external factors, for example, weather patterns (IEA – ETSAP and IRENA, 2015).

Some countries, such as Costa Rica and Norway, have been able to achieve low carbon energy systems by drawing on large domestic high dispatchable renewable energy resources, in particular hydro-power. Nonetheless, the focus going forward for many countries will be on growing the level of VRES in the energy systems; Ren 21 (2015) found that in 2015, 90% of all investments into renewable energy went into expanding solar and wind capacity, and conclude that this trend is likely to continue. As such, with the exception of the countries able to benefit from large dispatchable resources, for most countries a low carbon energy pathway will necessarily involve a high level of variable renewable energy penetration in their overall electricity system.

However, high VRES systems face significant grid integration and balancing problems (IEA, 2011b). Therefore, in order to avoid high curtailment rates and ensure that electricity demand is consistently met countries need to develop their grid flexibility.
The recent Global Energy Assessment (GEA, 2012) highlights that securing the undisturbed provision of vital energy services, in particularly electricity, has been and will increasingly become, one of the key strategic challenges for policy-makers planning the transition towards LCES. While the planning of grid flexibility mechanisms has traditionally been the sphere of electricity services providers, with the increased influence of policy-makers on the target setting for LCES, a basic understanding of flexibility mechanisms and their planning will need to become part of national policy-makers’ toolkits. (Coehran et al., 2014).

2.1 Problem definition

Flexibility, the ability of an energy system to balance demand and supply at any given point of time, has historically been primarily a concern of transmission service operators, rather than governments. In the traditional energy system, it simply involved ensuring a sufficient level of back-up capacity, in the form of thermal generators, was on standby, to accommodate any short-term fluxes in demand. However, with targets to tackle climate change and other environmental concerns leading most countries to transition towards LCES, flexibility is increasingly becoming a concern for governments and policy-makers. As stated above, the majority of countries are facing integration of high levels of variable renewable energy source, in particular wind and solar energy, into their power system. High renewable energy targets, set externally by policy makers, require not merely a transition of energy sources, but of the overall structure of the power system. One of the most central changes will be the need to increase and diversify flexibility mechanisms within the national grid.

In recent decades, it has been primarily policy-makers, rather than electricity service providers, setting national climate, and therefore, renewable energy targets. As such, target setting has frequently occurred without explicit consideration of the consequent flexibility requirements. This has required electricity service providers to play catch-up and create ad-hoc solutions for delivering the increasing flexibility needs of transitioning systems. Given that flexibility needs are going to keep increasing as VRES penetration levels rise, it is necessary to facilitate the development of explicit flexibility strategies at the government level. As a step towards this, this thesis seeks to address the need for tools to enable policy-makers to plan more strategic flexibility systems going forward. This represents a bridging of the barrier between policy-makers, who are frequently generalists with a non-technical background, and electricity service providers, who frequently take a highly complex and detailed approach to the technicalities surrounding flexibility provision. As such, this thesis aims to develop an understanding of current best practises in flexibility strategies. Additionally, with the move away from fossil energy sources and towards high VRES systems, this thesis argues that security of flexibility, rather than security of fuel supply is likely to become one of the major energy security concerns of the 21st century energy system. In this context, it seeks to deliver an accessible framework for assessing the security of flexibility strategies.

2.2 Aims and objectives

To address the stated problem, this thesis will pursue the following aims and objectives:

Aim 1: to enable policy makers to more strategically plan flexibility strategies alongside VRES targets,

- Objective 1: identify “first movers” in the energy transition towards LCES with high VRES penetration
• **Objective 2:** identify current practises and trends in the flexibility strategy of these “first movers”

**Aim 2:** to provide a framework to understand and assess flexibility strategies in an energy security context, in order to facilitate policy makers’ ability to protect the grid from failures caused by the integration of high levels of renewables.

• **Objective 1:** identify why/if flexibility is an energy security concern for country’s transitioning to LCES with high VRES content.

• **Objective 2:** identify how security of flexibility strategies can be assessed.

• **Objective 3:** Assess comparative security of existing “first mover” flexibility strategies.

• **Objective 4:** identify policy recommendations for increasing the security of a country’s flexibility security.

In order to fulfil these aims and objectives, the thesis seeks to answer the following research questions:

1. **(1) Why is flexibility an energy security concern?** (Chapter 2)

2. **(2) How are countries with high VRES integration addressing their flexibility needs, that is, what are current practises and trends in flexibility strategies?** (Chapter 4)

3. **(3) How can countries ensure the security of their flexibility strategies?**
   a. **How can security of flexibility be assessed?** (Chapter 3.6)
   b. **How secure are existing flexibility strategies?** (Chapter 5)
   c. **What are policy recommendations for ensuring the security of flexibility?** (Chapter 7.4)

### 2.3 Limitations and Scope

The scope of this thesis is defined by the focus of the research questions, the adopted methodological approach and the external limitations faced in the data collection process. It is restricted in numerous aspects, but key among these are the following:

• Based on the problem statement and research questions identified, this thesis focuses on the current flexibility strategies (installed flexibility capacity) of the countries whose electricity systems are already showing higher VRES. In addressing flexibility strategies, the focus is on flexibility potential (i.e. installed flexibility capacity) rather than actual realized flexibility, which is situation and time-dependent. As such, this thesis excludes the role of electricity markets in flexibility provision, despite the central role they play in determining realized flexibility availability. Additionally, this thesis defines the relevant level of policy-making in the context of flexibility strategies for electricity systems as the national level, as this is the level on which the majority of final decisions driving the transition to LCES occur.
The focus of the research question determines that only countries with high levels of VRES are included in the analysis, as further explained in chapter 3. Because of this, only European countries with mature energy systems could be considered, the implications of which are further discussed in chapter 2 and 6. Widely however, this has implications for the temporal and geographic applicability of the findings.

In order to draw conclusions about current practises, the thesis considers only currently implemented flexibility mechanisms, rather than planned or stated flexibility strategies. Additionally, this limits the technologies that could be considered as flexibility mechanisms to the most mature, for which current installation data was available. This is further discussed in chapter 2 and 6.

2.4 Audience
The audience for this thesis is mainly national-level policy makers working on the transition to a LCES and seeking to obtain a better understanding about the nature and design of flexibility strategies. Additionally, due to the novel nature of the analysing flexibility from an energy security perspective, this thesis may also be of interest to academics seeking to further examine the interlinkages between low-carbon energy systems and energy security.

2.5 Disposition
Chapter 1 presents the nature of the research problem this thesis seeks to address, as well as the aims and research questions that guide it. It further outlines the scope and limitations of this research, identifies the intended audience and provides an overview of the thesis chapters.

Chapter 2 presents a deeper analysis of the two most relevant fields of studies, Grid integration literature and assessments, as well as energy security in LCES. By identifying potential interlinkages between these fields, the chapter seeks to answer research question 1.

Chapter 3 presents a comprehensive overview of the methodological approach adopted by this thesis; it provides details of country selection and terminology, while additionally, outlining an analytical framework for categorising flexibility strategies. Finally, it develops an indicator framework for assessing the comparative security of flexibility strategies, in answer to research question 3a.

Chapter 4 provides background information on the flexibility situation in each of the six case study countries, structured according to the flexibility components, before concluding with a comparative analysis of existing best practises in flexibility strategy that addresses research question 2.

Chapter 5 implements the comparative flexibility security assessment framework developed in chapter 2 for all six case study countries, thereby focusing on research question 3b.

Chapter 6 discusses the limitation and implications of the approach chosen by this thesis. By reflecting, in particular on the indicator framework, it seeks to augment the answer to research question 3a provided in chapter 3.

Chapter 7 summarizes the main conclusions and findings of this thesis and offers recommendations for policy makers and further research.
3 Literature analysis

The following chapter provides an overview of the relevant fields of study this thesis draws upon: (1) grid integration literature with a focus on grid integration literature and (2) energy security perspectives relevant to low-carbon energy systems. Both of these areas are highly complex, and it is out of the scope of this thesis to present a comprehensive review of either field. However, this section endeavours to provide an analysis of the aspects of each field most relevant to the research presented in this thesis, while providing an outline of the interlinkages between the two areas.

3.1 Variable renewable energy: Grid integration and its challenge

As Figure 1 shows, the integration of the VRES adds to the overall variability in the electricity system. Traditional power systems could focus on adjusting supply in the form of thermal and nuclear generation to meet the variable hourly demand, shown here by the yellow load section. However, the integration of VRES introduces variability on the supply side, demonstrated here by the green wind section. The effect this has on the total electricity system is shown by the orange net load curve, which illustrates the demand that needs to be met by the remaining dispatchable generation capacity, be it thermal, nuclear or renewable. By comparing the yellow section, demand that non-VRES system would have had to have met before integration of VRES, and the orange section, we can see that modern LCES have to adapt to respond to far greater variability in the electricity load.

The difficulty of balancing the electricity demand and supply of the grid at all times, is further exacerbated upon integration of higher VRES levels by the added uncertainty, and within a short time frame, unpredictability caused by weather condition forecast errors (Gross et al., 2006, Holttinen et al., 2009; Bertsch et al., 2012).

In cases where balancing is not possible, system operators have two choices:
(1) Temporarily curtail grid access of VRES (Curtailment), or
(2) Access available grid flexibility mechanisms.

The former, is only an option when the imbalance is caused by supply exceeding demand, and, if used repeatedly, can significantly increase the marginal cost of VRES energy generation, as it involves effectively wasting generated renewable energy. Therefore, the latter, engaging grid flexibility mechanisms, is the necessary solution for systems seeking to integrate high VRES levels effectively, as it does not negatively affect the cost efficiency of VRES generation, and allows for both upward and downward balancing of the load (Denholm and Hand, 2011).

3.2 Flexibility

Flexibility in a system with VRES generation can be defined as the ability of an electrical system to respond to changes in power demand and generation (Huber et al., 2014). However, in the context of this thesis, which excludes demand-side flexibility mechanisms for reasons outlined in the scope, the term flexibility or flexibility supply is used interchangeably with the term flexible electricity supply, i.e. electricity supplied by flexibility mechanisms.

3.2.1 Flexibility components and mechanisms

There is a widely accepted compartmentalization structure developed by the IEA (2011) which divides flexibility potential into four fundamental components:

1. Back-up capacity;
2. interconnection infrastructure;
3. Electricity storage; and
4. Demand-side integration.

This categorisation represents the accepted compartmentalization in the field of integration literature (Brouwer, 2015; Huber et al., 2014; Bertsch et al., 2012; Denholm and Hand, 2011, etc.), with all examined studies adopting this structure.

Additionally, a range of flexibility mechanisms (technologies and approaches) fall under each flexibility component. However, for reasons of scope, this thesis focuses on the most mature flexibility mechanisms. While more novel technologies, such as flexible nuclear generation, smart grid technology and the connected demand-side management option or various kinds of energy storage in the form of batteries, or electric vehicles, are likely to play an increasingly important role in future flexibility strategies, their novel nature means that they are unlikely to be major characteristics of the current flexibility strategies being examined by this thesis. The more mature flexibility mechanisms considered in this thesis, as well as their contribution to flexibility are outlined below.

Back-up capacity is considered in the form of reservoir hydro resources, as well as specific gas power plants, that allow particularly cost-effective flexible ramping (following Bertsch et al., 2012). Yasuda et al., (2013) further identifies combined heat and power plants (CHP), as well as combined cycle gas turbines (CCGT) plants, as the most relevant of these thermal generation technologies, currently in wide-spread use. They provide flexibility in the form of easily dispatchable (rampable) electricity generation.

1 For more information on flexibility mechanisms and novel technologies see Eurelectric 2011 (back-up capacity), IEA 2014 (storage), and for overviews IEA (2014)
Interconnection, a singular mechanism, though specific technologies used for interconnection may vary. Interconnection provides flexibility both by drawing on neighbouring flexibility resources, but also by allowing for “spatial smoothing” of variability caused by VRES integration (IEA, 2014).

Electricity storage, is considered only in the form of hydro reservoirs with pumping facilities. These provide flexibility by effectively storing excess VRES generated electricity potential, thereby preventing curtailment, and then releasing this stored potential through hydro-generation during peaks in demand. Pumped hydro storage is both the most mature and one of the most efficient storage technologies on the market, with a roundhouse efficiency of 80% (IEA, 2014). Compressed Air Energy systems were also considered for inclusion in the scope of the thesis, as a country’s pumped hydro availability is highly geographically dependent, however the lack of country-level data on installed capacity prevented the inclusion.

Demand-side integration, is not considered in this thesis, due mainly to the relative novelty of the smart grid technology underlying wide-spread demand-side management. However, similar to electricity storage, demand-side integration allows for flexibility through shifting peaks in demand to “smooth” overall demand-side variability.

3.2.2 Factors influencing electricity system flexibility

As Figure 2 shows, the need for flexibility in an electricity system is influenced by many variables; electricity demand and variable generation fluctuations, as well as vulnerability to unexpected outages, which determine the overall demand for flexibility services (i.e. the electricity level needed at any time to balance the electricity supply and demand). However, the level of flexibility that can be provided by flexible resources can also vary, as the efficiency of various sources of flexibility to deliver their full capacity are heavily determined by the system
context at any point in time, as outlined in Figure 2. Back-up capacity will have different abilities to cycle and operate flexibly depending on individual plant age and type, fuel availability, as well as levels of variable resources in the load (Bouwer et al., 2014). Similarly the ability of mechanisms such as pumped hydro, storage and interconnection to provide flexibility at a given point in time are dependent on factors such as the charging level, the state of reservoirs and the electricity balance in neighbouring countries. Finally, market design and effectiveness play a large role in the ability of a system to access it’s full flexibility potential (Cochran et al., 2014).

In this context, an electricity system’s flexibility needs and ability to fulfil them is highly time and system specific (IEA 2011, Cochran et al., 2014). This makes assessing a country’s flexibility strategy and its sufficiency an incredibly complex endeavour. However, we can distinguish flexibility potential (i.e. the maximum level of flexibility that could be provided under a wellfunctioning systems context) from situational flexibility (IEA 2011). The flexibility potential will be the focus of the thesis going forward, as it is this that policy-makers can realistically plan.

3.2.3 Flexibility planning and strategy

The recent Global Energy Assessment (GEA, 2012) highlights that securing the undisturbed provision of vital energy services, in particularly electricity, has been and will increasingly become one of the key strategic challenges for policy-makers planning the transition towards LCES.

Flexibility planning has been traditionally left to system operators, with policy makers having very little involvement or understanding of the process (Cochran et al., 2014). A good example of this are the National Renewable Energy Action plans of the six countries considered in this thesis (available at European Commission 2016) submitted by each member state under the Renewable Energy Directive (2009/28/EC). These plans, submitted to plan the future towards the European Commission’s 20202020 by 2020 targets, contain no comprehensive concrete targets on flexibility measures, despite the template including explicit questions on planned use of interconnection capacity and storage technologies. While some countries, including Denmark and Germany gave details of planned interconnection capacity expansion projects, commitments on storage capacities were vague across all six plans, while back-up capacity was not even mentioned. Nevertheless, all reports contained specific targets for renewable energy targets up to 2020 (European Commission, 2016). The trends in the National Renewable Energy Action plans is characteristic of flexibility planning in general.

Interconnection capacities are the most thoroughly planned and understood of all the flexibility components, mainly because of their international nature and joint coordination of planning under the European Network of Transmission Operator (ENTSO-E), with ENTSO-E releasing a bi-annual ten-year development plan of prospective interconnection expansion projects (ENTSO-E 2014). The report also includes some details on storage projects, but only those that have been deemed to be of relevance to the wider European system, and back-up capacity is not even mentioned (ENTSO-E 2014). The reliance on transmission system operators is not as big an issue in countries with only one transmission service operator, as is the case in Denmark, Portugal, Ireland and Spain, but becomes a bigger issue in countries with numerous service operators, as in Germany and the U.K. which both have four (ENTSO-E 2016a).

Given the complexity of assessing flexibility needs (see figure x), it is hardly surprising that grid flexibility has remained firmly in the domain of service providers and academia. Real-time flexibility needs assessments necessitate complex models, meaning that while there is a plethora of integration studies examining the optimal level of back-up capacity and storage (Denholm and Hand, 2011; Brouwer, 2015), interconnection and storage (Alexander et al., 2015) or elements of all components (Bertsch et al., 2012; Holttinen et al., 2013; EPRI, 2013).
Nevertheless, there has been a recent push to make flexibility assessments accessible to policymakers, most notably by Cochran et al., (2014), as well as through Yasuda et al.,’s (2013) flexibility charts, which are described further in the methodology section. This shows that there is a need for policymakers to understand and plan flexibility more actively.

In particular, this thesis notes that all of the technical literature takes an exclusively economics-focused approach, with all integration models and pathways adopting a least-cost approach. However, this does not allow for the assessment of non-economic factors, in particular the security of energy supply in choosing the composition of flexibility components within the overall national flexibility strategy. This thesis seeks to redress this gap, by pursuing an assessment of flexibility strategies from an energy security perspective.

### 3.3 Energy security

#### 3.3.1 Conceptions of energy security

Energy security as a concept originally evolved around the security of oil supply in the face of exporter imposed embargos and price manipulations, and were exacerbated by the consequences of the oil crises in the 1970s (Yergin 1991). However, these traditional conceptions of energy security have since expanded to include a wider understanding of modern energy challenges, including expanding the focus onto numerous energy sources, including natural gas supply and nuclear energy (Yergin 2006, Chester 2010). In particular, the past decade has seen an integration of wider energy policy issues, in particular energy policies driven by climate change mitigation needs (Goldthau 2011).

This expansion of what energy security can be understood to mean is so extensive, that Chester (2010) argues that energy security has become a polysemic term, consisting of numerous dimensions and capable of adapting to factors, including, country, timescale, and energy source. Because of this polysemic nature, there is a wide field of discourse surrounding what energy security entails and consequently, how it can be assessed. Though this adaptability of energy security conceptions impedes detailed definitions of what energy security means for all contexts, it actually becomes an asset when attempting to answer the research questions posed by this thesis. The polysemicity underlying energy security, allows it to be easily adapted to focus on the flexibility of LCES. The following section seeks to outline a general understanding of what energy broadly can be conceived to be, and what dimensions can be used to assess energy security in the context of both LCES and flexibility.

As the field of energy security has expanded, so have the myriad definitions of what energy security means (Chester 2010). However, at its core energy security can be connected back to general security theory (Cherp and Jewell 2014). Baldwin (1997) defines security as the “low probability of damage to acquired values” and specifies that any conception of security should answer the following three questions:

- Security for whom?
- Security for which values?
- From what threats?

Jewell et al., (2014) draw on Baldwin’s approach, as a basis for developing a conception of energy security as “low vulnerability of vital energy systems”. This definition has the advantage of not just building directly on Baldwin’s (1997) security definition, but also being easy to adapt and specialise according to the various timeframes, systems and issues being examined. This makes it a suitable conception for adaption to focusing on flexibility in electricity systems. Additionally,
this definition is aligned with the definition used in the recent Global Energy Assessment (Cherp et al., 2012). This conception of energy security also involves (i) the identification of the vital energy system, as well as (ii) the identification of threats and vulnerabilities of the vital system.

3.3.2 Perspectives on assessing energy security

Indicators are used throughout the field of energy security as proxies for system vulnerabilities, and are the most commonly used analytical framework in energy security literature for quantitative comparisons of country strategies (Jewell et al., 2014; IEA, 2011; Le Coq and Paltseva, 2009; Kruyt et al., 2009; Sovacool and Brown, 2010; IEA, 2011a). The dimensions of energy security included in the indicator framework vary depending on the adopted definition of energy security and the dimensions it entails. In reviewing modern energy security assessments, Månsson et al., (2014) find that energy security assessments can be categorised, mainly based on the part of the supply chain (supply of primary energy upstream markets and imports, domestic markets, and infrastructure, and finally economic vulnerability of the energy services market). As this thesis focuses mainly on the flexibility aspect of domestic electricity systems, the approaches taken by the energy security assessments of domestic markets and infrastructure, as well as to some extent by upstream markets and imports, are most relevant. These studies are generally concerned with dimensions that address “reliability, resilience and robustness of infrastructure” (Månsson et al., 2014).

Among the dimensions of energy security, the four A’s of energy security are chosen dimensions on which to study energy security (Cherp and Jewell 2014). The four A’s of energy security (availability, accessibility, affordability and acceptability), were initially introduced by the Asia Pacific Energy Research Centre (APERC 2007), though the two dimensions of availability and accessibility were already at the core of classical energy security conceptualizations, and remain integral to the IEA (2014a) definition of energy security as “the uninterrupted availability. The four A’s structure was taken up and adapted in the wider energy security literature (see for example Kruyt et al., 2009; Sovacool and Brown, 2010) and Chester (2010) adapting this framework into the four “dimensions” of flexibility (availability, adequacy, affordability and sustainability) in her seminal treatise on the conceptualizations of energy.

However, despite being heavily used in the original or augmented forms throughout much of the energy security literature, Cherp and Jewell (2011) criticize the four A’s and related approaches for failing to answer Baldwin’s (1997) three question for assessing security. Instead, Cherp and Jewell (2011) champion the adoption of the three perspectives of energy: sovereignty, resilience and robustness, as the guiding structure for energy security analysis. This structure is specifically adapted to analysing LCES futures in Jewel et al., (2014). This system not only aligns more closely with Baldwin’s (1997) seminal conception of security, but was also adopted in the recent Global Energy Assessment (Cherp et al., 2012).

The three perspectives of energy approach seek to identify system vulnerabilities by answering three guiding questions, closely aligned with Baldwin’s (1997) questions of security:

1. What are the vital systems?
2. What are the system vulnerabilities – i.e. to what extent is the system protected from the risks and uncertainties affecting the vital energy systems?
3. How can these vulnerabilities be quantified? Developing, applying and interpreting indicators that assess how countries address these vulnerabilities?
Jewell et al., (2014) consider vital systems to be those systems “whose failure may disrupt the functioning and stability of a society”. Vulnerabilities are mapped across the three perspectives of energy security: sovereignty, resilience and robustness, as seen in Table 1.

Table 2. Three perspectives on energy security (adapted from Jewell et al., 2014)

<table>
<thead>
<tr>
<th>Perspectives</th>
<th>Sovereignty</th>
<th>Robustness</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key risks and uncertainties for the vital system</td>
<td>Intentional actions by malevolent actors</td>
<td>Predictable natural and technical factors</td>
<td>Diverse and partially unpredictable factors</td>
</tr>
<tr>
<td>Primary protection mechanism</td>
<td>Control over energy systems and institutional arrangements to prevent disruptive actions</td>
<td>Upgrading infrastructure and switching to more abundant resources</td>
<td>Increasing the ability to withstand and recover from various disruption</td>
</tr>
</tbody>
</table>

3.4 Energy security and flexibility

3.5 Energy security and flexibility

This section is both a part of the literature review, but also already seeks to answer the first research question. This is done primarily through literature review, but some elements of qualitative analysis were integrated in the form of insights gained from attending the IRENA Innovation Week 2016 conference.

There has been an increase of interest in the reliability of LCES in the past decade, with numerous studies assessing various security aspects of LCES, including system stability (Kundur et al 2004), system resilience (UKERC 2011) and examining the security of renewable energy supply (Grave et al 2012) or the security of long term transitions to LCES (Jewell et al 2014). However, no study has yet focused specifically on the security of flexibility resources within the wider low-carbon electricity system. Additionally, the majority of the studies focus on creating either abstract framework (Kundur et al 2004) or the security of modelled future electricity systems (UKERC 2011, Grave et al 2012, Jewell et al 2014) rather than providing tools for policy maker to assess the security of flexibility services at a given time in the energy transition. As such, this thesis seeks to fill this research gap by developing a policy tool for the assessment of flexibility within the wider electricity system, to facilitate assessment of security at any point in the transition to low-carbon energy systems.

Jewell et al (2014) consider vital systems to be those systems “whose failure may disrupt the functioning and stability of a society”. In adapting this framework, the flexibility mechanisms are considered to be the vital system, because without them the balancing of the load necessary to consistently meet net demand. While this might initially appear to be an overstatement of the importance of flexibility to national or even national energy security, the ongoing energy transition not only foresees many countries reaching high levels of VRES penetration and therefore overall variability in the electricity sector, but also the electrification of many other end-use sectors, including transportation and buildings. As such, a consistent inability of flexibility mechanisms to balance electricity supply and demand would have wide-reaching impacts on the national economy, making the flexibility mechanisms systems a vital energy system for the 21st century low carbon energy system.
The topics discussed at the first annual IRENA Innovation Week conference (2016) reinforce the growing importance of flexibility provision and its services to policy makers, rather than just transmission systems operators. An entire day of the program was devoted to operational flexibility, with special session on grid design and energy storage being at the heart of programme.

As such, this thesis identifies flexibility as an energy security concern.
4 Methodology

4.1 Method
This thesis adopts a comparative analysis approach, focusing on six case-study countries with high variable renewable energy penetration. The comparative approach was selected in order to make findings more representative and allow for greater generalizability of results.

The research questions were answered using a mixture of methodological approaches, as outlined in Table 1:

<table>
<thead>
<tr>
<th>Research Question</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Why is flexibility an energy security concern? (Section 2)</td>
<td>Literature review and inputs gained from the IRENA 2016 Innovation Week sessions (qualitative)</td>
</tr>
<tr>
<td>(2) How are countries with a high VRES integration addressing their flexibility needs? i.e. what are current best practises in flexibility strategies? (Section 4.1)</td>
<td>Comparative case study approach drawing on the literature review and a quantitative assessment of flexibility data</td>
</tr>
<tr>
<td>3a How can security of flexibility be assessed? (Section 3.5)</td>
<td>Literature review and inputs gained from the IRENA 2016 Innovation Week sessions (qualitative)</td>
</tr>
<tr>
<td>3b. How secure are existing flexibility strategies? (Section 4.2)</td>
<td>Comparative case study approach using a quantitative assessment based on an indicator framework</td>
</tr>
<tr>
<td>3c. What are policy recommendations for ensuring the security of flexibility? (Section 7.4)</td>
<td>Conclusions draw from all of the above</td>
</tr>
</tbody>
</table>

4.2 Flexibility strategy conceptualisation
Because of dearth of consistent and comprehensive flexibility strategy planning highlighted in the previous chapter, this thesis adopts an understanding of flexibility strategies, as strategies that fall under the conceptualisation of strategy as a realized strategy developed by Mintzberg (1987).
Mintzberg argues against the understanding of strategy as a plan – a “deliberate strategy” – which is characterized by being (a) “made in advance” and (b) “developed consciously and purposefully”. Instead, Mintzberg defines strategy as “realised strategy”, which includes not only parts of any deliberate strategy, but instead also the idea of strategy a pattern in a collection of actions and decisions, that together form an “emergent strategy”, which, though not consciously planned, contribute to the final realised strategy. A combination of deliberate and emergent strategies produces the final “realised strategy” (see figure 3). Because of the aim of this thesis and its adopting a comparative case study approach we are interested not so much in the individual countries’ stated flexibility plan, but in the actions they are undertaking to deal with the already high variable renewable energy levels within their energy systems. As such, when addressing flexibility strategy within this thesis, there is always a focus on realised and emergent strategies.

Because of this conceptualisation, a predominantly quantitative approach was chosen, while some qualitative elements were also integrated, in order to allow for triangulation and the development of a more comprehensive and accurate assessment.

4.3 Country selection

In order to draw wider conclusions on potential flexibility strategies that could be relevant for countries pursuing low carbon energy transitions with high levels of VRES, the countries selected need to already be facing significant VRES penetration levels and, therefore, flexibility challenges. As already assessed in the literature review, flexibility becomes a significant issue when VRES penetration levels reach 20-30% of installed electricity capacity or above (Huber et al., 2014). On this basis, only the countries with the highest VRES penetration levels were considered for inclusion in this analysis. Initially, the countries with the highest share of renewables in total energy generation, as listed by REN 21 (2015), were considered. However, as
many of these, such as Costa Rica (90%), Uruguay (84%) and New Zealand (80%), were able to reach high renewable energy shares due to access to abundant hydro and geothermal resources (IRENA 2015), they were not included in the analysis. Instead, the countries with the highest VRES share of total installed electricity capacity were chosen; these are: Germany (39.3%), Denmark (36.7%), Spain (27.9%), Portugal (27.6%), Ireland (23.6) and the United Kingdom (UK) (22.3%).

4.4 Data Collection
Among the qualitative methods included in this thesis, the information gathered throughout attendance at the 2016 IRENA Innovation Week Conference, was used to (a) crystalize problem definition and ensure relevance of the thesis topic to its intended audience and (b) identify relevant decision-makers and data sources, as well as to (c) refine the analytical framework. Based on the identified decision-makers and data sources, a thorough literature review of secondary and primary documents, in particular policies, development plans and press releases was conducted. These were used primarily to help supplement or clarify incomplete or outdated quantitative data, such as in the case of unclear interconnection data for Spain and Portugal. While the inclusion of semi-structured interviews was considered, and would be recommended for inclusion in future/further research, the scope of the thesis, combined with its focus on realised, rather than deliberate strategy, led to their exclusion. The main concern was, that the interviews would contribute overwhelmingly to information about deliberate strategies, rather than provide sufficient supplementary information of realised strategies, which have already been provided by the data available.

While some qualitative methods were integrated into the wider analysis, at its core, this thesis draw on analysis of quantitative data sets, both using statistical analysis, as well as by employing them as inputs into the security indicator framework developed below (see Table 1). As such, data gathering focused on assembling a comprehensive dataset on installed flexibility capacity and electricity capacity, generation and demand for the year 2014/2015, and, in the case of CHP capacity 2013; in order to gain a comprehensive overview of the most current realised flexibility strategies of countries with high variable renewable energy levels.
Data was collected and presented according to the IEA flexibility component definitions: distinguishing interconnection, storage and (flexible) back-up capacity (IEA 2011b). Table 4 below outlines the key data sources:

**Table 4. Key data sources**

<table>
<thead>
<tr>
<th>Data</th>
<th>Data for</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total electricity generation and capacity data</td>
<td>2014</td>
<td>European Network of Transmission System Operators (ENTSO-E) 2015, except for where renewable generation values were incomplete for the UK and were instead sourced from IRENA Resource 2014 and the Digest of UK Energy Statistics (DUKES) database of the National Statistics UK 2015</td>
</tr>
<tr>
<td>Peak demand data</td>
<td>2014</td>
<td>ENTSO-E 2015</td>
</tr>
<tr>
<td>Combined heat and power capacity</td>
<td>2013</td>
<td>Eurostat 2013</td>
</tr>
<tr>
<td>Hydro capacity</td>
<td>2014</td>
<td>IRENA Resource 2016,</td>
</tr>
<tr>
<td>Pumped storage</td>
<td>2014</td>
<td>IRENA Resource 2016,</td>
</tr>
<tr>
<td>Interconnection capacity</td>
<td>2014</td>
<td>Interconnection capacity:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Denmark: Energinet.dk 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Germany: Agora 2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• UK: Ofgem 2016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Spain and Portugal: REE 2015 (2015 data)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ireland: Ofgem 2016</td>
</tr>
<tr>
<td>Electricity trade balances</td>
<td>2015</td>
<td>Frauenhofer ISE 2016</td>
</tr>
<tr>
<td>CCGT</td>
<td>2013, except for Spain (data for 2014)</td>
<td>IEA Electricity statistic 2015, except for:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spain: REE 2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Germany: Umweltamt 2016</td>
</tr>
</tbody>
</table>

### 4.5 Current strategy identification

To categorize countries’ current flexibility strategies, this thesis adopts a two-step process combining:

1. A detailed country profile, and
2. Comparative analysis based on country-specific flexibility charts, as developed by Yasuda et al., (2013).

Following Yasuda et al.,’s (2013) flexibility chart design, this thesis focuses on flexibility capacity in the form of interconnection, storage (pumped hydro) and easily dispatchable back-up capacity (hydro, combined heat and power (CHP) and combined cycle gas turbines (CCGT)). The flexibility chart (Figure x), as well as this thesis, exclude demand side management (DSM) from further consideration, as there is still no reasonable method for estimating DSM capacity (Yasuda et al., 2013) (Cochran et al., 2014).
### 4.5.1 Country Profiles

The individual country flexibility profile was analysed to provide a deeper insight into each individual countries’ installed capacity and usage of flexibility mechanisms. The country profile was structured according to flexibility components outlined in the IEA (2014) GIVAR’s FAST method, which divides the flexibility strategy into the three flexibility components of interconnection, storage, and flexible reserve capacity. The more detailed structure of each country profile is outlined in Table 5:

*Table 5. Country profile structure*

<table>
<thead>
<tr>
<th>Flexibility components</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial overview</td>
<td>1. Installed flexibility capacity portfolio</td>
</tr>
</tbody>
</table>
| Interconnection        | 1. Capacity  
|                        | a. Absolute (GW)  
|                        | b. Percentage of installed generation capacity  
|                        | c. Percentage of peak demand coverage  
|                        | 2. Capacity utilization  
|                        | a. Net importer or exporter  
|                        | b. Size of electricity balance  
|                        | c. Percentage of net generation exported  
|                        | d. Percentage of consumption imported  
|                        | 3. Conclusion on role of IC in overall FS |
| Storage (pumped hydro) | 1. Capacity  
|                        | a. Absolute (GW)  
|                        | b. Percentage of installed generation capacity  
|                        | c. Percentage of peak demand coverage  
|                        | 2. Capacity utilization data (not available)  
|                        | 3. Conclusion on role of storage in overall Flexibility System |
| Back-up capacity (hydro, CHP and CGT) | 1. Capacity (hydro, CHP and CGT)  
|                        | a. Absolute (GW) overall, and technology-specific  
|                        | b. Distribution of back-up capacity amongst technologies |
4.5.2 Comparative analysis of flexibility strategy

This is followed by a comparative analysis of each country’s flexibility charts, which maps the maximum possible penetration ration of each component as a percentage of peak demand.

As figure 4 shows, the flexibility chart was developed specifically for non-technical experts and policy makers to offer an accessible visual overview of a country’s flexibility strengths, and a quick and easy way to compare country performance. The comparison is possible, not only across countries, but also across flexibility mechanisms, because all dimensions, including the VRES penetration level, are mapped using the same metric. The version used by this thesis will be adapted to map all installed variable renewable capacity (wind and solar PV), rather than just wind power capacity, as in the original flexibility chart (Figure 4).

4.6 Comparative flexibility strategy security assessment: Dimensions of flexibility

Based on the findings of the initial flexibility portfolio analysis, as well as the literature review of flexibility and energy security literature, this thesis develops a new analytical framework for assessing and categorising flexibility strategies drawing upon the field of energy security. Unlike past categorisation and assessment methods, which are either highly simplified or technology-based – flexibility charts (Yasuda et al., 2013) – or highly complex and future-focused – integration studies – the new flexibility strategy assessment framework in this thesis seeks to
offer a meso-level approach to flexibility analysis, allowing for the assessment of the security of flexibility strategies.

While flexibility charts will allow for initial strategy categorisation, based on technology distribution, they are not a viable tool to assess the adequacy of a strategy, as they cannot provide a picture of the overall flexibility level (Cochran et al., 2014). This is because, as outlined in the literature review, flexibility is not a static phenomenon, but rather a complex time and system specific quality (Cochran et al., 2014); In this context, when creating flexibility charts, installed capacity is merely a proxy for true flexibility. Additionally, while the charts do map both VRES penetration levels, as well as installed flexibility capacity, they do not allow for assessing the relationship between the two, i.e. the adequacy of the flexibility mechanisms.

It is therefore necessary to bridge the gap between the highly simplified, technology-specific categorisation offered by flexibility charts, which offer no real assessment of the flexibility strategy beyond its make-up, and the highly complex, data-intensive and technical, integration studies, which rely on specific assumptions about current and future power systems and data availability so as to make assessments about adequate flexibility levels. In order to do so, this thesis focuses on the interpretation of flexibility mechanisms as a critical element of the electricity system for countries in the transition to LCES. In effect, by assessing the security that specifically flexibility mechanisms offer the vital electricity system, this thesis seeks to assess the security of a country’s flexibility strategy. In doing so, this thesis adapts the analytical structure developed by Jewell et al., (2014) for the comparative security assessment of low carbon energy scenarios.

Jewell et al.,’s (2014) framework is based on a three step process of:

1. Identifying vital systems
2. Identifying system vulnerabilities
3. Developing, applying and interpreting indicators that assess how countries address these vulnerabilities

Jewell et al., (2014) consider vital systems to be those systems “whose failure may disrupt the functioning and stability of a society”. In adapting this framework, the flexibility mechanisms are considered to be the vital system. While this might initially appear to be an overstatement of the importance of flexibility to national or even national energy security, the ongoing energy transition not only foresees many countries reaching high levels of VRES penetration and therefore overall variability in the electricity sector, but also the electrification of many other end-use sectors, including transportation and buildings. As such, a consistent inability of flexibility mechanisms to balance electricity supply and demand would have wide-reaching impacts on the national economy, making the flexibility mechanisms systems a vital energy system for the 21st century low carbon energy system.

In identifying the system vulnerabilities, this thesis draws on Jewell et al.,’s (2014) perspectives of energy approach, which proposes the use of three perspectives of energy security: Sovereignty, Robustness and Resilience in order to assess a system’s ability to withstand risks and uncertainties.
Table 6. Perspectives of Flexibility Security (adapted from Cherp and Jewell, 2011)

<table>
<thead>
<tr>
<th>Perspectives of Flexibility Security</th>
<th>Sovereignty</th>
<th>Robustness</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulnerabilities identified</td>
<td>Disruptive external shocks to the electricity trading market/ unavailability of exporting or importing capacity to address balancing needs</td>
<td>Predictable variations in balancing needs caused by daily or seasonal weather patterns or generator maintenance</td>
<td>Unpredictable failures in generation due to black-outs or extreme weather events. Unexpected variation in demand</td>
</tr>
<tr>
<td>Protection mechanism</td>
<td>Control over domestic flexibility mechanisms and electricity systems</td>
<td>Upgrade infrastructure and transition to more flexible resources and higher levels of flexibility in the system</td>
<td>Increase the ability of the flexibility mechanisms to adjust for and recover from unexpected variation in electricity and price shocks</td>
</tr>
</tbody>
</table>

These identified vulnerabilities that can be addressed by the flexibility strategy’s influence over the electricity system, as well as the protection mechanisms that could be put in place to ensure flexible energy supply availability are outlined in Table 6, above. These are the basis for the indicator framework to comparatively assess the ability flexibility strategies to protect the electricity system from the identified risks and uncertainties, which is outlined in Table 7. An indicator framework was chosen, as it is the standard approach for comparing quantitative performance across countries, as shown in the literature review section. The following section provides greater detail on the calculation of each indicator, as well as the comparative scoring criteria for each indicator. Following Jewell et al., (2014) indicators for the vulnerability of the flexibility component of electricity systems were selected according to their policy relevance and data availability.

Table 7. Dimensions of Flexibility: Indicators to assess the comparative security of electricity flexibility strategies (adapted from Jewell et al., 2014)

<table>
<thead>
<tr>
<th>Perspective of flexibility</th>
<th>Indicator</th>
<th>Vulnerability/Failure addressed</th>
<th>Unit</th>
<th>Definition (formula)n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td>Electricity trade intensity</td>
<td>Unavailability of flexibility through external electricity markets (Market failure)</td>
<td>Share (0-1)</td>
<td>Electricity trade divided by annual electricity generation</td>
</tr>
<tr>
<td></td>
<td>Import dependency</td>
<td>See above</td>
<td>Share (0-1)</td>
<td>Electricity import divided by net consumption</td>
</tr>
<tr>
<td></td>
<td>Export dependency</td>
<td>See above</td>
<td>Share (0-1)</td>
<td>Electricity export divided by net generation</td>
</tr>
<tr>
<td></td>
<td>Geographic diversity of interconnectors</td>
<td>Exposure to failure of any one external market</td>
<td>Non-dimensional</td>
<td>Shannon-Wiener Diversity index (SWDI)</td>
</tr>
<tr>
<td>Robustness</td>
<td>Potential VRES share of peak load</td>
<td>Potential variability of electricity generation at peak load</td>
<td>%</td>
<td>Installed VRES capacity divided by peak load</td>
</tr>
<tr>
<td></td>
<td>Spare back-up capacity at historic peak demand</td>
<td>Unexpected increase of peak demand</td>
<td>%</td>
<td>peak load divided by installed back-up capacity and subtracted from 1</td>
</tr>
<tr>
<td></td>
<td>Maximum potential flexibility capacity</td>
<td>Failure of VRES to supply sufficient peak</td>
<td>%</td>
<td>Installed flexibility capacity</td>
</tr>
</tbody>
</table>
Indicators are comparatively scored using a traffic light system (red, orange, green) for maximum accessibility, with those countries with the most scoring the best, according to individual scoring criteria receiving a green score, while the worst performers receive a red score. The traffic light scoring system was chosen both for its accessibility, but also because of the relative dearth of information on the performance bands of flexibility security (i.e. what constitutes an objectively good or bad score). As such, the traffic light system, which offers “relative better” versus “worse” scores are chosen.

**Sovereignty indicators**

The sovereignty indicators illustrate to what extent a country’s flexibility strategy protects against the risk of shocks or shortages in the electricity market. This aims to identify the country’s ability to provide flexibility in times when excess electricity may not be available from external sources. While cost-based indicators, such as the cost of electricity imports in relation to GDP or overall flexibility costs were considered, they were excluded from this analysis due to insufficient data availability.

**Electricity trade intensity** is an indicator adapted from the Global energy trade intensity indicator used by Jewel et al., (2014). The original indicator was calculated by dividing global energy trade by global energy supply; scaling this indicator down to the national level and focusing on the flexibility system, electricity trade intensity is calculated by dividing the sum of all electricity imports and exports and dividing it by overall annual electricity generation (i.e. the equivalent of global energy supply). While ideally, the indicator would be divided by annual flexible electricity generation, there is no available data on the overall level of flexibility delivered by pumped storage units. Calculating without this value risks overestimating the level of trade intensity in a way that is inconsistent across countries. As such, overall annual electricity generation is used as a proxy instead, despite the fact that it slightly underestimates electricity trade intensity.

**Scoring:** Energy intensity is scored using the assumption that the lower the intensity the more secure the flexibility strategy from a sovereignty perspective, as the flexibility system is less open to external shocks or market conditions.

**Import dependency and Export dependency** are two indicators adapted from the traditional energy security indicator of net import dependency (Jewell et al., 2014). Because flexibility needs are time specific, using net electricity imports would provide an inaccurate representation of the exposure of countries to risk from external shocks at any given time: if a country has high levels of electricity imports and exports, which are nevertheless fairly balanced, then it would have a very small net import dependency. However, this would not be representative of the fact that it has a far larger dependency on external markets than a country with a smaller, but more unbalanced import and export profile. As such, this thesis splits the indicator into import and export dependency, which are calculated by dividing the total import by annual electricity consumption and exports by annual electricity generation.
Scoring: Both of the dependency criteria are scored using the assumption that the lower the dependency the more secure the flexibility strategy from a sovereignty perspective, as the flexibility system is less open to external shocks or market conditions.

Geographic diversity of interconnectors is adapted from the original geographic diversity of fuel exports indicator, which is calculated using the Shannon Wiener diversity index (SWDI, see below) energy (Jewell et al., 2014). The aim of the indicator is to showcase whether a country’s flexibility strategy protects against an overreliance on any one external electricity source, leaving it unable to access external flexibility in times of shock within that external market.

Scoring: the diversity of interconnectors indicator is scored using the assumption that the higher the diversity, the more secure a system is against failure or shocks of any one interconnector, or connected market.

Robustness indicators

Robustness indicators evaluate a strategy’s ability to cope with predictable natural and technical shocks, for example the mid-term, foreseeable flexibility dips, such as the well-known CAISO duck-curve. In the case of flexibility systems, they evaluate the systems exposure to and ability to cope with routine variability.

Potential VRES share of peak load is a proxy for the level of exposure of an electricity system to variability. While ideally, this indicator would be calculated by analyzing the actual variability share and risk of variance at peak load based on historical time series, this is not possible, as flexibility data is still fairly undeveloped and lacking in granularity. Therefore, this variable is calculated using installed variable renewable energy capacity as a proxy, in effect calculating the maximum penetration level of VRES as if they were to be at full capacity during peak load. This is done by dividing the VRES capacity by peak load.

Scoring: The assumption underlying the scoring of this indicator is that the lower the VRES share of peak load, the higher the flexibility security. While this may be counter to the intention of a LCES, from a flexibility security perspective, the higher the VRES penetration level, the higher the risk of significant fluctuation.

Spare flexible capacity aims to provide an assessment of how well a flexibility strategy could protect an electricity system from unexpected increases in peak demand. Because of the time and situation specific nature of flexibility, it is unsure whether resources, such as storage facilities or interconnection, will be able to provide full flexibility capacity at any given time. Therefore, this indicator focuses on the most reliable flexibility component: back-up capacity, which is more likely to be able to cover flexibility needs at any given time. The indicator is calculated by first identifying the maximal share of installed back-up capacity that would be utilized at historic peak (i.e. maximum utilization share), this share is then subtracted from 1 in order to receive the minimum spare (i.e. historically unutilized) back-up capacity. It is adapted from the energy security indicator of spare capacities for electricity generation, which divides installed capacity by peak or average load. As not all countries exhibit overcapacity, in cases where the score is negative, the indicator defaults to a score of 0%.

Scoring: The assumption underlying the scoring of this indicator is that the higher the spare back-up capacity, the higher the security of flexible electricity supply.

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2 For more information of the CAISO duck curve phenomenon see CAISO 2016
Maximum potential flexibility capacity coverage assessed the maximum percentage of peak demand that could be covered if all flexibility capacity was engaged to its full potential. It is calculated by dividing the sum of all installed flexibility capacity by peak demand.

*Scoring:* this indicator is built on around the understanding that the higher peak coverage can be achieved through flexibility resources, the more secure the overall system. Therefore, the higher the coverage, the higher the score.

**Resilience indicators**

Resilience indicators show how well a flexibility strategy prepares a country for unexpected and unpredictable shocks to its flexibility system, such as unexpectedly high levels of variability due to extreme weather, or generator failures from back-up capacity. While the development of a flexibility intensity indicator, based on the traditional energy intensity indicator used in energy security indicator frameworks was considered, the lack of granular data about flexibility usage led to its exclusion from the framework.

*Diversity of flexibility sources* is an indicator adapted from the traditional indicator of diversity of energy sources in primary energy sources in carriers, which is calculated using the SWDI (see below) (Jewellet al., 2014). It assesses to what extent the flexibility strategy provides resilience in case one or more flexibility mechanisms fail.

*Scoring:* the diversity of flexibility mechanisms indicator is scored using the assumption that the higher the diversity, the more secure a system is against failure or shocks of any one mechanism.

**Calculating diversity indices:**

Diversity indicators allow for quantitative assessments of system resilience. According to Stirling (1988), an index of energy diversity should consider three aspects of the source mix: variety (how many types of resources are present), balance (relative sizes of each source), and disparity (to what extent is one type different from each other). However, Kruyt et al., (2009) argues that disparity is prohibitively hard to quantify, as such all commonly used diversity indices only account for variety and balance.

This thesis uses a Shannon-Wiener Diversity Index (SWDI) to calculate non-dimensional diversity indicator scores. Diversity indices were first utilized in an energy security context by Stirling (1994) to quantify the diversity of sources in an electricity system. This thesis follows Stirling (1988) and Jewell et al., (2014) in selecting a SWDI over another frequently used measure of diversity for low-carbon electricity systems (Jewell2011, Grubb et al., 2006), the Herfindahl-Hirschman index. While diversity indices have not yet been used to measure flexibility systems, this thesis argues that they are adaptable to flexibility systems, as these are in fact functioning vital energy systems. The SWDI is calculate using the formula below:

\[
SWDI = \Sigma_i (p_i \ln(p_i))
\]

With \(p_i\) being the share of the respective source \(i\).
This thesis considers two diversity indicators:

(a) The geographic diversity of interconnections, where the $p_i$ represents the relative share of overall annual import and exports made up by imports and exports exchanged with country $i$.

(b) The diversity of flexibility sources (i.e. flexibility technologies), where $p_i$ represents the relative share of overall installed flexibility capacity made up by installed flexibility capacity from technology $i$ (interconnection, pumped-hydro storage, hydro capacity, CHP capacity and CCGT capacity)
5 Flexibility strategies: a comparative case study analysis

5.1 Country profiles

5.1.1 Denmark

As Figure 5 shows, the Danish flexibility profile is dominated by interconnection, closely followed by flexible reserve capacity, in the form of combined heat and power plants. Combined cycle gas turbines also play a minor role in terms of installed capacity, while hydro, and storage, in the form of pumped hydro, play no role at all in the flexibility capacity mix.

5.1.1.1 Interconnection

The Danish electricity system is highly interconnected, with an interconnection capacity of almost 6GW, equivalent to 39% of installed generation capacity. This allows for up to 97% of peak demand (ENTSO-E, 2014 peak demand data) to be covered by electricity import, if necessary.

Looking at the utilization of Danish interconnection capacity, Figure 2 shows that in 2015, Denmark was a net importer of electricity; importing almost 57% of its electricity usage in 2014; conversely, they exported ca. 30% of net generation in the same year (own calculations, based on...
data from Frauenhofer ISE 2016 and ENSTO-E 2016). This demonstrates that the Danish flexibility strategy is heavily reliant on interconnection; there is not just a high level of IC capacity, but also a high share of consumption and generation in the IC market.

5.1.1.2 Storage

Denmark does not possess any pumped hydro resources (IRENA 2015), and as such, is unable to pursue a flexibility strategy involving the building of traditional pumped hydro storage capacity.

5.1.1.3 Back-up capacity

Germany benefits from almost 7GW of installed dispatchable capacity, ca. 46% of installed generation capacity. This would allow it to cover overall peak demand (116% of peak demand), making dispatchable resources, and, particularly CHP, a core pillar of Denmark’s flexibility strategy.

Denmark has an incredibly large share of CHP generation, which makes up almost 40% of overall installed generation and could potentially cover up to 98% of its peak demand, (2014 peak demand figures from 2014, ENTSO-E 2015).

Although, it should be noted that not all of Denmark’s CHP capacity allows for easy dispatch and ramping due to the varying ages of CHP plants, as well as the need to expand the underlying communications infrastructure necessary to make CHP resources fully flexible (Yasuda et al., 2013).

However, outside of CHP plants, the country has only ca. 1 GW of installed CCGT capacity, as of 2013 (IEA 2015), which amounted to only about 7% of installed generation capacity in 2014 (own calculation). Furthermore, Denmark does not possess significant hydroelectric resources, boasting only 8.4 MW of installed small hydro resources.

Finally, the flexibly dispatchable capacity to peak demand ratio for 2014, shows that peak demand can be covered by just 63% of dispatchable generating capacity, leaving a minimum of 37% of back-up capacity unutilized, even at peak capacity. This is a sign that there is a significant potential for back-up and reserve capacity built into the Danish electricity system, and a sign of potential overcapacity in the Danish system.
5.1.2 Germany

The German flexibility capacity profile is very diversified, with all examined dimensions included in the capacity mix. Flexible fossil fuel generation dominates the flexibility capacity mix, with over 50%, followed by interconnection. However, both hydro and pumped hydro seem to also play a role in providing system flexibility.

5.1.2.1 Interconnection

The German electricity system is the most diversely interconnected of all examined systems, connecting into nine neighbouring systems. However, the overall interconnection level is not the highest of the examined countries, as it currently only has 21GW installed IC capacity, equivalent to 11% of installed generation capacity. This allows for up to 26% of peak demand (ENTSO-E 2014 peak demand data) to be covered by electricity imports, as and when needed.

Examining the utilization of IC capacity, Figure 3 shows that Germany is a significant net exporter of electricity, exporting 16% of net generation in 2014, creating an electricity balance of – 55 TWh with its neighboring countries. Electricity imports on the other hand accounted for less than 7% of consumption in 2014 (own calculations, based on data from Frauenhofer ISE 2016 and ENSTO-E 2016).
Although interconnection does not dominate Germany’s flexibility strategy, covering at most just 26% of peak demand and being equivalent to 11% of installed generation capacity, it is nevertheless a flexibility dimension that is vital to allowing high VRES penetration in the German market. This is particularly the case when it comes to preventing VRES spillage and curtailment, which has contributed greatly to Germany’s increasingly unbalanced electricity trade position, as a significant net exporter.

5.1.2.2 Storage
Germany has 6.8 GW of installed pumped hydro capacity, equivalent to 3.6% of net generating capacity. This allows for a maximum contribution of 8% of peak demand from conventional hydro storage, under ideal circumstances. As such, storage is currently a part of the German flexibility strategy, but does not define it.
5.1.2.3 Back-up capacity

Germany benefits from a high level – 44.7 GW – of installed back-up capacity, with, in particular CHP (27.3 GW) and CCGT (13 GW) taking a prominent role in contributing flexibility to its power system.

This installed capacity in hydro, CHP and CCGT made up almost 24 % of net generation capacity in 2014, allowing for a potential coverage of 54.66% of peak demand through dispatchable resources. CHP resources make up 14% of installed generation capacity and could cover up to 33% of peak demand.

When it comes to capacity sufficiency, the flexibly dispatchable capacity to peak demand ratio for 2014, shows that peak demand can be covered by 71% of dispatchable generating capacity, leaving a minimum of 29% of back-up capacity unutilized, even at peak load. This shows a high level of buffer flexibility in the system, but might also be a sign of overcapacity.

5.1.3 UK

The UK flexibility capacity profile is dominated by CCGT, which accounts for almost three-quarters of installed flexibility capacity. Nevertheless, the UK can also draw on all other forms of flexibility, including interconnection and pumped storage. However, flexible fossil generation (CHP and CCGT plants) makes up the vast majority of installed flexibility capacity.

5.1.3.1 Interconnection

The UK has only limited interconnection, with 4 GW installed connecting it to France, the Netherlands and Ireland (Ofgem 2016). This is equivalent to only 5% of NGC and allows for a maximum coverage of 6.7% of peak demand through imports (own calculations based on data from Ofgem 2016 and ENTSO-E 2015).
As the electricity exchange data for 2015 shows (Figure 12), the UK is highly reliant on imports from France and the Netherlands to balance its load, with the exchange capacity being used almost exclusively to import electricity from continental Europe. This has caused a significant negative electricity balance of 22 TWh. In 2014, the UK exported only 0.6% of net generation, but imported almost 8% of electricity consumption. The 500MW connection with Ireland is the only interconnector, which shows a reasonable balanced electricity flow.

While the overall interconnection capacity of the UK is currently very limited, the high reliance on electricity imports from the mainland European system, via France and the Netherlands, indicates that interconnection, while not the dominant flexibility measure, is nevertheless a core aspect of the current UK flexibility strategy.

5.1.3.2 Storage
While the UK does have access to 2.7 GW of installed pumped-hydro storage (Ofgem 2016), which is equivalent to 3% of installed NGC (own calculations, data from Ofgem 2016 and ENTSO-E 2015), storage is not currently a major pillar of the UK flexibility strategy. The installed capacity would allow for a maximum coverage of less than 5% of peak demand. Nevertheless, storage plays a role in smoothing the electricity demand spikes (Ofgem 2015).
5.1.3.3 Back-up capacity

The UK can draw on almost 51 GW of easily dispatchable capacity (calculated based on data from IRENA 2015, IEA 2015 and Eurostat 2014) and has particularly large CCGT capacities – almost 43 GW (IEA 2015) supporting flexible generation in the UK grid. Overall flexible capacity accounted for more than 61% of net generation capacity in 2014 (calculated based on data from (ENTSO-E 2015, IRENA 2015, IEA 2015 and Eurostat 2014). This would allow for a coverage of almost 85% of peak demand.

The majority of this flexible capacity comes from CCGT plants - 43 GW (IEA 2015).

CCGT plants account for almost 52% of installed generation capacity, compared to 7.5% from CHP and only 2% from hydro resources. This allows for CCGT plants to cover up to 71.5% of peak demand, while CHP (10.5% of peak demand) and hydro (3% of peak demand) can add only limited flexibility into the grid.

Looking at the sufficiency of back-up capacity, the flexibly dispatchable capacity to peak demand ratio for 2014, shows that peak demand can be covered by activating 93% of dispatchable generating capacity, leaving a minimum buffer of 7% of unutilized back-up capacity. This is a comparatively slim margin, compared to all other examined countries and might be a sign that flexible reserve capacity needs to be expanded if it is to continue to take the prominent role it currently plays in the UK’s flexibility strategy.

5.1.4 Spain

The Spanish flexibility capacity profile is dominated by CCGT capacity, and flexible fossil fuel generation (CHP and CCGT) make up just over half of installed capacity. Flexible hydro-power
makes up the second largest fraction of installed capacity, while limited interconnection and pumped storage capacity allow for access to a more diversified flexibility mix.

### 5.1.4.1 Interconnection

Spain, and in fact the entire Iberian Peninsula, have historically been highly isolated, with the interconnections to France providing the sole connection to the wider European grid. This isolation is mainly due to the geographic barrier of the Pyrenees, which make interconnection very costly, creating a virtual electricity island. Up until the expansion of interconnection capacity between France and Spain in 2015, the grid only had an interconnection capacity of 1.4 GW to the European grid for 30 years (REE 2012).

Since the opening of a new interconnection between Spain and France in October 2015, interconnection capacity has increased from 1.4 GW to 2 GW (ICIS 2016), bringing the country’s overall interconnection capacity up to 4.9 GW. However, the new interconnector was set to increase capacity by an additional 800 MW, but delays in installing the necessary phase-shifting transformer mean this additional capacity will not be available until 2017 (ICIS 2016).

Similarly, new interconnections originally set to be completed in 2015 between Spain and Portugal, were planned to increase the Iberian interconnection by 1 GW, to a total of 3 GW (REE 2012). However, these projects were excluded from the current situation analysis, as project completion has been delayed to 2016 (ENTSO-E 2014). Outside of the European grid, Spain also has limited exchange capacity with Morocco through two submarine cables, which provide a maximum capacity of ca.800 MW (REE 2012). It is currently the only existing operational interconnector between the European and the North African grid.

The country’s overall IC capacity of 4.9 GW is equivalent to 4.6% of installed generation capacity and allows for imports to cover less than 13% of peak demand.

As Figure 15 shows, Spain is a net exporter of electricity, though the electricity balance is very small at only 150 GWh, demonstrating a very balanced import and export system. This is particularly the case with the shared interconnections with the Portuguese system, as the two countries are interconnected to the extent that they have created a joint electricity market for the Iberian Peninsula, known as the MIBEL market. (REE 2012). This balance is also apparent in

![Spanish Electricity Balance 2015 (TWh)](image-url)
the fact that Spain exported only 5.7% of net generation, while importing 5.8% of consumption in 2014.

Despite recent interconnector expansions, the Iberian Peninsula, and Spain in particular, remains very isolated, limiting the role interconnection can play in the countries flexibility strategy.

### 5.1.4.2 Storage

Spain has access to fairly large hydro resources (see below in Figure 16). However, only a third of these have been adapted to provide pumped storage (own calculation, based on data from IRENA 2015). Nevertheless, Spain boasts 5.4 GW of installed pumped storage capacity, which, while only comprising 5% of installed generation capacity, could provide 14% of peak demand. As such, while storage does not make up a large portion of installed capacity, it still provides important flexibility services to the Iberian Peninsula electricity market, and has the potential to be expanded significantly.

### 5.1.4.3 Back-up capacity

![Back-up capacity breakdown](image)

Spain, alongside Portugal, has the largest level of flexible capacity when compared to peak demand; its 45 GW of dispatchable capacity can cover 117% of peak demand, despite only accounting for less than 43% of generation capacity.

CCGT provides the majority of this flexible capacity with 27 GW and could cover 70% of peak demand. However, hydro also contributed ca. 15 GW to overall generation capacity and could cover almost 40% of peak demand in 2014. CHP

Spain exhibits the lowest flexibly dispatchable capacity to peak demand ratio for 2014, with peak demand being coverable by just 50% of dispatchable generating capacity. As this leaves at least half of all installed flexible generation capacity unutilized, this is a sign of the significant overcapacity that the Spanish system is currently exhibiting (Deloitte 2015, REE 2012). This reinforces the need for interconnection, as a way to balance out potential overproduction, without risking making flexible fossil fuel generation capacity such as CCGT and CHP unprofitable due to low load rates.
5.1.5 Portugal

The Portuguese flexibility capacity profile is highly diversified; Flexible generation capacity, both fossil fuel and renewable, dominates the strategy, accounting for almost three quarters of installed flexibility capacity. Hydro has the highest level of installed capacity, closely followed by CCGT. However, both interconnection and storage account for 15% and 11% of installed flexibility capacity respectively.

5.1.5.1 Interconnection

While the Portuguese grid might appear to be, along with the Irish grid, the most isolated of all examined power systems, with its only interconnection capacity of 2 GW being with Spain (REE 2012), the comparatively small size of the Portuguese electricity system, this 2GW capacity is equivalent to 11% of generating capacity, and could therefore potentially cover 24% of peak demand.

Additionally, as Figure 18 shows, this interconnection capacity allows for a fairly balanced electricity balance within the MIBEL market. Portugal has a slightly higher electricity balance of 2.3 GW, making it a net importer. In 2014 it imported 7% of consumption, while exporting 4.3% of annual electricity generation.

Overall, interconnection is important to the Portuguese system, in the sense that it allows for the unified MIBEL market. But in comparison to Portugal’s flexible resources, in particular its hydro power, interconnection is not a key pillar of the Portuguese flexibility strategy.
5.1.5.2 Storage
Portugal has the largest relative storage share of all countries studied, with its 1.4 GW of pumped storage accounting for 8% of total generation capacity. Like its partner in the MIBEL electricity market, Spain, Portugal also benefits from the ability to expand its pumped storage capacity, as only a third of all hydro capacity is currently adapted to offer storage. While storage does not dominate the Portuguese flexibility strategy, it does provide the highest peak demand coverage of all studies countries, and would have been able to deliver up to 17% of peak demand in 2014.

5.1.5.3 Back-up capacity

The Portuguese flexible capacity is jointly dominated by hydro (4.3 GW) and CCGT (4 GW), with the former accounting for 24% and the latter from 22% of installed generation. This allows hydro and CCGT to cover up to 52% and 48% of peak demand respectively.

Overall flexible capacity accounts for 54% of generation capacity with 9.7 GW and, as in Spain, could cover up to 117% of peak demand.

The Portuguese easily dispatchable capacity to peak demand ratio for 2014, shows that 64% of dispatchable generating capacity can cover peak demand, leaving a minimum of 36% of back-up capacity unutilized.

5.1.6 Ireland

The Irish flexibility capacity profile is dominated by flexible fossil fuel generation, which makes up almost three quarters of installed flexibility capacity, with in particular CCGT making up 64% of capacity. However, all other flexibility dimensions are represented in the flexibility capacity mix, providing some potential for diversity of flexibility supply.
5.1.6.1 Interconnection

The Irish grid is the most isolated of all countries analysed in this thesis. It has only 500 MW of interconnection capacity with the UK, which could only cover 11% of peak demand, and is equivalent to only 5.5% of generation capacity. Figure 21 shows that Ireland is a net electricity importer and that it managed to retain a very low electricity balance of only 800GWh in 2015.

![Figure 21. Irish Electricity Balance 2015 (TWh)](image)

Overall, the limited and undiversified nature of the Irish interconnection, shows that interconnection is not a significant dimension of the current Irish flexibility strategy.

5.1.6.2 Storage

Ireland has the lowest absolute amount of pumped storage capacity, with only 300MW accounting for 3% of generation capacity. Nevertheless, this would still be able to cover up to 6% of peak demand. Storage is currently not a significant aspect of the Irish flexibility strategy, and cannot be easily expanded, as all installed hydro capacity in the country has already been storage enabled.

5.1.6.3 Back-up capacity

Flexible back-up capacity is the single most important flexibility resource for the Irish power system, making up 80% of all examined flexibility capacities. Still, flexible back-up capacity—with 3 GW only accounts for 32% of overall generation capacity, but is able to cover up to 65% of peak demand.

Within flexible capacity, CCGT is the dominant technology in the Irish power system, providing up to 53% of peak demand, thanks to 2.4 GW of installed capacity, ca. 26.5% of overall generation capacity.

Examination of capacity sufficiency, the Irish flexibly dispatchable capacity to peak demand ratio for 2014, shows that peak demand can be covered by 65% of dispatchable generating capacity, leaving a minimum of 35% of back-up capacity unutilized, even at peak demand.
5.2 Comparative flexibility strategy analysis

This next section compares the case study countries’ flexibility strategies through comparing their flexibility charts. On the basis of these findings, some trends in flexibility strategy are identified.

Figure 21 shows that strategies across the six countries are fairly diverse, though the Spanish and Portuguese strategies share similarities, while the UK and Irish strategies are almost identical in design. The UK and Ireland have the most similar strategies, both focusing almost exclusively on CCGT-based reserve capacity. A factor for this could be the relatively isolated nature of both islands. Portugal and Spain also share fairly similar strategies, both focusing on CCGT and hydro power. This similarity is unsurprising, as the countries have strongly interconnected electricity systems, and even share the MIBEL energy market (REE 2012). Finally, Denmark and Germany, while both pursuing a reserve capacity and interconnection focused strategy, shape these strategies in very different ways: Germany exhibits the most diverse strategy while ostensibly CHP and interconnection focused. Germany’s strategy could also be described as a mixed strategy, as all three components of flexibility make-up significant portions of the strategy. Meanwhile, Denmark’s strategy is a lot less diverse than Germany’s and is almost completely split between interconnection and CHP.

Looking at interconnection capacity, Figure 21 shows that it is a significant flexibility component for Germany and Denmark, the countries with the high VRES penetration levels, as well as for Portugal, which exhibits medium levels of VRES penetration. Meanwhile, those countries exhibiting low VRES penetration also exhibit lower interconnection levels in their flexibility strategy. As such, we can conclude that the countries with higher VRES penetration tend to prioritise interconnection in their flexibility strategies.

Storage does not currently appear to be a strong factor for any assessed country’s flexibility strategy, as shown in Figure 21. However, this is likely more a factor of the relatively underdeveloped nature of storage technologies, and the fact that because of this, the flexibility chart only assesses pumped storage, as the only mature storage technology with enough data available. Because pumped-storage is dependent on a country’s geographically determined hydro resources, only countries with higher levels of installed hydro can consider this mechanism. However, it should be noted that even countries with relatively large hydro resources, Portugal and Spain, have not significantly developed their pumped-storage capacity.

Reserve capacity remains the dominant flexibility component of all examined countries’ flexibility strategies. This is likely due to back-up, thermal generation being the traditional form of flexibility throughout the 20th Century, allowing countries to benefit from existing flexibility infrastructure. However, it should be noted that countries with the highest VRES penetration levels show signs of diversifying their flexibility strategy away from a pure-back-up capacity approach. When it comes to technological preferences, there is a preference for CCGT over CHP and a trend across all countries to choose to either rely on flexibility from CCGT or CH, rather than adopting a mixed technology approach.

In terms of the level of potential peak coverage for each of these countries, there does not seem to be a clear trend with increasing VRES penetration. While Denmark does exhibit the highest potential for interconnection and back-up capacity to cover peak demand, both above 90% coverage, Germany, which has the second highest VRES penetration cannot cover more than 40% of peak demand through any one individual technology.
Jennifer Tollmann, IIIEE, Lund University

Interconnection and reserve capacity focused (CHP and IC)

Reserve capacity – focused (CCGT and hydro)

Reserve capacity and Interconnection-focuses (CHP and IC)

Reserve capacity – focused (CCGT and hydro)

Reserve capacity- focused (CCGT)

Reserve capacity- focused (CCGT)

Figure 23: Flexibility charts for Denmark, Germany, the UK, Spain, Portugal and Ireland (Data sources: ENTSO-E 2015, IRENA RESsource 2016, Eurostat 2013, Energinet.dk 2014, Agora 2015, Ofgem 2016, REE 2015, Ofgem 2016, IEA 2015, Umweltamt 2016.)
Additionally, there is a trend of increased diversification of dominant mechanisms, as VRES penetration increases: the UK and Ireland, which exhibit the lowest VRES penetration level, each falling below 50%, exhibit flexibility strategies dominated by one flexibility component: reserve capacity, which is in turn provided almost exclusively by one technology: CCGT. Meanwhile, the countries with medium VRES penetration between 50% and 80%, exhibit a slightly more diverse flexibility strategy, with flexibility provided by both CCGT and hydro power. While this still represents a reserve capacity focused strategy, as seen with the UK and Ireland, it is less one-sided. Finally, Germany and Denmark, the countries with the highest VRES penetration levels, demonstrate the greatest diversity of dominant mechanisms, with both countries building their flexibility strategies on the dual pillars of interconnection and reserve capacity, in the form of CHP. However, it should be noted that this trend might have less to do with VRES penetration levels than with the similarity of the respective country’s markets and electricity system.

In conclusion, it is possible to make the following statements about trends in flexibility strategies exhibited by the countries analysed:

- Flexibility strategies are still dominated by reliance on back-up capacity, with most countries relying on either CHP or CCGT to provide flexibility.
- Storage is not yet a significant component of any country’s flexibility strategy, though this may change as more storage technologies reach technical maturity.
- Interconnection penetration is highest in the countries with the highest VRES penetration. This suggests that interconnection is likely to play an increasingly important role in flexibility strategies as VRES levels rise.
- Finally, there is a trend to diversify the dominant flexibility components with rising VRES share, with both Germany and Denmark demonstrating a fairly balanced split between interconnection and back-up capacity penetration.
6 Comparative flexibility strategy security assessment

This section will contain a comparative analysis of the security of the flexibility strategies exhibited by the six case study countries: Denmark, Germany, United Kingdom, Spain, Portugal and Ireland. The analysis will be conducted using the “dimensions of flexibility” indicator framework developed in the methodology section.

6.1 Sovereignty

6.1.1 Electricity trade intensity

![Figure 24. Electricity trade intensity comparison (Data sources: ENTSO-E 2015, National Statistics UK, 2015; and Frauenhofer ISE, 2016)](image)

As figure 24 shows, Denmark exhibits by far the highest electricity trade intensity, with more than triple the electricity intensity of the next most intensive trader, Portugal. The lowest trade intensity is exhibited by the UK, which only displays an 8% trade intensity. Figure 3 demonstrates three categories of electricity intensity: (1) the extremely trade dependent strategy, exhibited by Denmark, (2) the moderately trade-reliant strategy, exhibited by Portugal, and to a certain extent by Germany and finally (3) the domestic-focused strategy, which is characterized by low electricity trade intensity, exhibited by Ireland, Spain and the UK.

**Scoring:** Denmark scores the lowest in this indicator, having the highest electricity trade intensity. Germany and Portugal score in the middle range, having comparatively high levels of electricity intensity, while the UK, Spain and Ireland exhibit the highest security scores in this category.
6.1.2 Import and export dependency

As in the previous indicator, figure 25 shows that Denmark exhibits disproportionately high import and export dependency, with a particularly high import dependency. Germany is the sole country to exhibit a higher export than import dependency, which is indicative of the need to prevent curtailment of expanding VRES electricity through exporting to neighbouring electricity markets. The UK shows an almost exclusive import dependency, while Denmark and Portugal also show a greater reliance on imports than exports. Finally, Spain and Ireland are not only two of the least trade-dependent countries, but also exhibit the most balanced trade dependency.

**Scoring:** The UK, Spain and Ireland score the highest, having both the lowest export and import dependency. Germany scores highly in import dependency, but scores in the middle range on Export dependency, while Portugal scores in the middle range for both indicators. Denmark’s flexibility strategy again scores as the least secure with low scores in both categories.
6.1.3 Geographic diversity of interconnectors

As Figure 5 shows, Germany exhibits almost double the interconnection diversity of any other country, with a SWDI score of 0.9, while both Portugal and Ireland do not benefit from any interconnection diversity to protect them from external shocks, as they are both connected to only one country each, Spain and the UK respectively. The rest of the examined countries can be grouped into a moderate diversity category, with scores between 0.4 and .5.

**Scoring:** Germany is the only country to be awarded a high score in this indicator, while the UK, Spain and Denmark receive midrange scores. Meanwhile Portugal and Ireland both receive the lowest security score for lacking any interconnector diversity.
6.2 Robustness

6.2.1 Potential VRES share of peak load

As figure 27 shows, Denmark and Germany exhibit the highest potential VRES share of peak load, while Spain and Portugal exhibit relatively lower penetration levels. The UK and Ireland are most secure in this dimension, as they have the lowest VRES penetration levels and are, therefore, exposed to the lowest risk of variability in their electricity supply at peak load.

**Scoring:** The UK and Ireland score the highest, while Spain and Portugal score in the middle range. Germany and Denmark are assigned the lowest scores, as their high VRES penetrations cores expose them to potentially higher variability risks.

*Figure 27. Maximum potential VRES share of peak demand (Data Source: ENTSO-E, 2015)*
6.2.2 Maximum spare back-up capacity at historic peak demand

![Graph showing spare back-up capacity at peak demand for different countries.]

Figure 28. Minimum spare back-up capacity at peak demand (Data source: ENTSO-E 2015, IRENA REsource 2016, Eurostat 2013, RED 2015, IEA 2015, Umweltamt 2016)

As shown in figure x, Denmark, Spain and Portugal exhibit the highest level of spare back-up capacity, while Germany, the UK and Ireland are not able to guarantee a minimum level of spare back-up capacity at the current peak load levels.

Scoring: Denmark, Spain and Portugal are all awarded the higher scores, due to being able to provide a minimum level of spare back-up capacity at peak level, while the rest of the countries are given the lowest score. No medium score was awarded.

6.2.3 Maximum potential flexibility capacity coverage

![Graph showing maximum potential flexibility capacity peak coverage for different countries.]

In figure x, Denmark exhibits the greatest ability to secure flexibility need by being able to cover more than double the critical demand at maximum flexibility potential. Meanwhile, Spain and Portugal are also both able to cover significantly more than critical load at maximum flexibility potential. However, the German, the UK, and Irish strategies fail to ensure full full-peak load coverage through flexibility resources, therefore demonstrating the comparatively poorest flexibility robustness in this criteria.

**Scoring:** Denmark achieves the highest score, while Spain and Portugal both receive the medium score. However, Germany, the UK and Ireland are awarded the lowest score, for comparatively low flexibility security in this category.

### 6.3 Resilience

#### 6.3.1 Diversity of flexibility sources

![Diversity of flexibility capacity](chart.png)


Contrary to the interconnection diversity indicator, Figure 6 shows that when it comes to diversification of flexibility sources, all countries have pursued at least some level of diversification. Portugal and Germany can draw on the most diverse flexibility portfolio, with a diversity score of over 1.4; while the Danish and the UK score the lowest diversity ratings of under 1. Meanwhile, Ireland and Spain also score comparatively highly with scores between 1 and 1.3.

**Scoring:** Germany and Portugal are awarded the highest security score in the resilience category, while Spain and Ireland receive scores in the mid-range. The UK and Denmark receive the lowest security scores, for their lack of diversified flexibility portfolios.
6.4 Summary

Table 8. Comparing security scores across the three dimensions of security

<table>
<thead>
<tr>
<th>Perspective</th>
<th>DK</th>
<th>DE</th>
<th>UK</th>
<th>ES</th>
<th>PT</th>
<th>IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td>Red</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>Robustness</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>Resilience</td>
<td>Red</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
</tbody>
</table>

Overall, Table 8 allows for a comparative ranking of the security of the six examined countries’ flexibility strategy: Denmark’s strategy shows the poorest performance, followed by the UK. The fact that both the country with the highest and lowest VRES penetration levels for peak demand, shows that security is not necessarily simply determined by the stage in the transition to low-carbon energy systems. Germany and Ireland rank in the middle, while Spain and Portugal exhibit the comparatively most secure flexibility strategies.

Table 9. Scoring the security of countries’ flexibility strategy across the dimensions of flexibility indicator framework

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Indicator</th>
<th>DK</th>
<th>DE</th>
<th>UK</th>
<th>ES</th>
<th>PT</th>
<th>IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td>Electricity trade intensity</td>
<td>92%</td>
<td>22%</td>
<td>8%</td>
<td>11%</td>
<td>28%</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>Import dependency</td>
<td>57%</td>
<td>7%</td>
<td>8%</td>
<td>6%</td>
<td>17%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>Export dependency</td>
<td>31%</td>
<td>16%</td>
<td>1%</td>
<td>6%</td>
<td>-12%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Geographic diversity of interconnectors</td>
<td>0.47</td>
<td>0.90</td>
<td>0.40</td>
<td>0.44</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Robustness</td>
<td>Potential VRES share of peak load</td>
<td>92%</td>
<td>91%</td>
<td>31%</td>
<td>77%</td>
<td>60%</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>Spare back-up capacity at historic peak demand</td>
<td>14%</td>
<td>0%</td>
<td>0%</td>
<td>15%</td>
<td>15%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Maximum potential flexibility capacity coverage</td>
<td>213%</td>
<td>89%</td>
<td>96%</td>
<td>144%</td>
<td>158%</td>
<td>82%</td>
</tr>
<tr>
<td>Resilience</td>
<td>Diversity of flexibility sources</td>
<td>0.93</td>
<td>1.43</td>
<td>0.89</td>
<td>1.31</td>
<td>1.49</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Denmark’s flexibility strategy is comparatively the least secure of all assessed strategies, as it performs poorly from both a sovereignty and a resilience perspective. It particularly suffers from a high level of dependency on external markets, as well as a general lack of diversification across all flexibility sources, leaving its system open to failures from external markets. However, it scores very high in the robustness dimension, which mitigates its poor performance on sovereignty, as the internal flexibility mechanisms are likely to be able to deal with external market failures. Nevertheless, the country flexibility strategy’s poor performance on resilience should be addressed in future flexibility planning.

Germany’s flexibility strategy exhibits very mixed scores across the three perspectives. It scores in the mid-to-high range on sovereignty, as well as receiving one of the highest scores in the resilience perspective. This means that the German flexibility strategy protects its electricity system comparatively well from external shocks or shortages, while its internal flexibility systems are diversified enough to protect against a failure of any one particular flexibility mechanism. However, the poor score on the robustness perspective shows that while the German flexibility strategy protects well against external shocks, and that what
flexibility resources they do have are well diversified, they have not developed comparatively sufficient flexibility systems in order to be able to address internal flexibility issues. The robustness of the internal flexibility mechanisms would therefore need to be further addressed in future flexibility strategies.

The UK’s flexibility strategy produces the least consistent scores across the three flexibility security perspective and overall, ranks as the second weakest of all strategies across the three perspectives. It does exhibit comparatively high levels of flexibility sovereignty, protecting the electricity system from external shocks, but nevertheless, has a comparatively weak diversification of the interconnectors it does use. Furthermore, the overall robustness of the flexibility strategy is comparatively weaker, with the UK strategy not providing any spare flexible back-up capacity, and not being able to fully cover peak demand at maximum flexibility potential. Finally, the UK resilience score is the weakest of all analysed systems. As such, the UK needs to seriously examine its overall flexibility system. While it may not be comparatively dependent on external markets, the fact that its own internal flexibility system lacks comparative robustness and resilience is a matter that should be addressed going forward if further VRES integration is to not jeopardize flexibility security.

Spain has the most secure flexibility examined in this thesis, with high scores in both sovereignty and system robustness. The only real weakness of its flexibility strategy is the comparatively middling diversification of both interconnectors and flexibility mechanisms overall. Nevertheless, the Spanish flexibility strategy seems to offer comparatively strong protection against all identified risks of VRES integration.

Similar to Spain, Portugal also enjoys the second most secure flexibility strategy examined in this section, with high scores in both robustness and resilience. Its only weakness is its total dependency on its neighbour Spain for external flexibility. However, given the high robustness scores for the Spanish system, this is unlikely to be a significant security concern.

Ireland’s flexibility strategy affords it only a comparatively middling level of security. While it scores highly in the sovereignty perspective, despite having no diversity of interconnections, it performs less well in both the resilience and robustness perspectives. Similar to the UK, Ireland’s flexibility system lacks the robustness achieved by other countries’ flexibility strategies, as it is both unable to provide spare back-up capacity, and cannot completely cover critical capacity, even at full flexibility potential. Furthermore, its resilience score is only middling, showing a lack of diversification across flexibility sources. Going forward, Ireland can increase its flexibility capacity by diversifying not only its interconnections, but its flexibility mechanisms in general, which will increase comparative security across all perspectives.

In conclusion, it is possible to draw some general deductions about how to increase a flexibility strategy’s security level:

3. Diversification, of both interconnection partners and installed flexibility sources, is key to increasing the ability of the system to deal with and recover from not only foreseeable, as well as unexpected failures and shortages, both domestic and external in nature. As such, future flexibility strategies should take a systemic approach, incorporating all flexibility mechanisms that are relevant from both a geographic and cost perspective.

4. Strategies focusing on sovereignty, will not ensure security unless they are also able to ensure a high level of robustness and resilience of the domestic system, as
demonstrated by the UK. However, the same is not necessarily true in reverse, as even comparatively integrated systems, such as Portugal, can score highly if domestic resilience and robustness are ensured. As such, integration is not a significant security risk, as long as interconnections are diversified and internal flexibility mechanisms are designed to be robust and resilient.
7 Discussion

7.1 Reflection on methodological choices and future methodology recommendations:

The following sections reflect on the key aspects of the chosen methodology, and provide recommendation for future improvements in methodological approaches.

7.1.1 Comparative case study snapshot approach

This thesis adopted a snapshot approach to comparative analysis, focusing on analysing and comparing six country case studies, in order to draw conclusions regarding the current (2014/2015) state of flexibility strategies. The snapshot approach was legitimate given the scope of this project, as well as the relative recent commencement of comprehensively documenting flexibility components.

However, Future research could consider adopting a time-series approach, in order to more thoroughly assess trends and developments, as well as include a quantitative assessment of correlations between electricity system characteristics (size of system, VRES integration level etc.) with the composition of a country’s flexibility strategy.

7.1.2 Country selection

Furthermore, by limiting this assessment to a sample size of only six countries, it is difficult to make generalizable statements about trends and driving factors that determine the composition of flexibility strategies. Additionally, all six countries represent mature electricity systems and are, to varying extents part of the wider European electricity system, and so under the oversight of ENTSO-E. As such, it is difficult to tell what trends are representative for all energy systems, or even all mature energy systems, and what trends are just present because all countries are affected by central grid planning under ENTSO-E. As such, any trends and “best practises” identified are anecdotal in nature.

Future research could address this issue further along in the transition process by analysing a wider cross-section of countries, including developing electricity systems, once more countries reach higher VRES penetration and start documenting flexibility components in sufficient granularity.

7.1.3 Flexibility charts

The flexibility charts, developed by Yasuda et al., (2013) offer an accessible visual overview of each country’s flexibility strategy and provide a good basis for cross-country comparison. However, by limiting the assessed flexibility mechanisms to just interconnection, pumped hydro storage, reservoir hydro power, combined heat and power plants (CHP), and combined cycle gas turbines (CCGT), the flexibility charts possibly underestimate the level of flexibility provided by the growing number of novel flexibility mechanisms, particularly storage technologies, such as CAES, electric vehicles and battery storage technologies; and smart grid technologies which enable demand-side management.

Future research could aim to include the full range of flexibility mechanisms, in order to offer a more accurate overview of countries’ installed flexibility potential. The same is true of the indicator framework, which also only focuses on capacity data for the five main flexibility mechanisms.
### 7.1.4 Dimensions of flexibility indicator framework

This thesis is ambitious in attempting to develop a novel framework for assessing flexibility from an energy security context. As such, while methodology provides a solid basis for initial development, a large amount of further research and methodological development would be necessary to fully understand the security of flexibility systems, as well as the role that flexibility plays in overall energy security of future LCES. There are myriad ways in which this framework can and should be refined, however the following are some of the key reflections on areas for improvement:

- While it is possible and interesting to score comparative country performance across indicators, the small sample size of countries, as well as the fairly underdeveloped nature of flexibility systems and flexibility strategies, as a whole, mean that the score ranges that were ranked in the analysis are not necessarily representative of score ranges globally, or even for these countries once they transition to more mature low carbon energy system. By necessity, this thesis analyses a snapshot of a system in transition.

- The energy security perspective, and its normative view on the importance of sovereignty has affected the relative security assessment of interconnection as a flexibility component. While an excessive reliance on interconnection to solve flexibility needs is not a secure way to plan a flexibility strategy, a certain level of interconnection has been proven to be actively beneficial to reducing flexibility needs through spatial smoothing (IEA 2014). Traditionally, the sovereignty perspective assessed the risks associated with fossil fuel supplies affected by longer and more complex supply chains, as well as the geopolitical risk factors of many key supply regions. However, in the flexibility system, interconnections are fairly secure, as they are, inevitably, right at the country border. This leads to an overestimation of the security risk presented by interconnection. Additionally, while from an energy security perspective excess spare back-up capacity is a positive attribute, overcapacity can lead to increasing marginal cost of flexible generation. Initially, this thesis sought to develop an indicator for the efficiency of back-up capacity. However, as there was still no clarity about the most appropriate way to calculate and score the indicator at time of submission, the decision was made to remove the indicator from the framework, in order to further work on the best way to assess back-up efficiency.

- The market perspective and economic vulnerability dimension has been largely excluded from the initial development stage of this framework. However, both market design and price developments on international electricity markets are important elements determining the security of external flexible electricity supply, and should be assessed under the sovereignty perspective in any future versions of the framework.

**Future research:**

- A more comprehensive testing of the indicator framework on a larger sample size of countries needs to be conducted to derive a more representative understanding of comparative security ranges, and what connotes a secure, versus a vulnerable flexibility strategy.

- The included indicators should be reviewed and potentially augmented by new indicators that could aid in reducing bias caused by the influence of traditional energy systems on the underlying energy security paradigms shaping the framework. Additional indicators could include:
  - Indicators assessing efficiency, especially of back-up capacity;
7.2 Legitimacy and further research needs:

Overall, this thesis maintains that the research questions are and will remain legitimate and relevant to policy makers and academics alike. The thesis has fully or at least partially answered all of the thesis’s research questions. However, given the novelty of the field and current scarcity of granular data on flexibility mechanisms, as well as for reasons outlined in the limitations and methodological reflections section, these research questions will remain in need of answering for the foreseeable future. All of the research questions address specifically systems in transition, and as such will need to be re-visited and the answers updated and refined as the transitions of various countries progress.

Additionally, the initial work conducted by this thesis has opened up a set of new research questions, including inter alia:

- What are key determinants of a country’s flexibility strategy?
- How can the security of flexibility strategies be globally benchmarked?
- What are best practises and trends of emerging electricity systems transitioning to LCES with high VRES penetration?

7.3 Generalizability:

The findings of this thesis show different levels of generalizability:

The developed indicator framework is widely applicable for any country transitioning to a LCES. However, further research needs to be performed on benchmarking in order to assess what score a “Secure” flexibility strategy would reach when compared globally.

The practices and trends identified both for flexibility strategies, and their security are not fully generalizable. As outlined in the previous two sections, it is difficult to tell what trends are representative for all energy systems, or even all mature energy systems, and what trends are just present because all countries are affected by central grid planning under ENTSO-E. As such, any trends and “best practises” identified are anecdotal in nature, with findings being of limited geographic and temporal relevance. Nevertheless, these findings could serve as a guide to policy makers of similar mature energy systems in shaping their flexibility strategies.


8 Conclusions

8.1 Problem and Research questions

This study addresses the growing need for policy makers to strategically plan flexibility strategies alongside renewable energy targets. This is necessary to ensure the security of electricity supply in energy systems transitioning to LCES with high VRES levels. In addition, in order to ensure ongoing security of the flexible electricity supply, it is necessary to develop an understanding of the role flexibility plays in energy security.

In order to address this problem, this thesis pursues the following aims and objectives

**Aim 1:** to enable policy makers to more strategically plan flexibility strategies alongside VRES targets.

- **Objective 1:** identify “first movers” in the energy transition towards LCES with high VRES penetration.

- **Objective 2:** identify current practises and trends in the flexibility strategy of these “first movers”.

**Aim 2:** to provide a framework to understand and assess flexibility strategies in an energy security context, in order to facilitate policy makers’ ability to protect the grid from failures caused by the integration of high levels of renewables.

- **Objective 1:** Identify why/if flexibility is an energy security concern for country’s transitioning to LCES with high VRES content.

- **Objective 2:** Identify how security of flexibility strategies can be assessed.

- **Objective 3:** Assess comparative security of existing “first mover” flexibility strategies.

- **Objective 4:** Identify policy recommendations for increasing the security of a country’s flexibility security.

On the basis of these aims and objectives this thesis developed the following research questions:

1. **Why is flexibility an energy security concern?** (Chapter 2)

2. **How are countries with high VRES integration addressing their flexibility needs -that is, what are current practises and trends in flexibility strategies?** (Chapter 4)

3. **How can countries ensure the security of their flexibility strategies?**
   - a. **How can security of flexibility be assessed?** (Chapter 3.6)
   - b. **How secure are existing flexibility strategies?** (Chapter 5)
c. What are policy recommendations for ensuring the security of flexibility? (Chapter 7.4)

8.2 Main findings and conclusions

Why is flexibility an energy security concern? (Chapter 2)

This thesis found that flexibility has become an energy security concern because of the transition to LCES dominated by VRES. Already, countries with higher VRES potential are struggling to provide sufficient flexibility in order to prevent cost inefficient curtailment of installed VRES. As flexibility affects a high VRES dominated electricity system’s ability to provide vital energy survives, in an increasingly electricity-based LCES, it should be considered a matter of concern from an energy security perspective. This finding in the literature was reinforced by the insights gained from attending the IRENA Innovation Week conference (IRENA, 2016).

How are countries with high VRES integration addressing their flexibility needs - that is, what are current practises and trends in flexibility strategies? (Chapter 4)

The examination and comparison of the six case study countries’ flexibility strategies highlighted the following trends in how countries with high variable renewable energy integration are addressing their flexibility needs:

- Flexibility strategies are still dominated by reliance on back-up capacity, with most countries relying on either CHP or CCGT to provide flexibility.
- Storage is not yet a significant component of any country’s flexibility strategy, though this may change as more storage technologies reach technical maturity.
- Interconnection penetration is highest in the countries with the highest VRES penetration. This suggests that interconnection is likely to play an increasingly important role in flexibility strategies as VRES levels rise.
- Finally, there is a trend to diversify the dominant flexibility components with rising VRES share, with both Germany and Denmark demonstrating a fairly balanced split between interconnection and back-up capacity penetration.

How can countries ensure the security of their flexibility strategies?

How can security of flexibility be assessed? (Chapter 3.6)

To provide an initial answer to research question (3.a) this thesis develops an indicator framework to assess how well a country’s flexibility strategy is comparatively able to protect against the vulnerabilities of the electricity system resulting from high VRES integration. The indicator system was developed to assess a flexibility strategy’s performance across the three perspectives of energy security: sovereignty, robustness and resilience, as developed by Cherp and Jewell (2011). The identified vulnerabilities across the three perspectives, as we well as the resulting indicator framework is shown below in Table 10 and 11:
Table 10. Perspectives of Flexibility Security (adapted from Cherp and Jewell, 2011)

<table>
<thead>
<tr>
<th>Vulnerabilities identified</th>
<th>Sovereignty</th>
<th>Robustness</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disruptive external shocks to the electricity trading market/ unavailability of exporting or importing capacity to address balancing needs</td>
<td>Predictable variations in balancing needs caused by daily or seasonal weather patterns or generator maintenance</td>
<td>Unpredictable failures in generation due to black-outs or extreme weather events. Unexpected variation in demand</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Protection mechanism</th>
<th>Sovereignty</th>
<th>Robustness</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control over domestic flexibility mechanisms and electricity systems</td>
<td>Upgrade infrastructure and transition to more flexible resources and higher levels of flexibility in the system</td>
<td>Increase the ability of the flexibility mechanisms to adjust for and recover from unexpected variation in electricity and price shocks</td>
<td></td>
</tr>
</tbody>
</table>

Table 11. Dimensions of Flexibility: Indicators to assess the comparative security of electricity flexibility strategies (adapted from Jewell et al., 2014)

<table>
<thead>
<tr>
<th>Perspective of flexibility</th>
<th>Indicator</th>
<th>Vulnerability/ Failure addressed</th>
<th>Unit</th>
<th>Definition (formula)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td>Electricity trade intensity</td>
<td>Unavailability of flexibility through external electricity markets (Market failure)</td>
<td>Share (0-1)</td>
<td>Electricity trade divided by annual electricity generation</td>
</tr>
<tr>
<td></td>
<td>Import dependency</td>
<td>See above</td>
<td>Share (0-1)</td>
<td>Electricity import divided by net consumption</td>
</tr>
<tr>
<td></td>
<td>Export dependency</td>
<td>See above</td>
<td>Share (0-1)</td>
<td>Electricity export divided by net generation</td>
</tr>
<tr>
<td></td>
<td>Geographic diversity of interconnectors</td>
<td>Exposure to failure of any one external market</td>
<td>Non-dimensional</td>
<td>Shannon-Wiener Diversity index (SWDI)</td>
</tr>
<tr>
<td>Robustness</td>
<td>Potential VRES share of peak load</td>
<td>Potential variability of electricity generation at peak load</td>
<td>%</td>
<td>Installed VRES capacity divided by peak load</td>
</tr>
<tr>
<td></td>
<td>Spare back-up capacity at historic peak demand</td>
<td>Unexpected increase of peak demand</td>
<td>%</td>
<td>Peak load divided by installed back-up capacity and subtracted from 1</td>
</tr>
<tr>
<td></td>
<td>Maximum potential flexibility capacity coverage</td>
<td>Failure of VRES to supply sufficient peak load</td>
<td>%</td>
<td>Installed flexibility capacity divided by peak load</td>
</tr>
<tr>
<td>Resilience</td>
<td>Diversity of flexibility sources</td>
<td>Vulnerability to disruptions of any one flexibility component</td>
<td>Non-dimensional</td>
<td>SWDI</td>
</tr>
</tbody>
</table>
How secure are existing flexibility strategies? (Chapter 5)

Utilizing this indicator framework, this thesis was able to identify the following comparative flexibility securities for the six examined countries:

**Table 12: Comparing security scores across the three dimensions of security**

<table>
<thead>
<tr>
<th>Perspective</th>
<th>DK</th>
<th>DE</th>
<th>UK</th>
<th>ES</th>
<th>PT</th>
<th>IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sovereignty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robustness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resilience</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overall, Table 12 allows for a comparative ranking of the security of the six examined countries’ flexibility strategy: Denmark’s strategy shows the poorest performance, followed by the UK. The fact that both the country with the highest and lowest VRES penetration levels for peak demand, shows that security is not necessarily simply determined by the stage in the transition to low-carbon energy systems. Germany and Ireland rank in the middle, while Spain and Portugal exhibit the comparatively most secure flexibility strategies.

This thesis cannot make any conclusive statements about the objective security of each country’s flexibility strategy, both because of the lack of sufficient sample countries to benchmark this indicator framework, but also because of the need to further refine the indicators chosen, which are discussed in the previous chapter. However, it does provide the following general insights into how to increase comparative security of flexibility strategies:

1. Diversification, of both interconnection partners and installed flexibility sources, is key to increasing the ability of the system to deal with and recover from not only foreseeable, but especially unpredictable failures and shortages, both domestic and external in nature. As such, future flexibility strategies should take a systemic approach, incorporating all flexibility mechanisms that are relevant and realistic from both a geographic and cost perspective.

2. Strategies focusing on sovereignty, will not ensure security unless they are also able to ensure a high level of robustness and resilience of the domestic system, as demonstrated by the UK. However, the same is not necessarily true in reverse, as even comparatively integrated systems, such as Portugal, can score highly if domestic resilience and robustness are ensured. As such, integration is not a significant security risk, as long as interconnections are diversified and internal flexibility mechanisms are designed to be robust and resilient.

**8.3 Contribution to theory**

This thesis contributes to existing research in two important ways:

Firstly, it contributes to the field of grid integration literature by identifying current flexibility strategies exhibited by the countries with the highest VRES penetration levels. This provides an up-to-date overview of the practises implemented by the “first mover” countries in the transition to LCES with high VRES penetration, as well as identifying trends across countries. This provides a basis, which facilitates the more systematic planning of flexibility strategies alongside renewable energy targets for countries transitioning to high VRES energy systems.
Secondly, it addresses a research gap by connecting the fields of grid integration and energy security in low carbon energy systems. It argues that flexibility systems will increasingly become a vital energy system, at least for those countries aiming to integrate high VRES levels. In order to facilitate the design of secure flexibility strategies going forward, it develops an initial framework for assessing the security of flexibility systems, adapted from traditional energy security indicator frameworks. Although this framework still needs to be further tested and refined, as more countries reach later stages of transitioning to LCES and higher VRES penetration levels, it nevertheless represents a novel contribution to both the field of grid integration and energy security literature. This initial framework provides a basis which can be built upon to further expand our understanding of the security of flexibility in electricity systems.

8.4 Recommendations:

8.4.1 Policy recommendations

In answer to the final research question (3.c) this thesis makes the following policy recommendations for policy-makers to increase their national flexibility strategy’s security level:

1. Diversify both domestic flexibility resources, as well as sources of external flexible electricity (i.e. interconnections). Diversification is key to ensuring resilience of the system against internal and external failure.
2. Consequently, take a systemic approach, incorporating all flexibility mechanisms that are relevant from both a geographic and cost perspective.
3. Irrespective of interconnection levels, ensuring a high level of robustness and resilience of the domestic system is at the heart of securing flexibility supply. As such, focus on ensuring sufficient, diversified back-up capacity, as well as diverse storage solutions.

8.4.2 Future research recommendations

This thesis recommends that future research could both follow up on the research questions posed in this thesis at various time points throughout the global energy transition, as well as pursue new research questions identified in this thesis, including, inter alia:

- What are key determinants of a country’s flexibility strategy?
- How can the security of flexibility strategies be globally benchmarked?
- What are best practises and trends of emerging electricity systems transitioning to LCES with high VRES penetration?

Following up on the research questions posed in this thesis, future research should include novel technologies, particularly in the field energy storage, as well as demand-side management, wherever data availability allows, in order to provide a more comprehensive understanding of the full flexibility strategy. Additionally, it could augment the indicators considered in this thesis.

In identifying what key determinants of a country’s flexibility strategy, future research could consider adopting a time-series approach, in order to more thoroughly assess trends and developments, as well as include a quantitative assessment of correlations between electricity system characteristics (size of system, VRES integration level etc.) with the composition of a country’s flexibility strategy.
**Benchmarking** could be achieved by conducting a more comprehensive testing of indicator frameworks on a larger sample size of countries in order to derive a more representative understanding of comparative security ranges and allow for benchmarking of secure, versus vulnerable strategies.

In identifying best practises and trends, either further along in the energy transition, or for **emerging electricity systems** transitioning to LCES with high VRES penetration, future research should analyse a wider cross-section of countries, including developing electricity systems, once more countries reach higher VRES penetration and start documenting flexibility components in sufficient granularity.
Bibliography


Assessing the security of flexibility strategies for low carbon electricity systems


