The Impact of Liberalisation on the Resilience of Electricity Systems

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Declaration

I, Christopher Collins, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been appropriately referenced in the text.

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Signed:

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Abstract

Over the past three decades concerns have arisen about the ability of deregulated electricity systems such as the UK's to deliver secure supplies. Capacity margins have drawn particular attention, but a number of apparently secure systems have failed for unanticipated reasons. This has led some to question whether risk-based measures fully capture the uncertainties to which such systems are exposed, and whether the concept of "resilience" provides a framework around which to discuss less quantitative indicators.

This work attempts to answer four questions. First, what are the characteristics of a resilient and secure electricity system? Second, how have these characteristics evolved over the past 25 years? Third, to what extent can these changes be attributed to privatisation & liberalisation and to the introduction of new forms of renewable generation? Fourth, how might the UK Government's proposed policies affect the security of electricity supply?

'Resilience' was found to be a multi-faceted concept, but five indicators were chosen for further investigation: generation margins, system diversity, energy intensity, electricity prices and energy independence. It was shown that a decline in margins can probably not be attributed to privatisation, but that renewable generation can have a positive effect depending on the support mechanism. Diversity can be enhanced by both privatisation and some forms of renewable support, the latter also seemingly reducing a country's import dependence, but also increasing prices.

Whilst there is some evidence that policy changes can affect a system's resilience, the suggestion is that liberalisation has not had a strong overall impact. Furthermore, achieving 'optimal resilience' may be inherently unachievable, meaning that policies will always need to flexible enough to respond to change, but constant enough to encourage the necessary investment for the future.

Acronyms and Abbreviations

ARIMA Autoregressive integrated moving average

BERR Department of Business, Enterprise and Regulatory Reform

BERR Department for Business, Enterprise and Regulatory Reform

BWEA British Wind Energy Association

CCGT Combined Cycle Gas Turbine

CCS Carbon Capture and Storage

CEGB Central Electricity Generating Board

CfD Contract for Difference

CPS Carbon Price Floor

DECC Department of Energy and Climate Change

DM Derated Margin

DSM Demand Side Management

DSR Demand Side Response

DTI Department of Trade and Industry

EMO Energy Markets Outlook

EMR Electricity Market Reform

ENS Energy Not Served

EPS Emissions Performance Standards

ESDS Economic and Social Data Service

EU ETS European Union Emissions Trading Scheme

FIT Feed-In Tariff

GDP Gross Domestic Product

GW Gigawatt

HHI Herfindahl-Hirschman Index

HILP High Impact Low Probability

IA Intervention Analysis

IDI Import Dependence Indicator

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

kWh Kilowatt hour

LCPD Large Combustion Plant Directive

LCTP Low Carbon Transition Plan

LOLP Loss of Load Probability

MTBF Mean Time Between Failures

OCGT Open Cycle Gas Turbine

OECD Organisation for Economic Co-operation and Development

PST Performance-Survival Threshold

RO Renewables Obligation

SES Social-Ecological System

SOP Standard Operating Procedure

SR Systematic Review

SWI Shannon-Wiener Index

SYS Seven Year Statement

TEPCO Tokyo Electric Power Company

TGC Tradeable Green Certificates

TPA Third Party Access

TSO Transmission System Operator

UKERC UK Energy Research Centre

VOLL Value of Lost Load

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Part I

Preliminaries, Definitions and Indicator Development

1

Introduction

1.1 Background

The privatisation of the UK electricity system in the 1990s put the generation, transmission, distribution and supply of electricity into private ownership (Helm, 2004; Surrey, 1996). This process of privatisation was not isolated to the power sector, but was, argues David Newbery (2001), a manifestation of the Conservative philosophy at the time that "the business of Government is not the government of business". Within this broader ideological framework, it was argued that government ownership and operation of electricity utilities was inefficient, and that economic benefits could be achieved by introducing a free market for electricity (Newbery, 2001). In fact, the decision is better understood by noting that electricity privatisation was part of a wider ideological shift away from state ownership of a number of public services such as transport, also providing the government of the time with a means of raising capital, thereby reducing

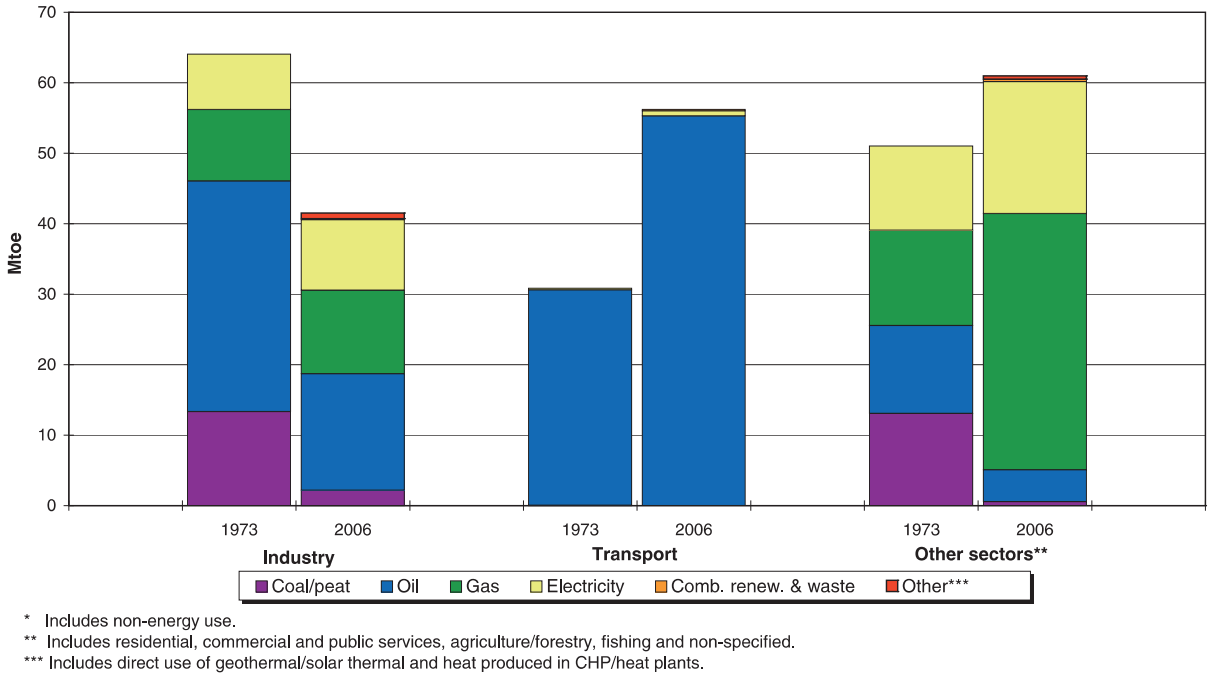
the levels of public debt (Kay and Thompson, 1986).

Whatever the initial intentions of the Government at the time, the benefits of privatisation have been reiterated by subsequent Governments. The 2003 Energy White Paper is described as being "based on the four pillars of the *environment*, *energy reliability*, *affordable energy* for the poorest, and *competitive markets* for our businesses, industries and households"(emphasis added) (DTI, 2003). These same pillars are described as the "four long-term goals for energy policy" in the DTI's 2006 Energy Review DTI (2006a):

- To put the UK on a path to cut our carbon dioxide emissions by some 60% by about 2050, with real progress by 2020;
- To maintain reliable energy supplies;
- To promote competitive markets in the UK and beyond, helping to raise the rate of sustainable economic growth and to improve our productivity; and
- To ensure that every home is adequately and affordably heated.

By including competition as one of the 'four pillars' of energy policy, the government implicitly defines how the other three – low-carbon, secure and affordable energy supplies – are to be achieved. Seeing competition not as a means to an end, but as an ambition in its own right, has, it has been argued, dictated the government's approach to energy policy-making (Mitchell and Connor, 2004). Delivering secure energy supplies whilst allowing the market sufficient freedom to allocate resources has been consistently recognised as a particular challenge for the UK government's energy policy (DTI, 2006a, 2007).

Electricity systems face some particularly problematic security challenges. Electrical energy cannot be stored easily, meaning that it has to be generated to meet instantaneous demand (National Grid, 2008a; Newbery, 2002). The availability of generation and the demand for power must therefore be accurately predicted, continuously monitored, and adjusted when imbalances occur (National Grid, 2008a). Power supplies also need to meet stringent frequency and voltage quality standards in order to allow sophisticated electrical equipment to function correctly (National Grid, 2008a). The proportion of energy services delivered by the electricity system is increasing with the growing dependence of industries, services and domestic consumers on electrical appliances and information technology (National Grid, 2008a). The following chart from the IEA illustrates the differences in electricity use between 1973 and 2006:



* Includes non-energy use.
** Includes residential, commercial and public services, agriculture/forestry, fishing and non-specified.
*** Includes direct use of geothermal/solar thermal and heat produced in CHP/heat plants.

Figure 1.1: UK breakdown of sectoral final consumption by source

Over this period, industrial energy consumption has gone down by 35%, whereas the electricity consumption has gone up by over 30%. Industrial electricity use has therefore doubled from 12% in 1973 to 24% in 2006. Consumption of energy in the residential, commercial and other sectors has gone up over this period, but the proportion of that final consumption coming from electricity has climbed from 23% in 1973 to 34% in 2006. The electrification of the transport sector remains a small proportion of total final energy consumption, but plans to electrify more of the UK rail network (Brand *et al.*, 2010) and the potential electrification of road vehicles would increase further the demands placed on the electricity system.

The term 'energy security', defined as "a system's ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy" (Grubb *et al.*, 2006), covers a wide range of system characteristics, including import dependence, import diversity, storage levels, and generator and network reliability (Grubb *et al.*, 2006; Olz *et al.*, 2007). The focus of this research, however, is the 'resilience' of electricity systems. A 'resilient' system has the necessary technical, economic and institutional characteristics to minimise the impact of adverse events, and to reinstate the provision of energy services both quickly and with the minimum overall disruption. Resilience is just one component of electricity system security, but it is a useful concept to assess for a number of reasons. Numerous attempts have

been made to develop measures of a country's 'energy security' (Blyth and Lefevre, 2004; Jansen *et al.*, 2004). The concept has, however, remained difficult to quantify, since security of supply has a large number of factors whose relative importance are debatable, and many of which, such as 'geopolitical risk', are subject to large uncertainties (Blyth and Lefevre, 2004). The resilience of a system can be demonstrated through its ability to maintain adequate function despite a geopolitical risk being realised, but the resilience of the system itself is independent of the level of geopolitical risks to which it is exposed. 'Resilience' can therefore be used as a way of limiting the scope of the policy debate to quantifiable terms and, crucially, focusing on the system attributes that fall under the jurisdiction of national policymakers.

By transferring ownership and operation of the electricity generation, transmission, distribution and supply sectors to private companies, the government has effectively limited its role in ensuring security of supply to one of encouraging and enabling investment, discouraging market concentration and, where natural monopolies exist, regulating those industries (Helm, 2005). Whilst regulation has maintained many of the same security standards that applied in the nationalised era, these standards may now be in tension with the need to use resources as efficiently as possible (Helm, 2005; Strbac and Jenkins, 2001; Thomas and Hall, 2003). Government sees its role as being to "strengthen the UK energy investment framework so that investors have the confidence to make timely investments in new gas and electricity infrastructure consistent with our energy goals" (DTI, 2003). The energy regulator, Ofgem, also has a duty to ensure that electricity network costs are as low as possible. There has been discussion in recent years about the ability of the existing market system to deliver the "timely investments" necessary for maintaining secure supplies and in particular the ability of the existing framework to reconcile the potential conflict between operational efficiency and long-term supply security.

In recent years the current electricity market arrangements have come under increased scrutiny. There is broad agreement that liberalisation has resulted in benefits in terms of efficient system operation, but there are emerging concerns that the market forces alone will not be able to deliver the rate of capacity replacement and expansion that will be required. This has led some to ask what policy measures can be used to encourage new capacity construction, and others to consider the possibility that a completely new regulatory approach is required to maintain adequate levels of security (Henney, 2001; Newbery, 2006; Woo *et al.*, 2003). The government and regulator has begun to consult on these issues (Ofgem, 2010; DECC, 2010a) in order to decide how best to meet the need both to expand and decarbonise the electricity system, whilst still maintaining the levels of supply security on which industrial and domestic consumers are

becoming increasingly reliant.

1.2 Research Outline

The structure of this PhD thesis is in three sections. The first concerns the concept of "resilience" itself. It reviews the ecological, sociological and finance literature to bring together the various interpretations of the concept. Each interpretation is inevitably grounded in the discipline for which it was conceived. The same will be true for the use of the concept within the field of energy security. Having explored the various aspects of system resilience, this work then assesses whether the ideas that a resilience perspective raises are sufficiently distinct from those already used within the energy policy literature so as to be worth pursuing. In other words, it asks whether policy-making that addressed resilience would be substantively different from one that was based on the more conventional notion of energy security. Where such concepts are deemed useful, a set of quantitative and qualitative indicators are proposed as a basis for future policy assessment.

The second section concerns the historic record of electricity system operation. It attempts to analyse the impact of different policies on the resilience indicators identified in the first section. The UK has now experienced over 20 years of liberalised system operation. In that time the system has undergone a number of changes. As policymakers make decisions about the regulation of the system in the future, it is worth considering what the true effect of past policies has been thus far. When considering the UK alone, it is difficult to discern from the data alone which policy changes were responsible for which system changes. Across the OECD, nearly all countries have now undergone some level of privatisation or liberalisation of their electricity system, and most have begun to implement low-carbon policies. This allows a multi-country analysis to be conducted to identify the real impacts of policies, while controlling for sources of variation in the time series. The timescales over which these systems have operated are just beginning to be sufficiently long to attempt to discern the effects of different policies on electricity system operations. Nevertheless, the effects observed remain weak because of the large underlying variability in the data and the relatively short timescales. This should serve as a reminder that we have, as yet, only the most scant evidence of the many policy interventions working *in practice*, and perhaps that policymaking should choose policy pathways that acknowledge the level of uncertainty inherent in the system.

The third section concerns the current energy market reforms currently being considered. It begins by reviewing and synthesising both the consultation documents and the associated responses relating to Ofgem's Discovery (Ofgem, 2010) project and DECC's more recent Energy Market Reform proposals (DECC, 2010a). This systematic review assesses the security of supply implications anticipated in relation to these market changes. With reference to section 1, this section goes on to consider whether the "resilience" framework provides a different and meaningful perspective on the proposed policies changes. Further, the analysis conducted in section 2 is applied here to establish the extent to which proposed market reforms are supported by the historical evidence.

1.3 Aims and Objectives

This thesis has two overarching aims:

1. To understand the relationship between regulatory change and the resilience of the electricity system by analysing the historic evidence;
2. To use these findings to assess the impact that the range of proposed market reforms might have on the resilience of the UK electricity system in the future.

To this end, the work has a number of objectives:

- To conduct a literature review to understand the concept of 'resilience' as it has been used in a range of different academic disciplines;
- To use the results of the literature review to propose one or more definitions of resilience that have a useful bearing on the electricity system;
- To understand if, and to what extent, 'resilience' is distinct from 'energy security', and whether this distinction has any substantive implications for energy policymakers;
- To choose quantitative and qualitative indicators that describe the 'resilience' of an electricity system;
- To conduct an intervention analysis to understand whether, and to what extent, changes in the regulation of electricity systems internationally have a significant bearing on these 'resilience indicators';

  - Where such associations are found, to understand why such a relationship exists;
  - Where no association is found, to consider whether there is insufficient statistical power to see an effect, or whether the policy and the indicator do indeed have no real association;

- To conduct a review of the most recent UK energy policy documents
- To assess the UK energy policy proposals in light, both, of the emerging 'resilience' concept and the historic evidence of the relationship between regulatory design and the relevant resilience indicators.

2

Methodology

The methods applied in this research are predominantly evidence-based, systematically reviewing the existing literature and analysing primary data using statistical methods. The work attempts to assess the effect of policy change on the resilience of the electricity system. It does this by drawing on the extensive data that exist on the UK electricity system and on those of other countries (BERR, 2008b; IEA, 2008; Oxera, 2007). As will be discussed in this chapter, taking a strictly quantitative approach can limit the range and depth of conclusions that can be drawn by eliminating pertinent, but qualitative, evidence. Further, by defining a concept such as "resilience" in terms of quantifiable measures one risks focusing on indicators that do not properly reflect the concept they are intended to describe.

The statistical component of this research focuses on a number of quantitative indicators of electricity system 'resilience' and of privatisation and liberalisation. As will be discussed in chapter 3, the full range of potential indicators includes a number that are more qualitative, and not subject to numerical interrogation. Such qualitative indicators can be equally valid

interpretations, but do not lend themselves to statistical investigation of the sort carried out in this research. These indicators, therefore, are explored in some depth in chapter 3, are eliminated from the cross-country times series analysis, but are reintroduced as part of the synthesising work that forms the final chapters in this thesis. The intention is that robust numerical analysis be conducted to identify correlations between policy intervention and resilience indicators, but that the importance of these qualitative indicators not be lost in that process.

As will be explored further in chapter 3 there is a particular challenge presented by attempting to carry out a quantitative analysis on a concept such as resilience. For some authors the reason that resilience is useful is that it provides a way of thinking about a system that allows for a degree of ignorance on our part about system behaviour (Stirling, 1994). For others (Redman, 2008; Walker, 2008), "resilient" system design implies a degree of inefficiency – leaving some slack to allow for the possibility that our understanding of system behaviour is wrong. It can reasonably be argued that "resilience" should not be reduced only to quantitative indicators, and that to do so would leave it devoid of the qualities for which it was first conceived.

This chapter details the methodology used in this research; the following sections discuss the use of:

- *systematic reviews* to explore existing resilience definitions, define an appropriate set of 'resilience indicators' and to collect associated data on a number of electricity systems in order to make comparisons
- *indicators* as proxies for resilience, privatisation, liberalisation and regulation
- *statistical methods* (where the resilience indicators are quantifiable, and where the data allow) to identify correlations between resilience indicators and the indicators related to privatisation, liberalisation, regulation and market design

2.1 Systematic Review Methodology

For chapter 3, a conceptual analysis was conducted to explore the use of resilience and resilience-related concepts in the wider literature. A research methodology was required that could identify a large number of definitions from a sufficiently broad range of sources, in order to be confident that the breadth of the different meanings had been identified and that the prevalence of each was representative of the full body of literature that made use of the term.

A systematic review methodology (Mulrow, 1994) was chosen as the most effective way to identify the different conceptualisations of resilience in a large number of diverse sources. A computer-based systematic review offered access to a large number of papers, using research databases and online journals. Systematic Reviews were developed in the field of medical research to bring together and analyse the best evidence available from a wide range of sources (Clarke, 2004).

The procedure is most commonly used to answer specific quantitative medical questions, but has increasingly been used to synthesise qualitative data (Dixon-Woods *et al.*, 2001). Clinical trials literature has begun to discuss ways in which qualitative findings can be used to support the findings of quantitative meta-analyses. More recently still, systematic review methodologies have been applied to exclusively qualitative data. Of particular relevance to this research are the papers that use these techniques to understand how different concepts are defined. A definitive methodology for conducting a systematic review of definitions has yet to emerge. This review, therefore, has been guided by these conceptual reviews which have attempted to assess the definitions of medical concepts: namely, "anastomotic leak" (Bruce *et al.*, 2001), "falls" (Hauer *et al.*, 2006), "Sedation for Symptom Relief" (Morita *et al.*, 2002), "eHealth" (Oh *et al.*, 2005) and "drowning incidents" (Papa *et al.*, 2005). More recently, it has been suggested that energy policy research could benefit from this evidence-based approach (Sorrell, 2007).

The formal Systematic Review (SR) process described, for example, by the Cochrane Collection (Clarke, 2004) finds evidence using fixed search terms in agreed databases, pre-defined inclusion criteria based on quality assessments, and synthesises the data in a fixed way. None of these procedures is entirely applicable in this research, but they are nonetheless useful as providing a benchmark. The definition of terms and the review of literature to identify market and resilience indicators involved a large number of sources, so could not be constrained to a predefined set of databases. Definitions of resilience and associated indicators cannot be formally synthesised, since they are used in different ways for different disciplines.

Where it has been used in this research, the SR process has therefore been used only in a modified form that attempts to adhere to its underlying intentions, namely the unbiased synthesis of a wide range of sources (Clarke, 2004), whilst avoiding unhelpful constraints. This approach has allowed a large number of sources to be reviewed in order to ensure that the definition and choice of market and resilience indicators is as grounded in the existing literature as possible.

The biggest challenge for reviewing concepts is to assimilate them in a systematic way. There is always a risk that the conceptual categories chosen will reflect preconceived ideas about resilience,

rather than emerging impartially from the literature being reviewed. The eHealth paper (Oh *et al.*, 2005) used the "constant comparative method" to provide rigour for the categorisation of different definitions of eHealth. This is an iterative process in which words, sentences, or paragraphs are labelled, compared, and grouped until no new categories emerge. A similar approach has been used for this research, maintaining the impartiality afforded by the systematic searching methodology and minimising the opportunity for bias to enter the interpretation of the results.

2.1.1 Research Areas

The primary objective of the research documented in chapter 3 was to provide the conceptual context for answering the following question:

> "Is resilience a useful concept for informing policy decisions on energy security?

Answering this question required breaking it down into a number of sub-questions:

1. What is meant by resilience?
2. What is meant by *energy security*?
3. How does resilience apply to energy policy?
4. How would an attempt to enhance resilience change current approaches to energy policy?

In order to answer these questions, the search strategy was divided into three sections:

- How is *Energy Security* currently conceptualised?
- How has *Resilience* been used to date in the context of *energy security*?
- What conceptualisations of *Resilience* exist in the non-energy literature, and can these inform or expand the use of the term in energy policy.

2.1.1.1 Energy Security

The purpose of this thesis is to explore the ways in which the concept of *resilience* is, and can be, used to inform decisions on energy policy generally, and in particular its usefulness in the conceptualisation of *energy security*. In order to understand the impact of *resilience* thinking on *energy security* there is a need to appreciate the ways in which *energy security* is currently used. This was to provide a context into which a refined *resilience* concept can be placed.

As an indication of the prevalence of the term in the literature, a Google Scholar search of *energy security* yielded 11,500 records (going up to 16,400 records if *security of supply* was included in the search). Even if the search were restricted only to those articles that contain *energy security* in the title, this still found 834 results (977 including *security of supply*). A full search of the relevant academic database would have found even more articles, the digestion of which would have been unmanageable and disproportionate.

As a solution to this problem, it was decided to look only at the use of *energy security* in policy documents. This was intended to provide a snapshot of the use of the term as it evolved over time. The limitation of this approach was that it would fail to capture some of the more detailed analyses of *energy security* that might be found in the academic literature, and the assessments of the physical and institutional components that collectively comprise a secure energy supply system. However, as will be discussed in the next section, the review of the "resilience" literature, which is the primary focus of this work, covers both the policy and the academic literature.

The catalogue was searched using the search string given below. The resulting list of references was then manually checked, and those records that did not meet the inclusion criteria were excluded. The remaining documents were collected and each was visually searched in the following manner:

- Check the Index (if available) for *security*-related terms. Read any relevant sections in full.
- Check the Contents page (if available) for *security*-related terms. If Contents page is not available, check the chapter/section headings visually. Read any relevant sections in full.
- Where they exist, read the preface, introduction and abstract.

The search domain, search strings and inclusion/exclusion criteria used are detailed below:

Search Domain

- Imperial College Library Catalogue

Search String

The string chosen was designed to identify all energy-related documents published by HMSO (the asterisk (∗) denotes a wildcard, which can take any ending).

- Title:(energy OR power OR fuel OR electric∗OR gas OR oil) ***AND*** Words or phrase:(h.m.s.o. OR hmso OR majesty's OR stationery office)

Inclusion/Exclusion Criteria

- Only documents related to energy policy were included
- Only those results from the Environmental Reports series were included (Call Number: Rxxxx, e.g. R1234)
- Any document that made no mention of *energy security* (or a variant of that term) was excluded.

2.1.1.2 Resilience in the Energy Policy Literature

It was expected that there would not be a large number of papers on the subject of energy policy that contained references to resilience. A Google Scholar and CSA Illumina search for papers that contained *resilience* along with *energy policy*, *energy security*, or *security of supply* in the title both found only one paper (Lovins & Lovins (1981)). A similar ScienceDirect search produced no results.

It was therefore decided that all references to *resilience* in the body of the articles would be searched. The limitations of the search engines did not allow a search of papers with *energy* in the title and *resilience* anywhere. It was therefore decided to address the search in two steps:

1. Identify all the journals related to energy policy

2. Search for resilience only within those relevant journals.

The search criteria were as follows:

Search Domain

- Imperial College Library's ELECTRONIC JOURNALS TITLE SEARCH - Quick search function
- Search engine of each energy-related journal (or its associated database)

Search String

- Journal Search: (*energy* OR *power* OR *fuel* OR *electric* OR *gas* OR *oil* OR *coal*)
- Article Search: (full text) *resilience*

Inclusion/Exclusion Criteria

- Journal Search: Journals unrelated to energy policy were removed (e.g. *Journal of High* ***Energy*** *Physics*, e.g. *Applied s****OIL*** *ecology*)
- Article Search: Only articles that used *resilience* in the context of energy policy or energy security were included. Furthermore, those articles that used *resilience* in an ambiguous way were excluded.

2.1.1.3 Resilience in the Wider Literature

Searching for *resilience* in all academic fields yields a large number of hits (60,300 for Google Scholar at the time of writing). The term has been used for a number of decades, and is a fairly prominent concept in some academic disciplines such as ecology and psychology, so its prevalence is unsurprising.

In order to make this search manageable, a limited number of databases were chosen that were intended to capture the majority of natural and social science journals. Within each of these

journals a title search was conducted for *resilience*. If the number of hits exceeded 500, the search was restricted to references that contained *resilience* and one of the following: *ecolo** (where the *denotes a wildcard which can take any ending), *bio**, *soci**, *enviro**, *eco**, *engine**, *network* and *econo**to restrict the search to the physical, biological, and social sciences. A further search was then done to find references whose title contained *resilience* with *concept**, *construct**, *defin**, *metaphor**, *meaning* and *measure**to find articles that explicitly dealt with definitions of resilience.

Finally, to make the amount of reading manageable, only definitions of resilience found in the article abstract (rather than in the body of the text) were included in the analysis.

Search Domain

- CSA Illumina
- DTI Website
- Google Scholar
- ISI Web of Science
- JSTOR
- ScienceDirect

Search String

- (title only) *resilience* (if <500 records generated)
- (title only) *resilience* AND (*ecolo**OR *bio**OR *soci**OR *enviro**OR *eco**OR *engine**OR *network* OR *econo**OR *concept**OR *construct**OR *defin**OR *metaphor**OR *meaning* OR *measure**)

Inclusion/Exclusion Criteria

- The search for definitions was restricted to the abstracts of the retrieved papers. Only those papers that contained *resilience* in the abstract, therefore, were included in the final results list.

2.1.1.4 Resilience-Related Terms

Whilst the primary purpose of conducting a systematic review was to find definitions of resilience, a secondary benefit was that it identified a number of concepts that were related to resilience.

By understanding these other terms, a better understanding could be formed of the subtle differences between interpretations of resilience. Understanding, for example, how *resistance* is used in ecology could serve to clarify its distinction from *resilience*.

Furthermore, these secondary terms had the potential to be useful in their own right for the conceptualisation of energy security. For example, the notion of a *Performance-Survival Threshold*, as will be explained in chapter 3, could have offered a strategy for coping with adverse events in the energy supply chain.

The strategy for identifying these peripheral terms was less formalised than that used for finding definitions of *resilience*. There were fewer references to each of the secondary concepts (given that they were not in the primary search string), so the requirement that they be explicitly defined was relaxed. Where a potentially-relevant term was identified, the reference database was searched for all references to that concept to ensure that all instances were captured. In some cases a term was identified that seemed to be relevant but was unexplained in the abstract itself; where an explanation of a definition was lacking, therefore, a further search of the literature was conducted to provide a fuller description of the term.

2.2 The Use of Indicators

This research tests the relationship between different forms of regulation and their effect on resilience. In order to make meaningful comparisons between disparate electricity systems and regulatory regimes, the relevant characteristics are analysed indirectly through the use of 'indicators'. Each country, for example, will be unique in the precise way in which it implements policies, and each electricity system will have technologies and modes of operation that are particular to that country. The careful choice of indicators allows the quantitative measure of a relevant system characteristic and, crucially, allows the researcher to look at many different systems simultaneously and thereby draw generalisable conclusions that can inform future policy decisions.

The use of indicators for policy analysis is established practice in a number of different disciplines (Cust, 2008), and is a particularly useful approach to take when the subject of interest is not directly quantifiable. Their use policy-based research in particular is widespread (Hezri and Dovers, 2006). Indeed, the UK government has been producing data on a number of indicators to assess its progress towards its stated energy policy goals (DECC, 2009a).

The OECD (2001) defines an indicator as follows:

> "A parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value."

Well-chosen indicators, then, have the potential to allow quantitative comparisons to be made between different systems, to identify trends and to make inferences about the impact of different interventions.

'Resilience' itself is a qualitative concept, in the sense that it is subjective, and comprises a number of different system characteristics. No single metric, therefore, will be able to describe all the necessary dimensions of a resilient system. Similarly, 'privatisation' and 'liberalisation' can be measured in different ways, as can the forms and degrees of regulation that exist under privatised electricity systems. The first step in this research, therefore, was to provide a working definition for each of these concepts and to choose appropriate indicators that would allow meaningful relationships to be analysed between electricity system resilience and electricity market design.

2.3 Statistical Methods

A number of the indicators identified in chapter 3 are quantitative, and for a number of these some relevant data are available. In such cases, a statistical analysis can be performed to test the relationships between policies and resilience. One approach could be to take a snapshot of different electricity systems and to compare them at a single moment in time. For example, one could ask whether electricity systems that have been privatised are more or less diverse in their generation mix than those systems that have remained nationalised. This question can be answered by placing the systems into one of two groups – privatised and non-privatised – and using a t-test to determine whether the level of diversity (however defined) is significantly different between them.

The approach used in this research extends this idea in two ways:

- First, rather than using data from a snapshot in time, time series data are used (where available) to analyse how a change in 'privatisation' affects the resilience indicator over time.

By analysing how the resilience indicator has *changed* over time, rather than the absolute levels at one time-point, the effect of the policy change is more likely to be discerned.

- Second, the *forms* of regulation affecting resilience are investigated. Rather than simply studying whether, say, privatised systems are made more diverse, this research asks whether, for example, horizontal or vertical separation made more of an impact.

There are a number of advantages to assessing policy interventions through the use of these statistical methods:

1. The analysis of multi-country data allows us to control for effects other than the specific intervention under investigation (i.e. privatisation).
2. A snapshot in time of different electricity systems could reveal an association between privatisation and a given resilience indicator; this may be due to confounding (both privatisation and the resilience indicator are affected by an unseen third variable, such as GDP). The time series approach mitigates this possibility to some extent.
3. The statistical approach provides a way of making explicit those assumptions that are being made. If the approach fails to reveal an effect of privatisation on resilience, this is still informative, since it means that any analysis that does reveal an effect will be to a significant extent dependent on the additional assumptions being made.

2.3.1 Intervention Analysis

Investigating the effect of an event on a time-varying variable is known as an 'intervention analysis' (Angeriz and Arestis, 2008; Box and Tiao, 1965, 1975; Harvey, 1996; Lewis-Beck *et al.*, 2004). In this research, the interventions are different forms of privatisation, liberalisation and regulatory intervention. For illustrative purposes, a single-instance privatisation event (T_0) is first described below to show its effect on a hypothetical resilience indicator. This scenario is represented by Figure 2.1 below.

An Intervention Analysis (IA) can be conducted on a single time series, such as the UK's. To analyse the UK alone, the IA would be conducted by constructing an Auto-Regressive Integrated Moving Average (ARIMA) model. This uses the time series data prior to the intervention to identify the underlying structure of the series (Angeriz and Arestis, 2008) and compares it to the

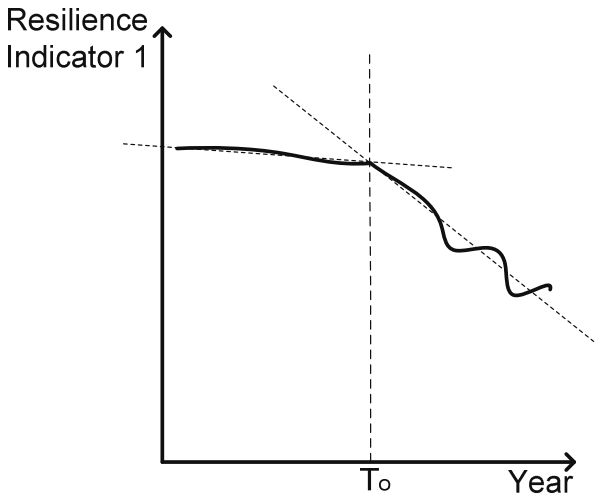


Figure 2.1: Resilience indicator change over time

behaviour after the intervention to look for evidence of a change. The question the intervention analysis asks is whether the behaviour of the resilience indicator is different after T_0 from how it was beforehand. The intervention analysis determines whether the act of privatisation at T_0 has a discernible effect on the resilience indicator beyond that which is explained by the random (or unexplained) variation in the data.

In the case of electricity systems, an analysis of this sort is less than satisfactory for a number of reasons. First, indicators can have noisy signals making it unlikely that a moderate change would be seen following the privatisation event, even if the effect were real. One of the resilience indicators chosen in Part 4 is the generation system margin, which, as Figure 2.2 shows, can vary greatly from one year to the next.

The second reason why this analysis is inadequate is that were a change in the indicator to be seen after the intervention occurred, it would not be possible to conclude that the intervention *caused* the change. It is possible that an entirely unrelated cause happened to coincide with the onset of privatisation, giving the impression that privatisation had an effect, when in reality its role may have been negligible or non-existent. With a system as complex as the electricity network, such coincidences are not unlikely. For instance, the cyclical behaviour of capacity margins that arises as a result of investment cycles has been well documented and modelled by a number of authors (Dixit and Pindyck, 1994; Ford, 1999; Gross *et al.*, 2007a; Neuhoff and De Vries, 2004; Roques *et al.*, 2005, 2006; Visudhiphan *et al.*, 2001). Such behaviour should be controlled for within the analysis in order to discern the effects of the regulatory intervention of

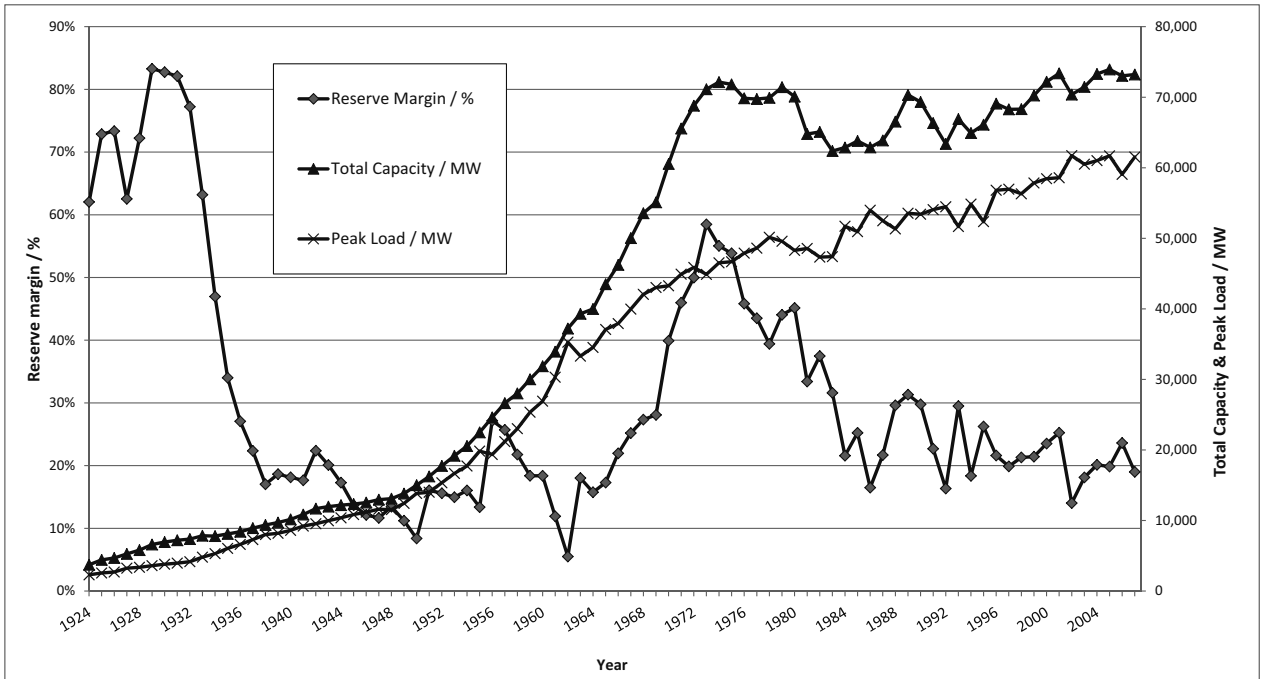


Figure 2.2: UK Reserve Margins 1924 – 2007

interest. Without knowing the specific characteristics of this, and other such, behaviour, it is not possible to subtract this variability from a single time series.

2.3.1.1 Panel Data Modelling

Some of the problems associated with conducting an intervention analysis on the UK alone can be mitigated by instead treating the data from multiple electricity system simultaneously (Harvey, 1996). Statistical methods have been developed specifically to analyse multiple time series in this way, and are well suited to conducting an intervention analysis. Intuitively, by using data from multiple countries to 'learn' about (and thus account for) the underlying structure of the time series, we increase our power to separate any signal, the real effect of a given regulatory change, from the noise. It also reduces the possibility that the effect of the change is disguised by a coincidental event, making it more plausible that a post-privatisation indicator change, if seen, is *caused* by privatisation.

2.3.1.2 Studying Different Regulatory and System Characteristics

The methodologies described above will examine the relationship between privatisation and a given quantifiable resilience indicator. The analysis can, however, be extended to study the impact of different *forms* of privatisation, and to consider the extent to which pre-existing system characteristics can change the impact that privatisation has.

1. Privatisation characteristics
The notion of 'privatisation' simply means the transfer of ownership from the state to private individuals. The extent to which this transfer of ownership carries with it a transfer of operation and planning control varies from system to system. Related to privatisation is the notion of 'liberalisation', which describes the extent to which ownership, both horizontally (across a level in the electricity supply value chain) and vertically (between different levels in the value chain), is divided into separate companies. Rather than just asking whether the data show that privatisation causes a decline in a given resilience indicator, this research is extended to ask about the impact of different degrees and types of privatisation on those margins.

2. System characteristics
In addition to studying the effect of modifying the intervention, this statistical approach can look at the impact of differences between the electricity systems at the point of privatisation. In the epidemiological literature, this is known as 'effect modification' – the extent to which system characteristics alter the effect of an intervention. By looking at such effect modifiers, this research attempts to identify the types of electricity system that are most amenable to a given form of privatisation.

What are the attributes of the electricity system in question? It might be important to know whether certain system types are more amenable to liberalisation. For example, such attributes might include the initial diversity of the generation mix, the proportion of wind, nuclear or hydroelectric generators in the system, the degree of national electrification, or some aspects of the grid such as its age or its size. The state of the wider economy might also be important, in which case characteristics such as national GDP perhaps should be considered.

With only 30 countries being sampled, these system characteristics can only be included selectively in the statistical model. The decision of whether to control for a variable (such as GDP) or instead to assume that it is not relevant to the association between liberalisation and resilience will, as with all statistical analyses, be a matter of informed choice. The choice of these variables

is informed by the literature identified in the systematic review process.

Data permitting, this statistical analysis allows statements of the following form to be made:

"The international experience of privatisation indicates that *[regulatory intervention]* alleviates the risk that *[resilience indicator]* will decline, provided that the system in question has adequate levels of *[system characteristic]*".

So, by way of example, the statement might be:

"The international experience of privatisation indicates that *a capacity payments scheme* alleviates the risk that *generation system margins* will decline, provided that the system in question has adequate levels of *gas-fired generation*".

2.4 Methodological Problems

The proposed methodology raises a number of potential concerns. The definition of 'resilience' and the choice of 'resilience indicators' are both somewhat subjective. The relationship between 'resilience' and 'energy security' can be presented in a number of different ways. There is a diverse range of system behaviours that can be classified as being 'resilient', but this classification is open to interpretation and there can be no assurance that all relevant characteristics have been included. Similarly, it may be that the chosen 'resilience indicators' do not encapsulate the intended range of resilient behaviours, or that the indicator set is incomplete. These problems are minimised by conducting a thorough systematic review of the relevant literature, but there will nonetheless remain a possibility that the interpretations used in this research are not widely accepted.

The quantitative analysis also presents a number of methodological problems. A statistical analysis relies on there being sufficient data and a sufficiently diverse sample to identify correlations between independent and dependent variables. There is a trade-off between the number of privatisation models tested and the ability of the data to reveal true effects. In other words, the data may be able to reveal whether privatisation has an effect on resilience, but less able to distinguish the effect of different forms of privatisation. At the extreme case, if 30 countries are sampled and 30 different interventions tested, the data can reveal nothing about the importance of each intervention.

The systematic review is therefore crucial in informing the selection of just a limited number of intervention types. Furthermore, the interpretative aspects of this research are as important as the numerical analysis. Reasoned arguments, closely tied to the existing energy policy literature, are required to explain the effects suggested by the data, to understand how they relate to the UK system in particular, and to examine how the implications of these results relate to the UK's broader energy policy objectives.

3

Resilience Concepts and Indicators

The use of the term 'resilience' in ecological management was coined by Buzz Holling in 1973 to mean a "measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling, 1973). Numerous revisions of this definition have been made, but they all incorporate some key ideas: a resilient system is persistent or sustainable despite being subjected to a disturbance. Perhaps a useful starting point for thinking about resilient energy systems comes from the following definition: "A resilient system, in a desirable state, has a greater capacity to continue providing us with the services that support our quality of life while being subjected to a variety of shocks" (Walker and Salt, 2006).

This chapter attempts both to expand on, and refine, the various uses of 'resilience' and resilience-related concepts in the wider literature to determine whether such a concept is useful within energy policy analysis, and whether it offers insights that might be missed my the more traditional *security*-driven approaches. As a basis for this work, a systematic review was conducted according

to the protocols described in chapter 2.

3.1 Search and Categorisation Results

The following section describes the results and analysis of the systematic review for each of four research areas:

1. *Energy Security*: the search began with a review of the existing energy security literature to understand the context in which a 'resilience' concept might be used;
2. *Resilience in the energy policy literature*: these results cover the (somewhat limited) existing literature on resilience as it has been applied to energy policy research;
3. *Resilience in the energy wider literature*: the search was extended to incorporate the original uses of the term 'resilience', and its use in the non-energy literature;
4. *Resilience-related concepts*: in order to present as full a search as possible, any concepts explicitly linked by the academic community to 'resilience' or resilient systems were also included in this review.

3.1.1 Energy Security

Applying the search string described in chapter 2 to the Imperial College Library Catalogue yielded 138 unique results. By applying the exclusion criteria, this number was reduced: of the 138 records found, only 117 were energy policy-related documents located in the Environmental Reports section of the library (Call number: Rxxxx), of which 71 did not mention energy security in any way. This left 46 documents that used or defined *energy security*, *security of supply* or a similar term.

The 46 energy policy documents that referred in some way to *energy security* were categorised by their use of the term. The search criteria were fairly broad (i.e. not restricted to strict definitions of the term *energy security*). Descriptions of desirable characteristics of a secure system (e.g. low price, infrequent supply interruptions), for example, were included, as were sources that gave discussed system components or characteristics that led to *system security* (e.g. diversity of sources).

3.1.1.1 Descriptors of a Secure System

Availability

The most commonly used description of energy security in the literature referred to the availability of energy. This availability applied to all stages of the supply chain, ranging from the availability of the primary fuels to the availability of electricity for domestic lighting. In most cases the degree of availability was not specified in the description of energy security but some described it as a relative term, recognising that absolutely guaranteed availability of energy supplies at all times would not be achievable. For example, both the 1997 and 1998 Energy Reports (DTI, 1997, 1998) give a measure of system security in terms of the number of interruptions per unit time or the proportion of time for which electricity is unavailable (minutes per year). There was no aspiration to get these numbers down to zero, but rather to ensure that they decrease year-on-year.

Cost

As well as requiring of a secure system that its supplies be available when required, the majority of policy documents referred to the requirement that these supplies also be affordable. Under this interpretation a system would be described as insecure if energy prices were to go over a certain level, or if the price were to fluctuate too much. The Atomic Energy Research Establishment's paper on renewable energy, for example, explains that the oil price fluctuations of the 1970s were a major driver of the search for more diverse, secure energy supplies (AERE, 1994).

Not only can cost be a *requirement* of a secure system, but it can also be a competing factor since, in general, increasing system security costs money. The 1977 Energy Policy Review (Department of Energy, 1977) recognises this point, saying that increased cost may have to be accepted in order to achieve increased security of supply. At any one time an insecure system could cost less than a secure one; for example, it costs money to ensure that there is a sufficient capacity margin and adequate fuel storage. Decreased risk, therefore, comes at a price, so there is a balance to be struck between security and cost.

Timescales

Three reports recognised that availability and affordability needed not only to be delivered on a timescale of days or even years, but that an energy system must continue to be secure for the foreseeable future. As the DoE's 1978 consultative document on energy policy (DoE, 1978) puts

it: "It is not sufficient to concentrate on achieving a low cost and secure energy supply in the present and immediate future. Energy policy is necessarily concerned with a long time horizon." This view elaborated on a similar consideration of future security needs expressed in the Energy Review published a year earlier (DoE, 1977).

The 1997 Energy Report (DTI, 1997) goes into more detail on the nature of energy security over different timescales:

> Short term security is about the adequacy of capacity at different points in the system as well as arrangements for ensuring the capacity is used in the best manner;
>
> Medium term security may be concerned with ensuring the reliability of existing capacity – making sure that plant is available for use when it is most needed;
>
> Longer term security may be concerned with whether adequate supplies of particular fuels will be available in the longer term – sometimes expressed as fears that a particular fuel will run out or will be available only at very high prices determined by some monopoly supplier or group of suppliers.

This three-tiered structure of security highlights some of the desirable features of a secure system: adequate capacity used effectively and reliably, along with available sources of fuel both now and in the future.

3.1.1.2 Characteristics of a Secure System

The majority of the reports reviewed did not explicitly give a definition of *energy security*, but instead described the concept in terms of the system components that give rise to it.

Diversity and Flexibility

Diversity was the most commonly-cited characteristic of a secure energy system. As was noted in a number of reports, however, diversity is a broad concept that can be applied to the fuels used, the sources of those fuels, and their means of delivery (DTI, 1998), all of which can contribute to energy security.

Diversity in the fuels used was seen as a good way of minimising the impact of global fuel price shocks. This diversity was seen to be particularly effective if the energy system was flexible

enough to make the switch from one fuel mix to another. A 1998 DTI report (DTI, 1998), for example, describes a hypothetical gas shortage which is mitigated by diverting gas supplies to domestic users while the power stations switch to running on distillate oil.

Diversity in the source of fuels was seen to be important for security as it reduced the dependence on a single country or region. Fears about unstable political regimes in oil and gas producing countries, combined with concerns over the activities of cartels (DTI, 1998), led to a belief that the geographical and political sources of fuel should be as varied as possible.

The role of competition in encouraging diversity was seen as important by a number of authors. The Seventeenth Report from the EC Communities (HoL, 1995), for example says: Most witnesses from the UK energy industry argued that diversity of supply was the key to security and that this was best guaranteed by a competitive market . Others, such as the French Ministry of Industry, believed that ensuring security of supply was government responsibility, and that the actions of the market should be monitored to ensure that they were delivering the required levels of security.

The final point on diversity worth mentioning is the DTI's suggestion that not only does the system need to be diverse, but that the means of providing security itself needs to be diverse (DTI, 1998). Storing gas as the sole means of providing security against interruptions is a less secure strategy than building a system that has gas storage, system balancing reserves and generator fuel-switching technologies.

Fuel sources, energy media, technologies and security features all need to be as diverse and flexible as possible in order to maximise the overall security of the system.

Capacity Margin and Storage

One way of delivering security is to have more generating capacity than is required at any time. A system margin is designed to provide a buffer against unexpectedly high demand combined with unexpectedly unavailable supply (perhaps due to a generator breakdown). The 1977 Energy Policy review (DoE, 1977) says that the high cost of a loss of load justifies having more capacity on the system than is expected to be needed.

Storage refers to retaining reserves of fuel to be ready for use should a supply route fail. The value of stored capacity was expressed by a representative of BP's in the EC committee report (HoL, 1995). The primary purpose of storage is to cover short interruptions in supply, but if

there is insufficient storage to accommodate a more prolonged interruption, the EC report noted, this capacity could provide some time to allow an alternative energy source to be found. Others noted the high cost of energy storage, in particular with electricity, and concluded that incentives might be necessary to ensure sufficient levels are maintained (DTI, 1998).

Interconnectedness

The interconnection of energy systems and the generators within that system was thought to increase diversity. One minister cited in the EC committee report (HoL, 1995) put it as definitively as saying the more interconnected you are, the more security of supply you have. This report stressed the importance of international integration, both in the market mechanisms and in the physical infrastructure (e.g. gas pipelines). Once a truly integrated European network is in place, security indicators such as diversity can be assessed at the community level, rather than at the national level.

Indigenous Supplies

Many of the policy documents reviewed were produced in response to one of two issues: the oil price shocks of the 1970s or the perceived need for non-fossil-based fuel sources. Responses to either of these tended to drive the debate of energy security towards finding indigenous sources of energy and minimising fuel imports.

Despite the decreased geographical diversity that comes from expanding the use of indigenous fuels, there appears to have been a widely-held belief that insecurity is to some extent a characteristic of any imported fuel (HoL, 1980), with the implication that this is less true for locally-sourced fuels. This view was partly driven by the British coal, nuclear and renewables industries, which had a vested interest in expanding local forms of energy and minimising competition from other nations.

The House of Commons Energy Committee report on fast breeder reactors (HoC, 1990), looking to the UK's existing oil and gas reserves, said: "The UK of course has no need to work about energy security in the short term." The strong implication here is that indigenous fuels have no implications for energy security whatsoever, ignoring the possibility of oil rig accidents, infrastructure damage or domestic political disruption. The 1977 Energy Review (DoE, 1977) took a more balanced view, considering it imprudent in the longer term to rely on energy imports, but also accepting that indigenous supplies are not always secure.

3.1.2 Resilience in the Energy Policy Literature

Having explored the range of interpretations of 'energy security' in the policy literature, the literature review turned to the concept of 'resilience' itself: first within only the energy policy domain, and then extending the search to include the ecology, psychology, social science and engineering literature.

The journal search for *Energy*, *Power*, *Fuel*, *Electric*, *Gas* and *Oil* gave 55, 36, 8, 31, 53 and 37 results, respectively (which are listed in Appendix B). Following the removal of duplicates and non-energy-related journals (e.g. *High energy chemistry* Journal), 112 unique energy journals remained. Each journal was searched individually, yielding a total of 242 articles containing *resilience* in their text. Each of these was searched visually and those with unrelated or ambiguous usage of *resilience* were removed, leaving just 43 articles from energy-related journals with informative descriptions of *resilience*.

The 43 relevant sources were categorised using the methodology described in section. The themes that emerged fell into three major categories:

1. The nature of the *disruption* to which the system is resilient
2. The *response* of the system to that disruption
3. *Strategies* or system *characteristics* that affect that resilient response.

The tables below describe the full range of resilience-related themes that were identified in the sources, along with the prevalence of each. It should be noted that the absence of a theme from a particular source should not be interpreted to mean that the author would not consider that theme to be a characteristic of *resilience*; it may be just that this meaning has not been explicitly stated in this particular case.

3.1.2.1 Disturbances

As might be expected based on the common sense definition of *resilience* given in the introduction, the majority of references describe resilience in the context of some sort of change or adverse event occurring to the system.

	Event / Change Occurs	Unexpected / Shock / Surprise	Abnormal adverse event?	Uncatastrophic Event	Supply Side Event	Demand Side Event	External Disruption	Internal Disruption	Event Timescale
Records	26	15	11	1	4	1	3	0	1
Percentage Use	60%	35%	26%	2%	9%	2%	7%	0%	2%

Table 3.1: Characteristics of disruption to which a system should be resilient

Disturbance Predictability

In just over a third of cases, this disturbance was taken to be unexpected or surprising in some way, rather than being a predictable or expected event.

Disturbance Magnitude

A quarter of the sources described this event as being abnormal in some way, either in terms of its magnitude or its cumulative effect. Only one source (2%) explicitly considered a system's resilience in terms of its capacity to deal with an uncatastrophic event.

Disturbance Origin

Those references that considered the origin of the disturbance all described it as being outside the system (exogenous) or on the supply side. Only one author referred to demand-side disturbances (Kahn, 1979), but this was to say that his variance model applied to either demand- or supply-side disturbances; this was not an assertion that *resilience* was a measure of a system's ability to cope with demand-side events. Energy system disturbances, therefore, are thought of either as occurring on the supply side of the system, or outside the system altogether. This would exclude, for example, the shock caused by a sudden surge in energy demand.

Disturbance Timescale

Only one author referred to the timescale of the disturbance (Nedic et al, 2006), restricting the use of *resilience* to short-term supply shocks . This reference, however, does not explicitly exclude long-term events such as price trends, and since timescales are mentioned nowhere else, there is little evidence to suggest that the energy policy literature tends to restrict the use of resilience to events of particular timescales.

3.1.2.2 System Responses

	Return / Continuation of Original State/Function	Resistance / Avoidance / Absorption / Tollerance	Reorganisation / Adaptation	Dynamic Effect	Rate of recovery	Cascading Effects	Multiple States / Equilibrium / Domanins / Boundaries / Structures / Processes	Amount of change caused	Level of Recovery
Records	6	8	5	3	2	1	0	0	0
Percentage Use	14%	19%	12%	7%	5%	2%	0%	0%	0%

Table 3.2: Resilient system response characteristics to disruption

The numbers of references using themes that describe the way the system responds to a disturbance were, in general, relatively low. Most references instead focussed on the disturbances to which a system is resilient or system characteristics that lead to system resilience.

Resistance or Adaptation?

Six of the records (14%) described resilience in terms of the ability or tendency of the system to remain in, or return to, its original state or function. An interesting distinction to be made

between the references is that 8 (19%) described this process of return or continuation as occurring through resistance, avoidance, absorption or tolerance. This can be contrasted with the 5 references (12%) that described the mechanism as being one of reorganisation or adaptation. As will be discussed in the analysis section, this distinction between resistance and adaptation may be significant for the design of measures intended to increase the resilience of a system.

Rate of Recovery

Two references (5%) described *resilience* as the rate at which the system returns to normal or the duration for which the system is in a disturbed state. A resilient system will recover quickly, whereas one that is not resilient will return to normal slowly, if indeed it does so at all.

Non-linearity

Four references (9%) described the effect of a disturbance as being dynamic or cascading, suggesting that there may be a non-linear response to a disturbance.

Omissions

Perhaps the most interesting feature of this section is that which is omitted. The final three themes in the above table occur in the following section on *resilience in the wider literature*, but are not mentioned in the energy literature.

Amount of Change: Resilience is not described as the amount of change (on whatever scale) inflicted on a system by a disturbance. One might expect a resilient system to be deflected only a small amount, whereas a system that is not resilient might be deflected much more. This interpretation of resilience was not used in the energy policy literature.

Degree of Recovery: *Resilience* is not described as the degree of the recovery (as opposed to the rate) from a disturbance. A system that returned to a state close to normality might be considered more resilient than one which remained far away from its normal state. These interpretations are not explicitly mentioned, but they may be implied in the use of terms such as resistance and absorption .

Multiple States: The most notable omission from descriptions of resilience is the notion of multiple states and equilibria. There is no mention of the possibility that a system might be pushed by a disturbance into a different equilibrium position with different processes and outputs. No attempt is made to describe the energy system in terms of state diagrams, domains and bound-

aries. As will be discussed in the next section, this approach to thinking about resilience is common in other fields.

3.1.2.3 Strategies or System Characteristics for Resilience

	Solution / Cause	Diversity	Flexibility	Decentralised Generation	Storage/ Reserves	Interconnectedness	Redundancy	Survivability	Size of Generator	Resilient as Local	Resilience through "Intelligent" Control	Scenario Planning
Records	25	10	7	4	4	4	3	3	3	3	3	3
Percentage Use	58%	23%	16%	9%	9%	9%	7%	7%	7%	7%	7%	7%
	Human Response	**Renewables**	**Role of Decision Making in Resilience**	**Self-healing Technologies**	**Efficiency**	**Backup Equipment**	**Supply Shortages**	**Facility Constraints**	**Electricity (as solution)**	**Minimising Elasticities of Uncertain Functions**	**Pattern Recognition**	**Learning**
Records	2	2	2	1	1	1	1	1	1	1	1	0
Percentage Use	5%	5%	5%	3%	2%	2%	2%	2%	2%	2%	2%	0%

Table 3.3: Strategies and characteristics of a resilient system

A combination of the broad search strategy chosen and the focus of the energy papers found a large number of references to resilience strategies and system characteristics that make a system more or less resilient. The thematic categorisation reflects the range of strategies and system characteristics that were identified.

Diversity

The most cited system property that was considered necessary for a resilient system was diversity.

It was argued that a system needed to be diverse in its fuels, generators and supply routes to minimise impact of a disturbance. By having a diverse system, any single adverse event would be unlikely to affect all parts of the system in the same way. A gas price shock, for example, would have less impact on a system for which gas is only a small contributor to the energy mix than it would on a system that is almost exclusively dependent on gas to deliver its energy services.

Flexibility

Flexibility allows the components of a system to change quickly and easily in the face of a change in the external environment. It may be, for example, that generators can switch from the use of one fuel to the use of another without a large investment of time or money. Alternatively, it may be the consumer who is flexible, being able to receive his energy services via a number of different energy vectors.

Decentralised Generation

9% of authors suggested that decentralisation of generators would increase the resilience of the energy system. A smaller number suggested that the size of the generators was important, an attribute that is related to the idea of reducing the prevalence of large, centralised units. Although not all renewable forms of energy are decentralised, some of the resilience-related arguments in favour of renewables focussed on their tendency to be geographically dispersed.

Storage and Supply Shortages

The traditional energy security policy of retaining fuel stores and maintaining capacity margins was reiterated in a number of papers related to resilience. Their authors argued that a system would be more resilient if it had more fuel and generating capacity than would be needed at any time under normal circumstances. Were there to be a sudden cut in supplies, the reserves would be brought online to match the deficit until the disturbance was rectified.

Interconnectedness

Four papers explicitly refer to the interconnection of elements of the energy system, and its impact on resilience. The more players there are in a system, the lower the cost of maintaining the required capacity margin for a given level of risk. If an individual consumer were to provide for his own electricity needs using a dedicated generator, in order to protect against the possibility of that generator failing he would require another unit in reserve. This equates to a 100% capacity margin. Two consumers, each with their own generators, could share a single backup generator,

since it would be very unlikely that both generators failed at the same time; this reduces the capacity margin to 50%. This simplistic example highlights the benefit of connecting as many generators and consumers as possible, and the argument can be extended to say that a European grid should be more resilient than a national one.

Local Generation

Three papers gave the indigenous nature of some forms of energy as a benefit to the resilience of the energy network. There is less uncertainty about the economic and political regime in one's own country, so sourcing and consuming energy within national borders reduces the exposure to adverse events about which one is uncertain or ignorant (to use Stirling's definitions of the terms).

Redundancy

A redundant system can deliver the same output via two or more processes. An electronic circuit may have two components performing the same function where only one might suffice, so that if one fails the other can continue to deliver the required function. The most common use of *redundancy* in an energy system refers to the transmission and distribution network. Wires and pipes are laid in parallel, so that if one breaks the gas or electricity can be transmitted via an alternative route. Total supply failure only occurs if all the parallel routes fail.

Planning and Decision Making

Three authors noted the value of scenario planning for improving the resilience of the system. Disturbances are anticipated and responses are devised that would allow the system to recover readily. Once a real disturbance occurs, the system controllers can make decisions based on these plans, thus maximising the chances that the correct response is chosen. A degree of learning and training of system controllers is implicit in this strategy. It also assumes that disturbances can be anticipated in a useful way.

Self-Healing and Intelligent Control Systems

Three papers discussed the role of intelligent control systems in the management of resilience, whilst one described the functioning of a self-healing system. These systems would respond automatically to changes in their environment, adjusting in order to deliver energy services as well as possible. In theory, they would automate the planning and decision making process described in the previous paragraph; rather than allowing humans to plan and react, this process

would be designed into the system itself.

3.1.3 Resilience in the Wider Literature

This section reviews the non-energy literature that focussed on the concept of 'resilience'. After removing duplicates and invalid records, 1506 unique references were found that contained the word resilience in their title. Some of these came from only one database, whereas some were found in a number of databases. The search results are summarised as follows:

Database Searched	Records Found
CSA Illumina	770
Google Scholar: Eco, Soc, etc.	506
Google Scholar: Concepts	150
JSTOR	63
ScienceDirect	297
ISI Web of Science: Eco, Soc, etc.	200
ISI Web of Science: Concepts	57
Total (including duplicates)	**2043**
Total (after duplicates removed)	**1506**

Table 3.4: Number of records in databases searched

The Eco, Soc, etc. and concepts tags associated with the Google Scholar and the Web of Science sources refer to the search terms used, as described in the Methodology section of this report.

Of these 1506 unique results, 238 did not have abstracts available, either because the articles had no abstract, or because the journal from which they came was not accessible from the Imperial College network. This left 1268 references with abstracts that could be searched for resilience definitions.

178 references were found to contain a definition of resilience in their abstracts. These are given in full in Appendix C. The decision whether to include or exclude a reference was open to a certain amount of subjectivity. Some abstracts had clear definitions (e.g. ... resilience was defined as...) whereas others treated resilience as a synonym of another concept, such as resistance or persistence (e.g. ... functional similarity... may be equally important in ensuring persistence (resilience) of ecosystem function...). All the uses of the term, ranging from the synonyms to the explicit definitions, were included in the conceptual analysis.

3.1.3.1 Academic Disciplines Reviewed

The literature search was very broad, and was not restricted to a few academic disciplines. Table 3.5 summarises the academic fields from which the definitions of *resilience* have been drawn. Where a reference refers to two or more fields (e.g. socio-ecological, or ecological & economic) both are counted.

Ecological	Human	Social	Psycho-logical	Bio-logical	Network	Economic	Family	Natural Disasters	Water
81	42	19	19	7	7	6	4	4	3
Coastal	Chemical Engineering	Genetic	Business	Dental	Educat-ional	Electronic	Engine-ering	Environ-mental	Supply Chain
2	2	1	1	1	1	1	1	1	1

Table 3.5: Record count by discipline

3.1.3.2 Thematic Categorisation

The definitions of *resilience* found within the various academic fields were compared and categorised. These themes fell into one of two categories:

- the nature of the adverse event experienced
- the response of the system/individual to that adverse event

Before analysing the prevalence of themes in the resilience literature it should again be noted that the search criteria for this section and the energy-specific resilience search were not the same as each other. In particular, given the number of resilience-related papers available in the full body of literature, the search was restricted to those articles that actually defined resilience in their abstract or introduction. The themes that emerged were therefore less broad than those for the energy-literature search; the latter included, for example, papers that described how to improve resilience, but that did not actually define it.

	Adverse Event			System response						
	Event / Change Occurs	Internal Event	Abnormal adverse event?	Return / Continuation of Original State/Function	Resistance / Avoidance / Absorption / Tollerance	Reorganisation / Adaptation	Multiple States / Equilibrium / Domanins / Boundaries / Structures / Processes	Rate of recovery	Amount of change caused	Level of Recovery
COUNT	**133**	**8**	**19**	**95**	**34**	**32**	**27**	**24**	**1**	**3**
PERCENTAGE USE	**75%**	**4%**	**11%**	**53%**	**19%**	**18%**	**15%**	**13%**	**1%**	**2%**

Table 3.6: Summary of the prevalence of themes in the resilience literature

3.1.3.3 Adverse Events

Three-quarters of the references surveyed defined *resilience* in terms of an adverse event or change, consistent with the use of the term in the energy literature. In the majority of these cases, the event was external to the individual or system. External events included natural disasters impacting on ecosystems, violence being inflicted on individuals, and stresses being applied to materials. Only 8 (4%) defined *resilience* in terms of the system's or individual's ability to respond to an endogenous event.

A larger proportion (19%) defined resilience in terms of explicitly abnormal events, rather than in terms of small variations in environmental conditions. This is consistent with the approach taken by *resilience* references from the energy literature.

3.1.3.4 System/Individual Response

Over half of the references defined *resilience* as the return to, or continuation of, the original state or function. This recovery was described in a number of different ways.

Resistance and Adaptation

There are two general ways in which the system or individual brings about that return/continuation: resistance (19%) or adaptation (18%). The resisting process involves attempting to continue in

exactly the same way despite the disturbance experienced, whereas the adapting process is an active response to a disturbance in which the primary system function is maintained, but the underlying processes are altered to accommodate the changed environment.

Rate of Return

As with the energy-related literature, some references (13%) defined resilience as a rate of recovery. A resilient system or individual returns to its original state quickly following a disturbance, whereas an unresilient system does not.

Amount of Change and Degree of Recovery

Three references define resilience as the degree of recovery a system can achieve, and one defines it as the amount of change a given disturbance can cause a system to undergo. Neither of these interpretations was found in the energy literature.

Multiple Equilibria

The most notable theme that emerged from the wider literature that was not present in the energy literature was that of multiple equilibria. 27 of the definitions (15%) defined *resilience* by using the visual representation of a phase diagram. Some defined resilience as the ability of the system to stay in one domain of attraction in the face of a disturbance, some defined it as the time taken to return to an equilibrium point, while others defined it as the ability of a system to stay in, or revert to, a useful equilibrium, even if this is not necessarily the original equilibrium.

3.1.4 Resilience-related Concepts

As was explained in the methodology section, concepts that were thought to be relevant to a discussion on *resilience* were recorded. This section describes each of these terms, and how the authors used them.

3.1.4.1 Adaptability and Adaptive Capacity

According to Walker (Walker et al, 2004), adaptability is the capacity of actors in the system to influence resilience. Gunderson provides a similar definition of the term: adaptive capacity is introduced to describe the processes that modify ecological resilience (Gunderson, 2000). Used

in this way, *adaptability* is not a property of a resilient system, but rather a property of a system that allows it to change its own resilience. A system may not be resilient at one time, but because of its high adaptability, it may be able to make itself more resilient to disturbances. The Resilience Alliance provides a more comprehensive definition:

> Adaptability is the capacity of a social-ecological system (SES) to manage resilience in relation to alternate regimes (sometimes called adaptive capacity). It involves either or both of two abilities:
>
> 1. The ability to determine the trajectory of the system state – the position within its current basin of attraction;
> 2. The ability to alter the shape of the basins, that is move the positions of thresholds or make the system more or less resistant to perturbation (Resilience Alliance, 2007)

Again, *adaptability* can change system resilience, but it is not necessarily a component of a resilient system. Rather it is a property that allows a system to change the size and shape of its domain of attraction to make itself resilient.

The definition of *adaptation* given by Chaplin *et al.* (2006) is similar to that of *adaptability* given above, but subtly different: adaptation is developing new socioecological configurations that function effectively under new conditions. The implication of this definition is that an adaptable system can respond to a disturbance or a change that has just occurred, whereas the previous definition of adaptability says that adaptable system can change to prepare for an unknown change, thus increasing its resilience.

3.1.4.2 Amplitude

Amplitude is Westman's second component of *resilience* (see also *elasticity*, *malleability,* and *damping*) (Westman & O'Leary, 1986), defined as the threshold of disturbance beyond which recovery to the original state no longer occurs . This is the systems equivalent of the elastic limit used in materials science. By implication, this definition applies to those systems with more than one equilibrium position.

3.1.4.3 Cascading Thresholds

Kinzig (2006) describes cascading thresholds as the tendency of the crossing of one threshold to induce the crossing of other thresholds . He goes on to explain that these events often lead to very resilient, although often less desirable, alternative states . Linked to the notion of non-linearity, this concept addresses the possibility that the final equilibrium position following a regime shift may not be the one expected. On a network level, a disturbance that causes one region to become unstable can destabilise regions that might not be expected to be affected. This makes the calculation of risk assessments for responses of this sort very difficult to calculate.

As an aside, the explanation of this concept provides one of the few references that recognises that a system state may be very resilient but undesirable. Resilience is therefore only desirable if the configuration that it is attributed to is itself desirable.

3.1.4.4 Damping

Damping is Westman's fourth component of *resilience*, defined as the extent and duration of oscillation in an ecosystem parameter following disturbance (Westman & O'Leary, 1986). This definition has parallels with those papers that define *resilience* as a rate of return to normality or the deviation from normality caused by a disturbance. Resilience might therefore be treated as a weighted combination of different damping values for each of the system parameters.

3.1.4.5 Disturbances

The range of possible disturbances has to some extent been covered in the discussion of *resilience* definitions in the sections. In addition, it is worth mentioning Bengtsson's description of disturbances as it highlights the distinction between disturbances of different timescales, and between disturbances of different origins (whether they are endogenous or exogenous):

There are basically three types of disturbances:

1. pulse disturbances that are parts of ecosystem dynamics and to which most organisms are adapted

2. large infrequent disturbances, and

3. press disturbances, which are usually anthropogenic and to which organisms are seldom pre-adapted (Bengtsson, 2002)

An ecological disturbance might be a natural disaster or a chemical or biological pollutant (produced either exogenously or endogenously). An energy system disturbance, by analogy, might be a physical malfunction of the network, the collapse of an energy supply company, or a shift in the political regime of an oil-producing company.

3.1.4.6 Elasticity

Elasticity is given by Westman as the first component of resilience (see also *amplitude*, *malleability* and *damping)*, defined as the rate of recovery following disturbance Westman & O'Leary (1986). Related to *damping*, this system property describes resilience in terms the *duration* for which a system is outside its bounds of normal operation.

3.1.4.7 Inertia

Inertia is a word used by Westman to describe the resistance of an ecosystem property to change under stress Westman (1986). There is a further discussion of *resistance* below.

3.1.4.8 Stability Landscape

A *stability landscape* is a metaphor used by Walker *et al* (2004) to portray what they see as the four components of resilience: latitude, resistance, precariousness and panarchy. They go on to define the concept as the various basins that a system may occupy, and the boundaries that separate them . In other words, the *stability landscape* defines the shape and size of the domains of attraction in a multi-equilibrium system.

3.1.4.9 Latitude

One of the four components of resilience described by Walker *et al.* (2004), *latitude* is the maximum amount a system can be changed before losing its ability to recover (before crossing a threshold which, if breached, makes recovery difficult or impossible).

3.1.4.10 Malleability

Westman's third component of *resilience* (see also *elasticity*, *amplitude* and *damping*), *malleability* is defined as the extent of alteration of the new stable-state from the original (Westman and O'Leary, 1986).

3.1.4.11 Memory

Bengtsson *et al.* 2003 say that for ecosystems to reorganize after large-scale natural and human-induced disturbances, spatial resilience in the form of ecological memory is a prerequisite. The ecological memory is composed of the species, interactions and structures that make ecosystem reorganization possible . Peterson (2002) provides a definition of ecological memory: "the degree to which an ecological process is shaped by its past modifications of a landscape." To clarify, he gives an example: "if the location of tree-fall gaps is influenced by where past tree falls occurred or if fire spread is influenced by previous fires, then memory is shaping their dynamics."

3.1.4.12 Panarchy

Panarchy is a term coined to describe the interactions between the different scales of structures and processes in an ecological system:

> No system can be understood or managed by focusing on it at a single scale. All systems (and SESs especially) exist and function at multiple scales of space, time and social organization, and the interactions across scales are fundamentally important in determining the dynamics of the system at any particular focal scale. This interacting set of hierarchically structured scales has been termed a panarchy (ResAlliance, 2009a).

3.1.4.13 Performance-Survival Threshold (PST)

The PST is the level of disturbance beyond which a system's actors switch from performance strategies to survival strategies (Bradley and Grainger, 2004). In other words, the system shifts

from a state in which it delivers its required output in the optimal way, into a state in which it operates sub-optimally in order to survive.

3.1.4.14 Persistence

Beddington *et al.* use *persistence* simply to mean the ability of an individual or population to continue to exist in the face of disturbances: The persistence of populations in the real world depends on their ability to withstand perturbations imposed by either exogenous or endogenous factors (Beddington *et al.*, 1976).

3.1.4.15 Precariousness

One of the components of *resilience* identified in a paper by Walker *et al.* (2004), describing how close the current state of the system is to a limit or 'threshold.'

3.1.4.16 Protective Factors

Protective factors are specific competencies that are necessary for the process of resilience to occur (Dyer and McGuinness, 1996).

3.1.4.17 Quality

Quality can be used to describe the ability of an entity or system to deliver the services required of it: The term soil quality refers to the soil's capacity to perform its three principal functions e.g. economic productivity, environment regulation, and aesthetic and cultural values (Lal, 1993).

3.1.4.18 Reliability

Reliability, vulnerability, and resilience provide measures of the frequency, magnitude, and duration of the failure of water resources systems, respectively (Maier *et al.*, 2001).

This description suggests that reliability measures the frequency of failure of a system. This concurs with the use of the term in Safety and Reliability Engineering, which defines the reliability of a component as the probability that it will continue to deliver the required function for the specified period. Overall system reliability is then calculated by combining the reliabilities of the respective components. The method of combination depends on the relationship between the components. For example, if two resistors, A *and* B, are both required for a system to work, their reliabilities are combined multiplicatively; if the system can work with either A *or* B (i.e. the system has redundancy) the respective reliabilities are combined additively. The overall system reliability is therefore a function of the reliability of its components and the way in which those components are configured.

3.1.4.19 Resistance

Resistance is used by a number of authors as a generic term meaning tolerance of change. Others use it in a way that makes it indistinguishable from some interpretations of *resilience*: " . . . it is important to determine factors which prevent the ecosystem from assuming a new organizational state following disturbance (ecosystem resistance). . . " (Waide, 1988).

Another interpretation of resistance is that it is a measure of the initial response of the system, whereas resilience is a measure of the long-term response. For example, Cole (1995) uses resistance in the following way: Resistance and tolerance are determined from the vegetation surviving 2 weeks and 1 year after trampling, respectively. Resistance, therefore, describes the initial response of the system to a disturbance.

Perhaps the most useful conceptualisation of resistance is as a preventative measure, as opposed to a coping mechanism: "Resistance strategies aim at flood prevention, while resilience strategies aim at minimising flood impacts and enhancing the recovery from those impacts." (de Bruijn, 2004). Resilience strategies, therefore, would not attempt to prevent disruptions from occurring, but would focus on mitigating their effects. De Bruijn goes on to say that a resilience strategy is supposed to be able to better cope with uncertainties than a resistance strategy. It is not feasible to try to shield the energy system from all disruptions, and it may make more sense to attempt to minimise the impacts and enhance the subsequent recovery when the unexpected happens.

3.1.4.20 Services

Ecological services are the products of an ecosystem that are of value to humans. Examples include the conversion of solar energy into food, the provision of clean water, the balance of gas mixes in the atmosphere and even the aesthetic value of, say, a woodland area. Energy services by analogy include the provision of light, warmth, transport, cleaning services, communication and entertainment. The link between ecosystem and energy services is particularly strong if one takes an entirely anthropocentric view of ecological systems, treating their products and functions solely as a means of sustaining and enhancing human existence.

An energy service, rather than energy itself, is what matters to a consumer. A requirement of a resilient system, therefore, might be that it continues to deliver the required energy services (regardless of the energy source used) in the face of a disturbance.

3.1.4.21 Social Learning

Social learning is used by Folke (2006), Moench (2005), Thompkins and Adger (2004) in the context of resource management. Social learning theory, propounded by Bandura (1977), says that learning only happens in a social context, through the observation, imitation and modelling of the actions of others.

Whatever the precise relevance of this type of learning to resilience, what is interesting is that the sentient actors in a system are considered by some authors to be important for ensuring a resilient system: this is seen both in this concept of *learning* and, by others, in the concept of *memory*. It is not sufficient to build a robust physical infrastructure, or even to have strong economic and political measures in place to respond to disturbances. The management of resilience in a system is a process that relies on the continual exchange of experiences between the system actors, and the ongoing effort to learn from these experiences to make the system more able to respond to unknown future events.

3.1.4.22 Stability

Stability, like resilience, is a term that is used in a number of different ways. A number of authors use these two terms interchangeably, using stability almost as a synonym of resilience.

It might be more useful to use *stability* in a way that is distinguishable from *resilience*. Westman defines *stability* as "the pattern of natural fluctuation in ecosystem properties in the absence of major exogenous disturbance" (Westman, 1986). Notable in this definition is that it excludes the system response to large external disturbances.

Gunderson (2000) provides a clear distinction between stability and resilience. Stability of a system, he says, is characterised by the time taken to return to equilibrium following a disturbance, whereas *resilience* is the amount of disturbance that a system can absorb without changing state. Stability is concerned with the system response close to the equilibrium, whereas resilience is concerned with the system far away from equilibrium, near the boundaries of the domain of attraction.

A system may be stable (quickly returning to equilibrium) but not resilient (a relatively small disturbance will push the system into a new equilibrium) or vice versa. The analogy with materials science would be a material that was very stiff (did not deform much under stress) but was also very brittle (once it is taken past a certain level of strain it fails irreversibly).

3.1.4.23 Stable States

The state of a system at any time is defined by the values (amounts) of the variables that constitute the system (Resilience Alliance, 2007). For example, an ecological system might have two stable states: one that has 80% of Species A and 20% of Species B, and one that has 30% of Species A, 40% of Species B and 30% of Species C. These proportions would define each state, and would remain at these levels (allowing for random fluctuations) in the absence of external disturbances. An energy system's stable state might be defined by the proportion of its fuels, of its power stations, or by the energy services it provides.

3.1.4.24 Transformability

Transformability is related to adaptability, but the degree of change is more substantial. Walker defines the term as the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable (Walker and Meyers, 2004). The Resilience Alliance uses the concept in a similar way:

> In cases where a system is already in an undesirable regime and efforts to get it back into a desirable regime are no longer possible (or worse, make the undesirable basin larger), one option for resolving the predicament is transformation to a different kind of system – new variables, new ways of making a living, different scales – a different panarchy (Resilience Alliance, 2007).

Whereas adaptability is the ability of the system to alter its processes enough to be able to continue delivering a similar output, transformability is the ability to change into an entirely new system, delivering an entirely different set of services. To use a managed ecosystem as an example of this distinction, an adaptation may be the shift from one crop to another because of a rapid change in the local climate. A transformation might be shifting from agricultural farming to, say, cattle rearing. The line between adaptation and transformation is clearly not fixed, but the distinction between the two concepts might be useful.

From an energy perspective it is unclear what sort of change would constitute a transformation. It may be that it applies more to the individual actors in an energy system: for example, an energy supplier might decide that telecommunication is a more viable industry, and apply resources to that end instead. A transformation of the energy system as a whole is harder to imagine.

3.1.4.25 Vulnerability

Most definitions appear to use vulnerability as a measure of a response to a disturbance: either in terms of the magnitude of the failure caused (Maier et al, 2001), or the shortfall in system output as compared with normal performance (Moy et al, 1986).

Perhaps the most comprehensive definition of this term found in the literature review comes from Adger's article, *Vulnerability*:

> Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt (Adger, 2006)

The inability of vulnerable systems to adapt was also identified in the IPCC report:

> ...a highly vulnerable system would be a system that is very sensitive to modest changes in climate, where the sensitivity includes the potential for substantial harmful effects, and for which the ability to adapt is severely constrained. (IPCC, 2001)

Vulnerability, therefore, is the sensitivity of a system to change – although the magnitude of that change is not agreed – and the inability to respond positively when such a change occurs. As regards its relation to *resilience*, the IPCC report goes on to say:

> Resilience is the flip side of vulnerability—a resilient system or population is not sensitive to climate variability and change and has the capacity to adapt.

The value of the *vulnerability* concept, therefore, appears to be that it provides a description of a system that lacks the quality of *resilience.*

3.2 Analysis and Discussion

The purpose of this analysis is to bring together the concepts of *energy security* and *resilience* found in the academic and policy literature in order to understand the meaning and value of *resilience* to an energy system. The results section identified *energy security* and *resilience* themes in the energy literature and in the wider academic literature. This section develops some of these themes further, focusing on those that appear to be the most relevant to resilience in the context of energy security.

3.2.1 The System

A detailed description of the *system* to which the concept of *resilience* can be applied was somewhat lacking in the majority of the papers reviewed. Such a description is crucial for defining resilience, and for developing strategies to manage it. The *system* is described by its geographical and political boundaries, and the elements contained within it.

3.2.1.1 System Scale

Most of the papers reviewed described a resilient system as one that responds positively to a disturbance. Almost none suggested that a resilient system would prevent the disturbance from happening at all; perhaps the term *resistance* discussed in paragraph would be more appropriate for this type of disturbance avoidance. A policy devoted to energy security more widely may indeed attempt to prevent disturbances (e.g. attempting to prevent oil supply disruptions through diplomatic intervention) but *resilience* is an intrinsic property of the system that allows it to deal with shocks but has nothing to do with preventing their occurrence.

A system's resilience, therefore, is independent of events and circumstances outside the influence of the system itself. This assessment is largely in agreement with the working paper produced by Skea (2007) in which he says the energy system is effectively bounded by what is in the sphere of influence of UK institutions . As he notes, the sphere of influence over energy infrastructures and policies does not have well-defined edges. The UK has some influence over European energy policies, for example, through its role in the EC, but much less than the influence exerted within its own national boundaries. Deciding how to quantify this partial control is a challenge in itself, but it is sufficient for the purposes of this discussion to say that a boundary exists, and that UK resilience-building strategies apply to those parts of the energy system under some degree of UK control.

3.2.1.2 System Elements

As well as defining the scale of the resilient system, one also needs to specify its *components*. The House of Commons Trade and Industry Committee report (2004), *Resilience of the National Electricity Network* suggests that resilience is brought about by strengthening the physical energy infrastructure. While the physical network is certainly important, it is not the only component of resilience. As well as the wires and pipes, the type and quality of the generators have an impact on resilience, as do any storage systems, designed to smooth out mismatches between supply and demand.

But the energy system consists of more than just physical components; it also includes economic and political mechanisms. Two systems could have the exact same physical configuration, but because of a difference in the way that their fuels are traded, one could be more resilient than the other. For example, one could purchase a year's worth of fuel in advance and over a period of

time to protect against price shocks, whereas the other could buy its fuel 'just in time' to meet the current demand, exposing it to price rises but also reaping the benefits of dips in the market. An example of a political difference between the two systems might be the government's attitude towards nuclear power or CO_2 emissions. Both systems might have a number nuclear generators and a large proportion of coal-fired power stations on standby, but because of the political climate in one scenario, its ability to ramp-up its coal-fired generation may be restricted.

The third component of the energy system consists of the human decision-makers. For a given physical system, with given economic and political mechanisms in place, the ability of human actors to communicate with each other, respond to crises and learn from prior experience may be extremely important for the resilience of an energy system.

The supply side of an energy system should not be overlooked in a resilience management strategy. Resilience affects consumers, but the actions of consumers can also affect the resilience of the system. There currently exist contracts between electricity suppliers and large electricity consumers (such as aluminium smelters) to switch off during periods in which demand threatens to outstrip supply. Such a strategy could, in theory, be extended to incorporate individual domestic appliances. Let us imagine a situation in which electricity demand exceeds the ability of the system to supply electricity. The system is designed in such a way that the lights in 1000 houses dim to 80% of their normal brightness. There are two ways of categorising this event. The first is to argue that this is an example of a failure to supply, and is therefore indicative of a system that is not sufficiently resilient. The other view of this event is that the loss of 20% of brightness was a mechanism by which the system was able to act in a resilient manner. The energy consumers would probably have been largely unaffected by the dimming, and it allowed more critical appliances to continue operating.

The domestic lighting scenario is only a hypothetical scenario, and does not explain how these different priority levels would be assigned to individual appliances, but it serves as a reminder that a resilience strategy needs to consider both supply and demand. Large negative load suppliers already add to the resilience of the system, and an argument can be made for including examples such as the brown out scenario as a last-resort resilience mechanism by which the critical parts of an energy system can survive. This way of thinking could lead to the development of technologies and domestic supply contracts that take full advantage of the ability of some appliances to operate at sub-optimal levels (e.g. light bulbs) or switch off for a period of time (e.g. refrigerators, immersion heaters) in order to ensure that more sensitive appliances such as computers and televisions can be supplied with power more reliably.

3.2.1.3 System Summary

An energy system extends as far as its actors exert political or corporate influence over its operation. Within those boundaries, the system includes the entire physical infrastructure (including wires, pipes, generators, storage units and end-user loads), the economic and political infrastructure, and the actions of the human players in the system, either as generators, suppliers or consumers. To fail to recognise any of these system elements is to risk missing an opportunity to improve the resilience of the system.

3.2.2 Disturbances

Resilience is mostly considered in terms of the response of a system to an adverse event. In order to assess the resilience of a system, therefore, it is necessary to decide what it needs to be resilient to. These disturbances, as will be discussed, tend to be unpredicted, or even unpredictable. As a result, it is not possible to construct a comprehensive list of all the adverse events that might befall an energy system. As the 2006 incident involving the contamination of petrol by silicone (Smithers and Adam, 2007) demonstrated, no energy security model can hope to anticipate every eventuality.

Instead of defining resilience in terms of a list of exemplar disturbances (which can never comprise the full list of possible events), it makes more sense to define it in terms of a range of disturbance characteristics. For example, one can say whether a resilient system needs to deal with only unexpected events beyond the control of traditional energy security measures, or whether it should also respond to statistically predictable *risks*. Alternatively, one might ask whether resilience applies only to potentially catastrophic events, or whether minor variations should be included. The following sections discuss each of these disturbance characteristics in turn.

3.2.2.1 Disturbance Predictability

The adverse events to which a system should be resilient can differ in their predictability. This predictability has been categorized by Stirling (1998), placing future events into one of three categories: *risk*, *uncertainty* and *ignorance*.

A *risk* is an adverse event which can be anticipated and has a known probability of occurring.

Each of the engineered components of the electrical network, for example, will have a number of known failure modes, each of which will have a certain estimable chance of occurring, based on testing or observation of similar components in operation.

An *uncertain* event is one which can be anticipated but not with a particular probability of occurring. It may be that the event has never happened before, or it could be that the existing circumstances have sufficiently altered since the last time the event occurred, so that past instances are a poor predictor of future instances. A changing climate, for example, may place certain extreme weather events into this *uncertain* category.

An event about which one is *ignorant* is one that cannot be anticipated at all, and certainly not with any meaningful probability. By the nature of these events it is difficult to suggest examples, as to do so would be to anticipate them. It is possible, however, to reflect on past events and to ascertain whether a resilient system would have been more able to cope with them. The silicone-contamination of petrol incident, for example, was not anticipated, and could be reasonably described as an event about which we were ignorant. Nonetheless, one can still say that one sort of transport network would have been more able to cope than another, by nature of its fuel diversity (e.g. through the use of flex-fuel vehicles), or the ability of travellers to use alternative modes of transport.

There is no reason to exclude any of these types of incertitude from a definition of *resilience*. The more predictable disturbances will, however, already be managed by more traditional forms of energy security provisions. Engineering *risks*, for example, are already well understood, and are minimised through system design approaches outlined in the *reliability engineering* literature: building redundancy into critical systems, having sufficient margins to minimise risks of overload, deliberately stressing components prior to installation to minimise the risks of infant mortality, staggered monitoring and replacement of system elements, and the implementation of strict quality control measures in the design of system components.

Resilience management can inform these existing approaches to maintaining system reliability, but it will be most useful in dealing with the less predictable disturbances, which may not be encompassed by risk-based measures.

3.2.2.2 Disturbance Magnitude and Timescale

Related to the predictability of adverse events is their magnitude. Large adverse events tend to occur less frequently and be less predictable than more minor system variations. *Resilience* has tended to be used to describe the system's ability to respond to these abnormally large disturbances. Like the disturbance predictability described above, however, there seems to be little reason why resilience should not be concerned with smaller-scale variations as well as large disturbances.

The approach to managing the small changes may be rather different from the approach to managing the more catastrophic events. It this proves to be the case, a resilience management strategy would probably be more concerned with the system's response to the larger events. *Stability management* could instead be the concept used to describe steps taken to minimise these smaller variations, leaving *resilience management* to cope with the system's response to larger, less frequent, disturbances.

3.2.2.3 Disturbance Timescale

The timescale of the disturbance can have a strong effect on the ability of the system to recover. A system can be disrupted by a slowly-developing event, whose impact can be larger then a short-lived large disturbance. An ecological system, for example, can be disturbed by a single flooding event, but the cumulative effect of wetter weather brought about by climate change may be more destructive for the system overall. An energy system may be disturbed by a short-lived fuel price shock, but it also needs to be able to cope with a gradual, but sustained, increase in the price of fuel over the long-term.

A system, therefore, needs to be able to resilient to disturbances ranging from the very short timescales to the very long. The approach to delivering this resilient response may be different in each case, but they are all important for maintaining the integrity of the system both now and in the future.

3.2.2.4 Disturbance Type

Disturbances can be categorised into different *types*, such as physical, economic or political. Physical disturbances include weather-related events and the breakdown of generators or cabling. Economic disturbances include price shocks and the collapse of energy companies. Political disturbances are those related to political decisions or regime changes. Any of these can affect the integrity of an energy system, so a resilience model will have to consider all these disturbance types separately, as well as combining them is a meaningful way to create an overall picture of the resilience of a system.

3.2.2.5 Disturbance Origin (External or Internal)

Should a resilient system be able to respond to endogenous disturbances, exogenous disturbances or both? Those authors who addressed this point mostly considered only exogenous disturbances, that is to say those disturbances that occur outside the sphere of influence of the affected system. This would exclude those events which the system itself has caused; a domestic fuel blockade and the simultaneous collapse of a number of large UK power stations are both events that are endogenous to the UK energy system. A direct carry-over of definitions from the wider resilience literature would suggest that a resilient system need not be designed to respond to such events, the logic perhaps being that they would be dealt with via a mechanism other than resilience management.

Determination of the origin of the disturbance is reliant on the definition of the *system scale* discussed above (paragraph). The energy system extends as far as its actors can exert influence over the decisions made. For the sake of consistency, an exogenous disturbance must have a similarly gradual transition; an adverse event that occurs in Europe is partially exogenous to the UK, as it occurs in a region over which the UK has partial influence.

Despite the conviction in the wider resilience literature that *resilience* is the ability of the system to respond only to external events, it does not seem to be a particularly useful restriction to make on the use of the concept. From the point of view of the system, there is little difference between an exogenous and an endogenous disturbance. Let us imagine two large transmission lines: one running from the north to the south of Britain, and the other running from France to the UK. Any elements of the UK energy system that rely on these lines will experience the same effect regardless of which one breaks. Designs that help the system to respond positively to one of these

events will inevitably be protecting against the other. The intuitive interpretation of *resilience* would suggest that a resilient system should respond positively in either scenario.

3.2.3 System Response

The generally agreed definition of a resilient system was that it had the ability to maintain or recover its original processes in the face of a disturbance. However, the means by which this process occurs, and the precise nature of the recovery, is open to discussion.

3.2.3.1 Resistance or Adaptation?

One of the most striking differences found in the *resilience* literature is the distinction between systems that *resist* change and those that *adapt* to it. A system that resists a disturbance will have components that are individually and collectively resistant to change. A resistant system will not only maintain the same outputs following a disturbance, but will also maintain all its underlying processes. A system that is resilient by means of its adaptability will continue to deliver the same outputs following a disturbance, but not necessarily through the continuation of the same underlying processes.

A related term to resistance is *stability* which can be described as the invariance of a system. A system that is stable will tend to keep the same configuration regardless of changes in its external environment. This, however, is not necessarily synonymous with *resilience*, since a system can be unstable, in the sense that it varies considerably around an equilibrium configuration, but resilient, in the sense that it is very unlikely to change into a different equilibrium that has undesirable outputs. Holling (1973) even goes so far as to say that *instability* is a mechanism by which a system can enhance its resilience:

> ... a system can be very resilient and still fluctuate greatly, i.e. have low stability. I have touched above on examples like the spruce budworm forest community in which the very fact of low stability seems to introduce high resilience... This statistical analysis shows that in those areas subjected to extreme climatic conditions the populations fluctuate widely but have a high capability of absorbing periodic extremes of fluctuation. They are, therefore, unstable using the restricted definition above, but highly resilient. In more benign, less variable climatic regions the populations are

> much less able to absorb chance climatic extremes even though the populations tend to be more constant. These situations show a high degree of stability and a lower resilience.

Holling's argument is that ecosystems that face regular disturbance may have large fluctuations in population, but they have evolved to persist in the face of larger disturbances. By analogy, attempting to optimise the stability of the energy system could have a negative effect on its resilience.

Managing *resistance* might involve protecting generators and suppliers from fluctuations in energy prices or subsidising large fuel depots to allow the incumbent generators to continue delivering energy to the consumer in times of crisis. Conversely, managing *adaptability* might involve exposing generators and suppliers to market fluctuations and encouraging fast transitions between different supply routes and generating options.

Stability itself may be desirable, in order, say, to protect poor consumers against unstable energy prices, but it should be realised that there can be consequences for the ability of the system to respond to recover from larger disturbances. Consumers and generators might suffer in the short-term from an unstable energy system, but this might be acceptable given the longer-term benefits of resilience. Whatever the relationship between resilience and stability, it would seem sensible to treat these two policy objectives separately.

3.2.3.2 Energy Services

In order to understand the most appropriate conceptualisation of resilience in the context of energy security one must consider what it is that we want from an energy system. One of the closest analogies to the energy system is the ecological system. Both have a number of interacting components that are constantly changing and are subject to external disturbances. A number of authors refer specifically to the maintenance of ecological services as the goal of resilience management. In other words, one can think of ecological systems as networks of components and interactions that serve to deliver humans with some sort of benefit. Examples of such benefit include food, oxygen and clean water supplies.

This anthropocentric view of nature provides the closest analogy with energy system resilience. Purely as end users of energy we have little interest in the form or source of that energy or

how it arrives at the point of use. What interests us as consumers is the function that the energy provides. These *energy services* include lighting, heating and communication, and are analogous with the concept of *ecological services*. An energy system, then, is resilient in the face of disturbances if it can continue to deliver these energy services to the consumers, regardless of the means by which this is achieved.

The idea of *quality* discussed in the section might be useful as an umbrella term to measure the ability of an energy system to deliver energy services. Resilience could then be defined in terms of the change in system quality that occurs following a range of possible disturbances.

The focus on energy services could be considered too narrow a way of thinking about system resilience as it ignores the needs of those employed in the delivery of energy services. Just as an anthropocentric view of nature might only consider species in the context of their role in delivering ecological services, so a consumer-centric view of energy systems only looks at individual generators and suppliers in the context of the delivery of energy services. To broaden the focus, one might also want to consider, for example, the plight of coal mining communities in the dash for gas period. Rather than just thinking about the impact on resilience of the shift from coal fired to gas fired power stations (say, the effect of a loss of indigenous supply options), one might want to take the protection of these mining communities as a social policy in its own right.

While it is important to consider the needs of energy workers, there does not appear to be a compelling reason why this needs to be integrated into a resilience strategy. The interests of the generators and suppliers can still be met, as can those of CO_2 reductions or the eradication of fuel poverty, in conjunction with resilience policies. There may be some overlap between these objectives and that of resilience, but it should be possible to analyse them separately and apply them collectively when developing national energy policies. Resilience management, then, can then be thought of solely in terms of the ability of the energy system to deliver energy services to the end users.

3.2.3.3 System Equilibria

There is a large discrepancy between the representations of resilient systems used in the energy policy literature and in other fields such as ecology. Ecological representations of resilience often describe a system in terms of stable states with multiple equilibrium positions and domain

boundaries. This provides a framework for discussing how a system reacts when it is close either to an equilibrium point or a tipping point, and allows comparisons to be made between systems with different configurations. None of the energy papers described an energy system in these terms, and did not offer a similar framework for the analysis of system properties.

These graphical representations of a resilient system nearly exclusively came from the ecological literature. This can partly be explained because of the maturity of the concept of *resilience* in this field, resulting in sophisticated techniques for analysing the concept in a quantitative way. However, the use of *resilience* in materials science is probably even older and this graphical representation is not used here. The definitions of resilience most commonly used in materials science and engineering tend to be scalar quantities, such as the amount of energy stored in a body when it is stressed or the speed at which the body returns to its original shape after deformation. Both of these deal with entities that only have one equilibrium position – the resting state.

Ecology, however, is a discipline concerned with treating nature as a system. A system is made up of a number of components interacting in a complicated set of processes. These components and processes can be configured in a number of different ways, a number of which might be called stable . This is also true for an energy system: it can have a number of different configurations, characterised by, say, the ratios of its fuels, generators and energy services. Some of these configurations will be in equilibrium, some will not. Of the equilibrium configurations, some will be desirable (that is to say, meeting energy service requirements of the consumers without conflicting with wider policy objectives) and some will be undesirable.

There may be cases in which thinking about the energy system as having a single equilibrium is preferable. The system response to small-scale disturbances, for example, might best be modelled by considering the restoring force on the system components. If the system is near a tipping point, or the disturbance is particularly large, however, these assumptions may not hold true. As Holling argues, an equilibrium-centred view is essentially static and provides little insight into the transient behaviour of systems that are not near the equilibrium. (Holling (1973)). The energy system is dynamic and changing, so an accurate representation of its resilience will need to include the notion of multiple equilibria, and to differentiate between system behaviour both near these equilibria and far away from them.

3.2.4 Characteristics of a Resilient System

The majority of the energy policy literature dealt with the concept of *resilience* with reference to qualities of the system that brought it about (such as diversity and flexibility) the technologies that affected it, or strategies that could enhance it.

It is notable that the main resilience-related themes that emerged in the review had been identified in the *energy security* literature; the themes of *diversity*, *flexibility*, *storage*, *interconnectedness* and *indigenous supplies* all occur in both *resilience*- and *energy security*-related papers.

3.2.4.1 Diversity and Flexibility

Diversity and flexibility were given most often as characteristics of a resilient system. In theory, flexibility is independent of diversity. A system could have the minimum diversity (only one fuel and one type of generator) but the maximum flexibility (the incumbent fuel and generator technology can be changed instantly for zero cost). In practicality, however, diversity and flexibility are linked, as it is a prerequisite for a flexible system that alternatives are readily available to allow a switch to occur. It is much easier to ramp up use of a small fuel source than it is to create it from absolutely nothing. A system that is flexible, therefore, will also probably have a good level of diversity.

Diversity can apply to all stages in the supply chain: in the fuel routes from the fuel-producing countries, in the commercial organisations that refine and distribute the energy to the end user, and in the technologies used to conduct these operations. The most diverse energy system, therefore, would use a number of different primary fuels from a number of different countries in a number of different regions; they would be imported (or extracted indigenously) by a number of different companies using different technologies and processes, and the energy would be supplied to the end user in a number of different forms via a number of different supply routes.

Diversity is not a straightforward property to measure. Stirling (1998) breaks it into three components: *variety*, *balance* and *disparity*. Variety is a measure of the number of different system components (e.g. the number of different fuels), balance is a measure of how equally those components are spread (a 90:10 split is less balanced than a 50:50 fuel mix) and disparity is a measure of the degree of difference between them. A very diverse energy system will have a large number of fuels and generating options (variety), each taking an equal share of the mix

(balance), and each of vary independently of each other (disparity).

One advantage of diversity from the point of view of resilience is that it protects the system against the more unpredictable events. Risks can be minimized by using high quality components and through the use of backup generators to a level that is deemed to be appropriate for the probability of failure. Unpredictable events (about which we are uncertain or ignorant) cannot be handled in this probabilistic way, as their nature and magnitude are completely unknown. Diversity can protect against all disturbances, and as such is useful for minimizing the impact of unforeseeable events.

Where it does not conflict with other policy objectives, then, diversity should be encouraged at all stages of the supply chain. The portfolio of fuels should be diverse, as should the technologies used to deliver them in useful forms to the point at which they are required. Even diversity of energy options in the home can add resilience to the energy system; a consumer who has a gas hob with an electric oven can still cook in the event of a gas or electricity interruption, whereas a gas-only or electric-only home is fully reliant on one source of energy and is thus much more vulnerable should that supply fail.

3.2.4.2 Decentralisation

Decentralisation might be thought of as a subset of diversity in that it can increase the number and range of generator locations, physical environments and commercial organisations involved in the production of useful energy. By increasing the number of generators (and thus decreasing the average size for a given system) the chance of a large failure is decreased. More small failures will occur since there are more components to the system, but these will be more manageable than the infrequent but catastrophic failures characterised by highly centralised systems.

This argument relies on the assumption that the smaller, decentralised generating units fail independently of each other; this assumption may not be valid for a number of reasons. For example, if the types of technology used are not diverse enough, they may all be subject to the same failure modes. Faults would be likely to occur at approximately the same stage of the components' life cycles, invalidating the assumption of independent failure events.

The most significant reason why decentralised units are not independent, however, is that they are all connected to a single system, and are thus commonly affected by system-wide events. A sudden surge or dip in the voltage of the electricity network could affect all generators at

the same time, and it could be that a smaller number of larger generators would have been more able to adapt to the sudden change. The existing rules for grid-connected decentralised generators highlight another problem: if the grid goes down in one region, the decentralised generators have to be switched off in order to protect the engineers who would need to fix the grid. Such a restriction diminishes the potential resilience benefits that could emerge from having grid-independent supplies available.

Decentralisation, therefore, may have benefits for the resilience of the energy system by reducing the dependence on large generators that present the risk of single large failures. This benefit, however, is not guaranteed, and requires good communication between the generators and grid operators, diversity in the technologies used by the different generators, and the implementation of appropriate legislation to take full advantage of the benefits of local generation and to minimise any additional system risks it poses.

3.2.4.3 Indigenous v. Interconnected Energy Systems

Two strategies emerged that might individually promote resilience: increasing the use of indigenous sources of energy and increasing the spread and range of fuel sources. These appear to conflict with one another, since an increased reliance on the fuels and networks of other energy systems would be at the expense of local forms of energy production.

It is true that one can be uncertain, perhaps even ignorant, about the reliability of fuel supply from foreign countries – certainly more so than about fuels from within one's national borders. A government has a degree of control over its national fuel strategy that allows it to avoid some risks that might be present when relying on others. It is also true that having a number of properly-functioning links to other energy systems provides security against local supply interruptions by taking advantage of a shared capacity margin and the redundancy of supply routes.

In order to establish which of these two strategies should be implemented, or where the balance lies between the two, it might be informative to consider as an analogy the combination of errors in the measurement of physical quantities. Consider the situation in which a physical value (say, the speed of a moving vehicle) is measured simultaneously using three different techniques. Two methods are very accurate, and give a value of 41mph and 43mph, respectively. The third is known to be inaccurate, and gives a value of 51mph. One might argue that only the first two measures should be used, as they are known to be more accurate than the third. Alternatively,

it could be argued that the inaccurate measure should be included since it still provides some information about the speed of the vehicle, albeit information that is relatively imprecise.

It can be shown statistically that the latter method tends to provide a better estimate for the true value if the measures are each given their appropriate weighting (the inverse of their variance) that reflects the relative precision of each method. In other words, one should consider all the data available, but give more weight to the data that is thought to be more accurate. The analogy is only for illustration, but it does suggest that an energy supplier whose reliability is thought to be poor should still be integrated into the larger network, but that individual operators' dependence on that supplier should be proportional to their confidence in that supply route.

The optimal balance from the point of view of resilience lies with widespread interconnection, but with most energy coming from sources about which one is confident.

3.2.4.4 The Human Dimension

The wider literature included *learning* as a mechanism by which a system can become resilient. This was not explicitly mentioned in any of the energy papers, but it was implied by the authors who noted the importance of planning for different scenarios, and practising decision-making under adverse conditions.

Berkes & Sexias (2005) describe the importance of nurturing ecological memory to maintain resilience. The concept of *ecological memory* might have a useful analogy in energy systems; one interpretation is that in order for an energy system to respond in a resilient manner, it must be able to revert to a previous, more suitable, configuration. For example, the extended inactivity of the British coal industry, or the long period since a nuclear generator has been constructed, might be an example of a loss in system memory; the longer this fallow period is, the harder it is restart these activities should the economic or political situation make coal or new nuclear builds once again desirable.

Whether *learning* and *memory* are thought to be useful concepts for an energy system, it seems clear that the human elements of the system are just as important for resilience as the physical elements. There is a tendency to think of the energy system as a series of physical structures and machines that transport and convert energy; resilience would then come about by choosing the best technologies and configuring them in the optimal way. To form a full picture of resilience,

however, one must also consider the actions of *all* the components of a system that affect its function, including the human actors who play a large role in choosing fuels, managing the infrastructure, and planning for the future. Even the political structure needs to be thought of as part of the energy system, as the decisions of policy makers can significantly affect the way in which a system responds to a disturbance.

3.3 The Resilience of a Generic System

The nominal purpose of this systematic review was to find a definition of *resilience* that was applicable to the energy system in order to inform energy policy. From looking at the use of the term in energy policy and in the wider literature it is apparent that a number of different definitions could apply. The system itself can be described in a number of different ways, as can the disturbances that might befall it.

A detailed, undisputable, definition of *resilience* is probably not achievable. A system has to be resilient to a wide range of possible disturbances, and it can respond in a number of different ways. Even if one imagines that a well-defined quantity, *resilience*, exists, two systems with the same amount may still respond differently to different disturbances. Therein lies the problem of finding a single definition of the term that is meaningful. We want a system to be resilient, but we cannot be sure what it needs to be resilient to. We can categorise disturbances according to their type, their duration, their predictability or their magnitude, but these categories will never be able to fully characterise any future disturbance. Two disturbances with exactly the same scores in each of our pre-assigned categories could still cause a system to respond in two very different ways. The non-linearity of system responses cited by some authors, combined with the large uncertainties about future disturbances, mean that *resilience* will never be an undisputable physical quantity like, for example, *mass* or *length*.

Nonetheless, by considering what might go into a definition of *resilience*, one is forced to consider the range of disturbances and system responses that we might want to include as part of a resilient system; this exercise has some value in itself, even if it does not result in a single unequivocal definition. A definition of a resilient system can be thought of in three parts:

1. What is the system to which the label resilient is being assigned?
2. What does the system do that identifies it as being resilient?

3. How does it achieve this resilient response?

3.3.1 A Resilient System: What it is

What is the *energy system*, which is being described as resilient? The energy system can be defined in a number of different ways, but the most useful depiction of an energy system is one that includes all the elements that affect its functioning. These include all the physical elements (fuels, generators, wires, pipes, etc.), all the human elements (investors, miners, operators, consumers, etc.), all the economic and political elements (primary fuel prices, electricity prices, taxes, incentives, contractual agreements, etc.) and the institutions that bring together all these constituent parts (corporations, unions, political organisations, etc.). These elements can all affect the ability of the system to function, so they all need to be included in an analysis of system security.

The other dimension that should be considered is the domain of the energy system. Again, this can be interpreted in a number of ways: for example, the UK energy system could be defined as the collection of elements situated within the UK's national boundaries. This turns out to be a rather arbitrary choice, and it makes more sense to consider the system in terms of the influence its actors have over it. The energy system then becomes the collection of system elements over which the UK has control. Rather than seeing the UK energy system in terms of strict boundaries, it has smooth edges defined by the degree of influence over which the UK can exert its influence. This brings us to the following definition of the UK energy system (but it can be applied to any nation or international body):

> The UK energy system is the collection of physical, human, economic and political entities over which the UK has a degree of control.

3.3.2 A Resilient System: What it does

Having established what an *energy* system is, we need to be able to establish whether it is resilient or not; in other words, we need to understand what *resilient* means. How can we say when an energy system is acting resiliently, and how can we compare the resilience of different systems?

A definition of resilience must be founded on the provision of energy services. These services, not the energy itself, are what we as consumers experience and demand. If exactly the same energy service can be delivered via a different energy carrier, this choice has little or no impact on the consumer. This point is crucial for conceptualisations of *resilience* as it recognises the ability of an energy system to reconfigure its fuels, supply routes and generating options in a variety of different ways, provided the continued supply of energy services is maintained.

The definition of *resilience* must also recognise that it is a system characteristic that is only visible when the system is under some sort of stress; an undisturbed system cannot exhibit resilient tendencies.

The combination of the concepts of *energy* services, disturbances, and the *system response* is sufficient to construct the following definition:

> *Resilience* is the ability of a system to *respond* to a *disturbance* in such a way that it can continue to deliver the *energy services* required of it

One might want to refine this definition by incorporating more detailed descriptions of the *disturbances* that the system is resilient to. The disturbances, as have been discussed, tend to be unpredictable and large, can be either endogenous or exogenous to the system itself, and can occur over a range of timescales. Incorporating these variables results in the following definition:

> *Resilience* is the ability of a system to *respond* to *large*, *unpredictable*, *exogenous* or *endogenous disturbances* occurring on timescales from the very *short-* to the very *long-term*, in such a way that it can continue to deliver the *energy services* required of it

One might also want to refine the definition of the *energy services*, including for example the requirement that they are affordable and that they are in adequate supply, leading to this definition:

> *Resilience* is the ability of a system to *respond* to *large*, *unpredictable*, *exogenous* or *endogenous disturbances* occurring on timescales from the very *short-* to the very *long-term*, in such a way that it can continue to deliver the required quantity of *energy services* at a *cost* acceptable to the consumer

A full description of a *resilient response* requires a consideration of the manner in which the system acts resiliently; this is described in the next section.

3.3.3 A Resilient System: How it does it

A system can be *resilient* by means of a number of different mechanisms, and a number of system attributes can increase or decrease this resilience. It is just as important to understand these mechanisms and attributes as is it is to understand what resilience actually means.

A resilient response may be characterised by the time taken to return to a desirable equilibrium. Alternatively, it can be described by the amount of deflection from an equilibrium position that a system experiences. The return to equilibrium may be brought about through the resistance of the individual system components, or it may be a result of their capacity to adapt in order to maintain the overall *service* provision.

All of these interpretations have potential use for defining *resilience*. Depending on the existing configuration of the system, and its reaction to a disturbance, one response characterisation may be more useful than another. Smaller disturbances that occur while the system is near an equilibrium configuration may be best characterised by the rate of return to that configuration, whereas a system that is already near a tipping point may be best characterised by its ability to avoid shifting into a new equilibrium or by its ability to reorganise into a new, desirable, equilibrium.

Similarly, system attributes that can bring about a resilient response are varied, and need to be considered in conjunction with each other. The diversity and flexibility of system elements can be pursued simultaneously, although their impact on other policy objectives needs to be considered. Indigenous supplies and international integration, however, are not complementary objectives, and may need to be traded off with each other to find the optimal balance from the point of view of *resilience*.

Rather than attempting to combine these various system responses and characteristics into a single definition of resilience, it is more useful simply to recognise that the variety exists. This complexity need not be seen as a barrier to enhancing system resilience. Rather, it can be seen as an opportunity to consider a number of different resilience strategies. Some may be more appropriate for one system than another, and some may be more compatible with wider political objectives. The crucial point is to recognise that a strategy based on one system attribute will

inevitably impact on others. It is likely, for example, that policies to enhance energy system *resistance* are not the same as those to enhance system *adaptability*. Attempting to design a resistant system that recovers quickly from small disturbances, for example, could well have negative implications for the ability of that system to reconfigure when required by the onset of a larger disturbance. Policies must recognise such relationships and be sympathetic to them.

- Resilience can only be understood in terms of the ability of an energy system to deliver energy services; the delivery of energy itself is only a means to an end. When assessing the impact of a policy on resilience, therefore, one needs to ask how it affects the ability of a system to provide consumers with what they want. Asking the question in this form opens up a range of measures that can improve the resilience of a system without necessarily improving the reliability of energy supplies. Improving the thermal efficiency of buildings, for example, has no impact on the reliability of energy supply, but it greatly improves the resilience of consumers to supply interruptions, since they can remain reasonably warm.
- In order to understand the resilience of an energy system it is necessary to consider all the system elements that can affect it. This includes more than just the physical entities such as the fuels, pipes and wires. It also includes the human elements, the economic structures and the political decisions that can significantly affect the ability of the system to respond to and recover from adverse events.
- It is important to recognise that a resilient response can be resistive or adaptive, and that strategies that enhance one may degrade the other. This may be appropriate in some situations, but the most likely depiction of a resilient energy system will incorporate elements of both rigidity and adaptability. The challenge is to develop a system that is strong but not brittle, and that is flexible but not chaotic.

3.4 Applying Resilience thinking to the energy system

Although the idea of making a system 'resilient', rather than 'secure', is relatively new in the energy policy literature, a variety of interpretations have been used for a number of decades in the wider literature, all of which centre around the idea that a resilient system can 'cope' with a disturbance (Benes, 2007; DTI, 2006b; Farrell *et al.*, 2004; Lovins and Lovins, 1981; ResAlliance, 2009a). Before attempting to define 'resilience' for use within an energy policy analysis, this chapter reviews the concept as it employed in these other disciplines.

3.4.1 The Transition between Multiple Equilibria

The analogies between ecosystem resilience and energy system resilience are potentially enlightening, but should not be over-stretched. One of the central features of 'ecological resilience' is that systems can fluctuate considerably around an equilibrium position, but that a resilient system will tend to remain in that stability domain. Conversely, a non-resilient ecosystem will be able to cross over a tipping point, placing the system in a new equilibrium delivering a different set of ecosystem services. This concept is predicated on the notion that ecological systems have multiple 'zones of attraction' with many equilibria. It is difficult to see how this would extend to an electricity system, which only has one primary service to provide – the provision of electricity to consumers.

Although an electricity system may not have multiple stable states, the notion of a tipping point may still be a useful one. As will be discussed later, there are at least two states of an electricity system: functioning and non-functioning. The message from the ecological resilience literature says that in order to understand how systems undergo sudden and catastrophic changes, we need to look not at the behaviour of the system at equilibrium (i.e. under 'normal' conditions), but at the behaviour of the system far away from equilibrium – close to the point beyond which recovery is automatic. For the electricity system, then, its vulnerability to catastrophic failure can only be understood by considering its behaviour near these tipping points, trying to understand where in relation to these points the system is, and what conditions could push it over the edge.

3.4.2 Efficiency vs Resilience

A related message from the ecological resilience literature is that resilience is potentially in direct conflict with efficiency, in the sense that certain efficiency gains inevitably lead to a reduction in the resilience of the system. Talking about the management of agricultural systems, Brian Walker is critical of the perceived need to optimise farming methods to maximise efficiency, arguing that such approaches only work when the future state of the world is fixed:

> Who would argue...that efficiency is a good thing? Of course it is, but you have to think very carefully about that because in many ways the pursuit of efficiency, in natural resource management and in economics ... is reducing resilience. 'Just-in-time' marketing is a very efficient way of going as long as nothing changes and as long

> as the supply chains don't break it's more efficient. This drive for squeezing the next buck out of the system is what has pushed the world into a very non-resilient state and so what we've got to try to accept now is that it's better to be in an acceptable state, albeit not the maximum productivity state, but a resilient state no matter what happens (Walker, 2008).

Charles Redman has been applying the concepts of ecological resilience to the study of cities. He takes a similar view to that of Walker's, arguing that striving for efficiency provides little protection against unforeseen events:

> We are moving into a world ... of increased ... efficiency. We try to minimise inventory..., to make the streets just wide enough to hold traffic, to distribute the electricity just so it works; we're wringing the last inefficiency ... out of the systems. All that's great until a Hurricane Katrina happens then all of a sudden this all comes apart ... and it doesn't even have to be that dramatic. We're doing a fine-tuned world, but what we need to do is to build resilience, or a cushion, into it. How much is society willing to invest ... in the resilience 'insurance policy' versus maximum efficiency? (Redman, 2008)

The pursuit of low-cost electricity supplies have tended to depress the levels of the 'cushion' built into the system. As will be discussed, privatisation in particular has created an incentive to reduce margins in the generation sector, and the obligations put on the energy regulator, Ofgem, have driven the electricity network to be operated with increased efficiency. It needs to be determined at what point the optimisation of the electricity system ceases to be of net benefit to consumers and, rather, begins to decrease the resilience of the system to unacceptable levels.

3.4.3 Adaptive Capacity

The term 'adaptive capacity', again from the ecological resilience literature, refers to the extent to which a system has within itself the necessary tools to react to an unexpected change.

With reference to ecological systems, Carl Folke (Folke et al. 2002) describe four system characteristics necessary to cope in the face of a changing environment (Resilience Alliance, 2009):

- learning to live with change and uncertainty;
- nurturing diversity for resilience;
- combining different types of knowledge for learning;
- creating opportunity for self-organization towards social-ecological sustainability.

The concept of adaptive capacity can be applied to electricity systems in a number of different ways:

- *Response Ability*: This concerns the behaviour of the system immediately after a disturbance, and relates to the ability of the entities within that system, both technical and human, to respond appropriately to mitigate the impact of that disturbance. This response ability includes the availability of ancillary services to minimise system disruption and to recover following a failure. It also concerns the ability of the human actors to communicate with each other both within their operational units and between these operational units – this is an issue that has been raised in particular as a result of the vertical unbundling of the electricity utilities.
- *Learning and Reconfiguration*: This concerns learning over a longer timescale. A resilient electricity system will be able to learn from past adverse events and change its components, configuration and operational processes to reduce the risk of such an occurrence being repeated.
- *Diversity*: The third aspect of system resilience to emerge from the notion of adaptive capacity is that of 'diversity'. This concept has direct analogies with ecological resilience. Brian Walker's objections to modern agricultural practices included the increasing prevalence of monocrop farming methods; these, he argues, emerge from a short-termist view, and make food production far less resilient to unexpected environmental changes. Similarly with the electricity system, a diversity of fuels and generating technologies provides some protection against an uncertain future, minimising the impact of individual failures when they do occur and allowing more capacity for the system to adapt over the longer-term to more slowly-changing external conditions.

3.5 Applying Ecological Resilience Concepts to the Electricity System

A 'secure' electricity system is able to provide consumers with a high level of electricity availability at an acceptable price level (IEA, 2007). If we set aside the price component and focus only on the availability aspect, 'energy security' can be defined as the probability that a given unavailability will not be exceeded over a given period of time. For the purposes of this research, the concept of 'security' is described as having three distinct components: *reliability*, *reliance* and *resilience*.

1. *Reliability* is the probability that a component within a system will fail within a specified time period. A classic measure of reliability is the Mean Time Between Failures (MTBF), which defines the expected lifetime of a component under a set of operating conditions (Todinov, 2005).

2. *Reliance* is a measure of the extent to which a system is dependent on external inputs, and the expected availability of those inputs. A system can have low reliance by being self-sufficient, by being dependent only on reliable external systems, or by diversifying import routes to minimise uncertainty.

3. *Resilience* is a measure of a system's ability to continue to deliver services despite the occurrence of a *reliability*- or *reliance*-type event. A resilient system will minimise the impact of an adverse event and will allow the system to recover as fully and as quickly as possible.

This research focuses on the *resilience* of the electricity system, where its *resilience* is independent of the *reliance* risks associated with each of its inputs, and is distinct from the *reliability* of its constituent components. If we consider the value chain of electricity provision, there are three areas of supply that can be affected by a disruption (Collins *et al.*, 2009).

1. A disruption in the supply chain causes insufficient *fuel* for generators to meet the demand for electrical energy.

2. Technical or human disruption makes a *generator* unavailable, meaning that the available fuel cannot be transformed into electrical energy.

3. *Network* disruption (transmission or distribution) means that the available electrical energy cannot be conveyed to consumers.

To determine the resilience of the electricity system, therefore, we need to understand its capacity to cope with *reliability*- and *reliance*-type shocks that concern fuelling, generation, transmission and distribution.

3.6 Conceptual Clarification

The *reliability-reliance-resilience* scheme goes some way towards distinguishing resilience from other energy security-related concepts, but there remains some discrepancy in the use of the term in the existing literature. The following sections attempt to resolve some of these differences by:

1. Examining the importance of defining the system boundaries explicitly.
2. Defining the extent to which energy efficiency improves resilience.
3. Defining the relationship between resilience and the size of a system shock.
4. Distinguishing between *resilient* response and *reactive* intervention.

3.6.1 Resilience and System Boundaries

One way of distinguishing between reliability and resilience is by using reliability to describe the probability or frequency of a single fault occurring and using resilience to describe the subsequent system response. These definitions are consistent with those used in some of the wider resilience literature. For example:

> Reliability, vulnerability, and resilience provide measures of the frequency, magnitude, and duration of the failure of water resources systems, respectively (Maier *et al.*, 2001).

Maier *et al.* (2001) suggest that reliability measures the frequency of failure of a system; this agrees with the use of the term in reliability engineering, where the reliability of a component or system is defined in terms of its Mean Time Between Failures (MTBF). The use of resilience in the definition above describes the system's reaction to a disturbance—in this case, the time

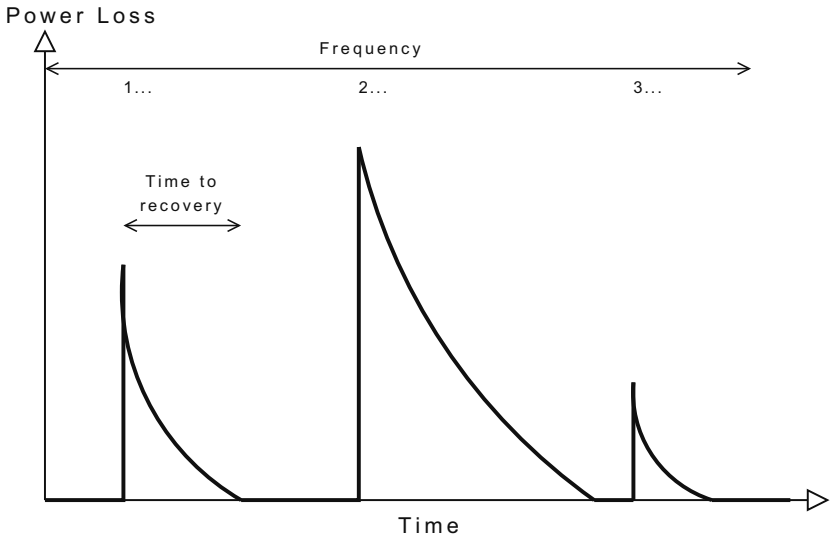


Figure 3.1: Representation of two aspects of system security

it takes to recover. In an energy system, therefore, *reliability* and *resilience* can be said to correspond to the frequency of failures and the time taken to recover, as illustrated in Figure 5.

The above distinction between the frequency and recovery is useful, but we will see that the distinction between reliability- and resilience-related events also depends on how we define the boundaries of the system under analysis. The need to choose appropriate system boundaries and the importance of 'scale' has been articulated in the ecological and engineering resilience literature, which argues that the boundary choice can affect the perceived purpose of the system (Dalziell and McManus, 2004), the choice of indicators and the apparent performance of a system against those indicators (Campbell *et al.*, 2001).

The reliability of a component, such as a capacitor, is defined as the probability that it will, under a set of given operating conditions, fail during a given time period (Todinov, 2005, p.1). This definition can also be applied to the reliability of a subsystem, expressing how likely it is to fail. The relationship between the reliability of a subsystem and its constituent components will depend on their relative importance to subsystem function and the level of redundancy in the design. This same logic can be applied to the relationship between the reliabilities of whole systems and their constituent subsystems.

As the systems we describe become larger and more complicated, design features and human behaviours are introduced that can be described as *resilient*, thus confusing the distinction be-

tween *resilience* and *reliability*. To use an example, a nuclear generator is both a system in its own right and a subsystem within the wider electricity network. Within the generator system, failures can occur as a result of the failure of one or more of its constituent parts – a reliability failure. Once this failure has occurred, human operators or automated processes can respond resiliently, minimising the magnitude and duration of the loss in system function – namely, the production of electrical energy.

If this response is perfectly resilient, there may be no reduction in electrical output, in which case, from the perspective of the grid operator, there has been no incident at all. If the generator's resilience is not perfect, power output will be reduced by some degree as a result of the initial failure. In this case, the grid operator sees this power reduction as a reduction in the *availability* of power to the system. If the generator is perceived as a system component, this reduction in availability is a *reliability*-type failure; if, however, the generator is perceived as an input to the grid system, it is the grid's *reliance* that is cause for concern. In either case, the measures the grid operator puts in place to cope with such a failure contribute to the *resilience* of the wider system.

A single scenario can, therefore, be viewed in different ways by different actors within the energy system. The Resilience Alliance (ResAlliance, 2009b) makes a similar point:

> There is no perfect way to set the boundaries of a system. Initial assessments may need to be changed as the understanding of the problem changes.

We can define a system in any number of ways: the UK electricity grid is physically connected to the European Grid (National Grid, 2008b); both are reliant on the domestic and EU gas network (National Grid, 2007), which require the electricity, communication and transportation systems to function (Rinaldi *et al.*, 2001; Rinaldi, 2004). These systems, therefore, are interdependent and can alternatively be viewed as a single system (Dalziell and McManus, 2004). We partition these systems not because the partitions are in any sense 'correct', or indeed fixed, but because they make their analysis feasible, and, crucially, because operational and strategic decisions about the system are made in terms of those same partitions (Campbell *et al.*, 2001; Medema *et al.*, 2008).

3.6.2 Resilience of the Wider Electricity-Based Economy

Following on from this point about resilient behaviour being dependent on the boundary of the system under investigation, we should distinguish between the resilience of the electricity system and the resilience of the electricity-based economy. An important area of discussion in the energy security debate concerns the dependence of the UK economy and wider society on the electricity system. This dependence makes us vulnerable to the failure of the electricity system. Our society could therefore increase its resilience to such a failure by finding non-electrical alternatives to delivering its required energy services. At the domestic level, the use of both gas and electric cooking appliances delivers resilience by allowing hot food to be prepared in the event of either a gas or an electricity failure.

Without wanting to dwell on what is excluded from this research, it is important to stress that this wider sense of 'energy resilience' is not discussed here. This research focuses on the resilience *of* the electricity system, not on society's resilience *to* failures of the electricity system. The policies and strategies that affect these two distinct ideas are not mutually exclusive. A single demand reduction measures, for example, can be used to improve societal resilience to electricity disruptions as well and improving the resilience of the electricity system itself.

3.6.3 Resilience and Shock Size

A source of confusion surrounding definitions of resilience concerns the size, or abnormal nature, of the disturbance to which a system needs to be resilient. A number of authors define resilience as the ability to cope with large, abnormal or unexpected disturbances (Holling and Gunderson, 2002; Kirschen *et al.*, 2004; Lachs and Sutanto, 1992; Owen, 2004). However, the *reliability-reliance-resilience* scheme established above makes no such distinction between regular and irregular events, suggesting, rather, that a system's resilience characterised by its ability to cope with any disturbance regardless of size, abnormality or unexpectedness.

Steve Epstein's paper on resilience and 'unexampled events' (Epstein, 2006) offers a way of reconciling these two viewpoints. Epstein argues that resilient behaviour is only observed after a disturbance has occurred, but that once it has occurred, this behaviour is "institutionalised". In other words, once an organisation has coped with an event, that coping mechanism is codified into a Standard Operating Procedure (SOP).

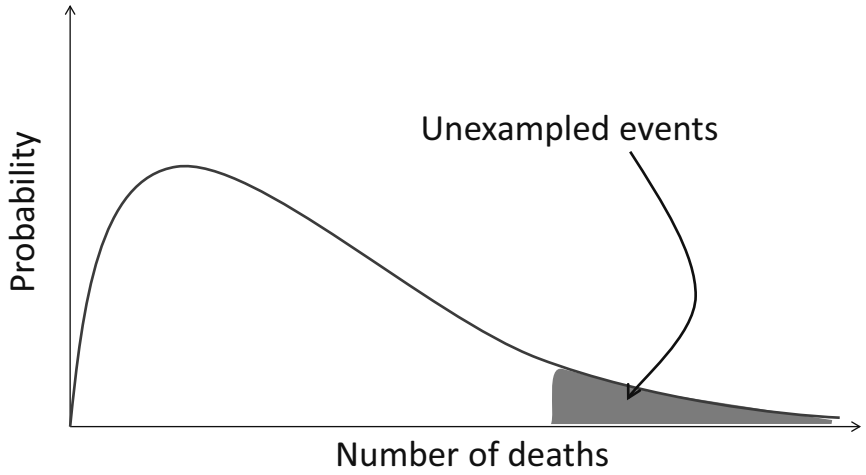


Figure 3.2: Representation of Resilience as Standard Operating Procedure

Resilience, then, is the ability to cope with a disturbance of any size; the reason that there is a tendency to talk about the concept in terms of rare events is that resilience for common events is already standard for most systems. Strategies for resilient behaviour and design are therefore likely to be sufficiently developed to cope with 'normal' disturbances, but may be less well developed for unexpected disturbances.

Once we have framed 'resilience' in this way, it becomes clear that any system will display some resilient characteristics, even if they are only able to cope with the most mundane of disturbances. In the case of modern electricity systems, resilient designs and operating procedures are widespread, which is unsurprising given the time-critical nature of electricity provision and the importance of electricity supplies to a modern economy. These resilient practices include the maintenance of system margins (National Grid, 2008a), the use of interruptible contracts (National Grid, 2009c), plans for rota disconnections (BERR, 2006), and redundancy in the design of electricity networks (n-1 and n-2 criteria) (National Grid, 2008a).

The focus of this research, therefore, is not to propose a raft of resilient designs and behaviours that should implemented. Rather, it is to ask whether the existing approaches to resilience are, and will remain, adequate given the technical, economic and policy pressures the electricity system is under.

3.6.4 Resilience vs Reactive Response

If we look at the use of 'resilience' in the ecological literature, systems that exhibit this property are said to be able to self-organise following a disturbance in order to maintain essential functions (Allen *et al.*, 2005; Berkes, 2007; Carpenter *et al.*, 2001; Carreras *et al.*, 2000; Carreras, 2002; Carreras *et al.*, 2004; Clar *et al.*, 1999; Dobson *et al.*, 2007; Drossel, 1996; Hui *et al.*, 2008). In a non-human system, such as an ecosystem, it is clear how to distinguish between automatic response and active intervention, since the latter is a conscious decision made by a human actor (by, say, cutting down trees to prevent a fire from spreading) and the former is not (e.g. small fires increase tree spacing and, as a result, minimise the risk of larger fires). Conscious decisions after a shock should not be seen as *resilient* responses, since they are not an inherent part of the system, whereas the system that evolves into a state that minimises the risk of wildfires is clearly exhibiting resilience.

In a human system such as the electricity network, it is less clear which responses are as a result of 'resilience' (i.e. internal to the system's design) and which are interventions that come 'after-the-fact', since by definition a human system is designed and a product of active decisions.

We can illustrate this distinction using an extreme case: the financial crisis of 2008 and 2009. We have seen that the UK's financial system was not resilient (Eijffinger, 2008) and this fact is not changed by any restorative measures subsequently put in place. It may be that these measures are successful in speeding the recovery of the financial system, but since these measures are purely reactive they cannot be called 'resilient'.

Using the financial system as an example, we can identify a number of system characteristics that would have made it resilient. It would have been more resilient if:

1. Early warning signals were given, and heeded by the regulators
2. The system was insulated from the failure of any single bank
3. There were no credible risks to which all the banks were exposed
4. The expected impact on any market participant was proportional to the perceived risk being taken by that participant
5. It was designed in such a way that a collapse could be recovered easily

Applying these ideas to the electricity system, then, we see that the resilience of the system depends on there being procedures and designs in place *in advance* of a disturbance event that allow the change to be managed and for any restorative action to occur effectively (Folke, 2006). This involves not only having Standard Operating Procedures (SOPs) for foreseeable disturbances, but also having more general strategies for coping with unforeseeable events. A study carried out for BERR (Collins and Gross, 2008), showed that the countries most able to implement short-term demand reductions were those that had already established public communication systems and had appropriate fiscal measures in place, which allowed mitigation to occur quickly and effectively (ESMAP, 2005; IEA, 2005a).

3.7 Categories of Resilience

The previous section distinguished between a system's resilience, reliability and reliance, and clarified some of the discrepancies that have emerged in the 'resilience' literature. The term can also be deconstructed to describe the different behaviours required of a 'resilient' system. Whether originating from inside or outside the system, a disturbance will ultimately manifest itself as a loss of power on one section of the grid. The test of a system's resilience is its ability to cope with, and respond to, this power loss, which it can do in a number of ways:

1. *Recovery Resilience*: It must recover quickly and automatically from a failure, or at least fail in such a way that manual recovery can be performed quickly and easily (Adger, 2000; Carpenter *et al.*, 2001; Gunderson, 2000; Holling, 1996; Pimm, 1991).

2. *ENS Resilience*: The expected amount of Energy Not Served (ENS) should be as low as possible following any given disturbance. ENS resilience simply means that for two systems experiencing identical disturbances, all other things being equal, the more resilient of the two systems will be expected to have a lower amount of energy not served to its consumers as a result of that disturbance (Kirschen and Strbac, 2004; Nedic *et al.*, 2006).

3. *Cascade Resilience:*It must not allow the failure to initiate other failures, and certainly must avoid large-scale blackouts by limiting the spread of a fault to the area in which it occurred (Ash and Newth, 2007; Leu and Namatame, 2009; Nedic *et al.*, 2006).

4. *Selective Failure:* If it has to fail, a resilient system will fail in such a way that the ENS has the lowest possible cost to society. Such a system can prioritise loads in terms of the

social value of the energy consumed, or the Value of Lost Load (VOLL) ensuring that any disturbance does not adversely affect essential services such as hospitals, emergency services and critical infrastructure. Other loads might be further prioritised according to some measure of willingness-to-pay or willingness-to-accept, allowing some loads to pay for local network upgrades and providing the means for others to face temporarily reduced service provision at the request of the system operator (de Nooij *et al.*, 2007, 2008).

A system that has high *ENS resilience* does not necessarily have high *cascade resilience*, since it may expect to cope well with normal disturbances but be brittle to the extent that an abnormal disturbance may be more likely cause a cascading failure than it would in a system that experienced more regular, smaller failures (Carreras *et al.*, 2003; Dobson *et al.*, 2007, 2002). It may also be that a high degree of *Selective Failure*, by restricting the range of responses available, impedes the ability of system operators to manage a cascading failure properly, thereby increasing the probability of total system collapse.

An increase in any one of these system attributes, all other things being equal, will increase the system's overall resilience. In practice, however, these attributes cannot be managed independently of each other. A resilience policy may therefore have to improve one dimension of resilience at the expense of another.

These aspects of resilience may not be directly measurable. Adverse events that test the limits of an electricity system's resilience are rare, and so offer little statistical power for understanding underlying system attributes. Furthermore, in order to be meaningful predictors of a system's future behaviour, these measures require that the magnitude of the initiating disturbance be known in each case. For example, the UK's electricity system may experience a blackout; if the initiating event was very small, this would indicate that the system was far less resilient than it would if the initiating failure had been catastrophic. The data collected on such system failures tends to keep, at best, only qualitative records of the nature of the initiating event (National Grid, 2009a), so a quantitative comparison of shocks and subsequent blackouts is not likely to be possible.

These resilience attributes, therefore, should not be viewed as quantities that might be measured directly from an electricity system's operational data. Rather, they allow us to elucidate the key features we require of a resilient system. Nonetheless, exploring these dimensions of resilience allows us to identify resilience *indicators* that can provide a proxy measure of system resilience.

3.8 Quantitative Electricity System Indicators

Research concerning the concept of 'resilience' is particularly suited to the 'indicator' approach. 'Resilience', like its parent concept of 'energy security', is not universally defined, and has a number of attributes. Attempting to talk in general terms about 'resilience' without disentangling these attributes runs the risk of introducing unnecessary ambiguities. In particular, policy decisions may increase a system's resilience in one dimension while decreasing it in another; by assessing each of these dimensions individually, such conflicting policy outcomes can more readily be seen.

Whilst all the interpretations of 'resilience' discussed in this chapter should be considered when deciding how to change the operation and regulation of an electricity system, it is also useful to select a subset of these that can be defined quantitatively.

The resilience indicators that have been considered for this research can be divided into two categories, which draw on the wider resilience literature cited in chapter 3. The indicators provide either:

(a) *passive resilience*: providing a buffer against a disturbance

(b) *active resilience*: enabling the system to respond to a disturbance

Figure 3.3 summarises these indicators and shows how they fit into the *passive* and *active* resilience groupings. Each of these indicators is discussed below, but as an explanatory point it should be noted that system diversity is shown as both a *passive* and an *active* resilience attribute. Diversity minimises the risk of common-mode failures, thereby building in some passive resilience, but it also increases the range of options available to mitigate a disturbance actively. It acts both as a buffer and a response mechanism and therefore can be thought of as belonging in both categories.

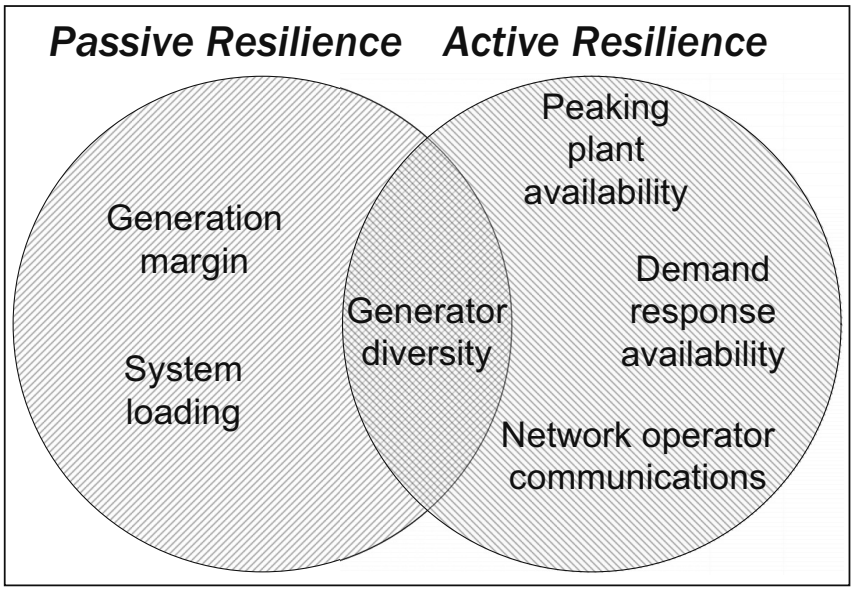


Figure 3.3: Active and Passive Resilience Indicators

The following sections introduce the four quantitative indicators that are to be investigated more fully in Part II, namely generation system margins, generator diversity, energy intensity and energy independence. As the discussion from this chapter illustrates, there are many different aspects of 'resilience' that should be considered when assessing an energy system. These have the advantage of being quantitative, measurable and widely recorded in a number of countries over a number of years. They also encapsulate not only the more traditional measures of energy security, but also the less risk-based measures that emerge from considering the resilience of the system to unforeseen changes.

3.8.1 Generation System Margin

'Generation system margin' is the level of generation capacity available on the system in addition to that required to meet the expected peak power demand in a given year (Gross *et al.*, 2006). An electricity system with an expected peak demand of 60 GW and an installed capacity of 75 GW would therefore have a system margin of 25%.

The requirement for system margin can be assessed statistically, taking into account factors such as generation plant reliability and demand prediction error (Gross *et al.*, 2006; Ilex Consulting, 2002). A common measure of reliability is the Loss of Load Probability (LOLP), which expresses

how likely it is that a load will need to be shed (forced to disconnect from the system) because insufficient generation is present (Gross *et al.*, 2006). LOLP can be thought of as having two components:

- The reliability of the generators on the system
- The generating margin available if a generator fails

Thinking about LOLP in this way shows that the expected availability of electricity for the end-consumer is a function of both the probability of a *reliability*-type failure and the ability of the other generators to respond to such a failure, or to respond 'resiliently'. Increasing the system margin (all other things being equal) increases the resilience of the electricity system, as it decreases the impact of a given amount of generation being disconnected unexpectedly from the system.

At any one time, the power being generated will be matched to the instantaneous demand; the spare capacity, therefore, only improves system resilience if it is able to be brought online quickly enough to mitigate the deficit without there being energy unserved on the system. An instantaneous resilience indicator, therefore, is the *operating margin*, which is a measure of the additional capacity available over a seconds-to-minutes timescale. This operating margin, however, is a function of the longer-term *system margin*, along with the economic incentives on the different generators to produce electricity at any given moment.

3.8.2 Generator Diversity

One indicator of resilience has been shown to be diversity, which, according to Grubb *et al.* (2006), provides resilience against risk, uncertainty and ignorance. Diversity can be subdivided into properties of variety, balance and disparity (Jansen *et al.*, 2004) referring, respectively, to the number of different elements in a system, their relative contribution and a measure of how different they are from each other. Variety and balance have been widely adopted as measures of diversity, and indices, such as the Shannon-Weiner index (Stirling, 1998), have been devised to compare the diversity of different systems.

A system with a large number of disparate technologies makes a system resilient for a number of reasons. First, if the generation mix runs on a number of different fuels, an adverse event cutting

off the supply of one of these fuels is unlikely to affect all generators. Second, any adverse-event that is technology-specific (such as droughts forcing certain generators to shut down as a result of a lack of coolant) is minimised if the affected technology represents only a small proportion of the overall technology mix.

3.8.3 Energy Intensity

It is not immediately apparent that energy intensity should be considered a direct indicator of resilience, whether considered in terms of kWh/GDP/year or kWh/capita/year. The impact of a change of energy intensity on the electricity system depends to a significant extent on the response of the supply side to that change. The initial impact of a reduction in the demand for electricity, as has been seen since the recent recession, is to increase the margin on the system. This effect, however, is already captured by the system margin indicator. What is less clear is how future supply investment would respond to this change. If investment dropped in anticipation of future demand reductions, the net effect on resilience in the medium term could be neutral or even detrimental.

There are three reasons in favour of the inclusion of some measure of energy demand or energy intensity in the definition of a resilient system.

1. Regardless of the impact of the indicator on the resilience of the electricity system itself, the resilience of the wider economy to a disruption in electricity supply *is* affected by the reliance that economy has on electricity use. As a UKERC working paper puts it, "... measures to reduce vulnerability include reducing energy demand to minimise the economic impacts of supply interruption or price fluctuations" (Chaudry *et al.*, 2009)

2. Similarly, if we think of resilience in terms of energy services, rather than electricity provision, there are grounds for including this indicator. Switching from tungsten bulbs to CFLs, say, does not change our demand for energy services. If all the technology currently in use were to be given an energy efficiency overhaul overnight, the economic value of the energy service (lighting, communication, computation, etc.) remains unchanged. So if there were a power cut, the economic impact would be the same in both the high efficiency and low efficiency scenarios. Improving the energy efficiency of electrical technologies would, however, reduce the running costs. Designing commercial buildings to maximise natural lighting, for instance, improves the resilience of the lighting system, as some economic productivity

could continue in the event of a power cut. An analogous example in space heating would be installing cavity wall insulation. If there is an interruption to gas supply in the middle of winter, a well-insulated home will emit heat at a lower rate, providing the occupants with acceptable warmth for longer than in a poorly insulated home (perhaps to the extent that they dont even notice the supply interruption).

3. The third reason for including some measure of demand reduction is because of the demonstrable link between long-term conservation efforts and the short-term Demand Side Management (DSM) efforts that a number of countries have had to employ to cope with capacity or fuel shortages. The Energy Market Reform report DECC (2010a) explicitly discusses the need to make full use of such measures. If the international experience provides evidence that DSM effectiveness is associated with general conversation efforts, this should be included as an indicator.

3.8.4 Energy Independence

One of the advantages about discussing resilience rather than energy security is that the latter (depending on one's definition) often focuses on the geopolitical risks associated with importing fuel. A resilience analysis, by contrast, makes no attempt to quantify such risks, as it is concerned with the response of the domestic system response to a disturbance, regardless of the source from which that disturbance originated.

Nonetheless, the systematic review showed a strong link between concepts of resilience and those of 'self-sufficiency'. It is argues that a system with little reliance on events outside its sphere of influence is more secure. The increasing globalisation of energy makes this assessment somewhat crude. The interconnection of electricity supplies between Great Britain, Ireland and mainland Europe, for example, provides benefits to the security of the UK electricity system. The domestic generation of renewable energy, by contrast, would reduce the impact of consumers of a rapid increase in global gas or coal prices.

The relationship between energy independence and resilience, therefore, is not a simple one. Rather than amalgamating different aspects of self-sufficiency into a single indicator, therefore, this chapter keeps these measures separate:

- Interconnection of the electricity grid between countries provides a means of sharing spare capacity, and, depending on the trading arrangements in place, can be treated as such.

- Reliance of the generating mix on non-indigenous fuels can be a problem for an electricity system. In terms of finding an appropriate indicator for this, such a measure needs to account for the reliance on a given fuel and the proportion of that fuel that needs to be imported into a country. The self-sufficiency indicator chosen to show this relationship is as follows:

$$\text{IDI} = \frac{1}{T}\left(\frac{C_g I_g}{P_g + I_g} + \frac{C_c I_c}{P_c + I_c} + \frac{C_o I_o}{P_o + I_o}\right) \tag{3.8.1}$$

where C is the installed capacity, I is the imported fuel and P is the amount of fuel produced indigenously; g, c and o refer to gas, coal and oil, respectively, and T is the total installed capacity in a given country.

Part II

Evidence Gathering and Analysis

4

Implementing the statistical analysis

This part of the thesis (chapters 4–8) is concerned with the impact of privatisation, liberalisation and regulatory change on each of the resilience indicators described in chapter 3. Specifically, it details the collection and analysis of the data relating to these resilience indicators. For each indicator, the method of obtaining and cleaning the data is described and justified. The statistical analysis laid out in chapter 2 is described for each indicator, and the results obtained are described.

4.1 The data

The data used in these analyses come from three sources; the first two providing explanatory variables and the third providing outcome variables:

1. OECD International Regulation Database (OECD, 2009). This contains annual data from 1960 onwards for 30 OECD countries (namely, Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States). It records each country's response to the following questions;
    - How are the terms and conditions of third party access (TPA) to the electricity transmission grid determined?
    - Is there a liberalised wholesale market for electricity (a wholesale pool)?
    - What is the minimum consumption threshold that consumers must exceed in order to be able to choose their electricity supplier?
    - What is the ownership structure of the largest companies in the generation, transmission, distribution, and supply segments of the electricity industry?
    - What is the degree of vertical separation between the transmission and generation segments of the electricity industry?
    - What is the overall degree of vertical integration in the electricity industry?
2. Eurostat database of annual data from 2000 for 28 EU nations, giving the market share of largest electricity generator
3. IEA Databases on Energy via the Economic and Social Data Service (ESDS), which contains the following time-series data on the same OECD countries:
    - Macro-economic data: GDP, population
    - Annual electricity consumption: total, per unit and per capita
    - Electricity capacity: total and disaggregated by fuel type
    - Peak load and capacity-at-peak

- Price data: electricity price for industry and households; gas and coal prices for electricity generators

In the following chapters, the impacts of different aspects of liberalisation and regulation are studied with respect to their effects on different resilience indicators. By way of an example, the method is described in detail for the example of generation diversity (as measured by the Herfindahl-Hirschman Index, or HHI).

In order to understand the relationship between the outcome variables and the different aspects of privatisation, liberalisation and regulation, a number of different statistical approaches can be taken. In order to explain the rationale behind the statistical method adopted for this analysis, we begin by looking at the relationship between HHI and a binary variable that defines whether or not, in a given year, a country has established a wholesale market, or electricity pool. This explanatory variable comes from the OECD International Regulation database, and records a 'yes' or 'no' answer to the following question:

> Is there a liberalised wholesale market for electricity (a wholesale pool)?

As an illustration, the HHI series for each country can be shown on a single plot, as shown in Figure 4.1, which represents the HHI for the 30 OECD countries between 1960 and 2007. HHI before privatisation is represented by a solid line and after privatisation by a dashed line. The yellow line representing data from the U.K. is identified. A more detailed plot for each country's resilience indicators is provided within each of the relevant chapters (4-8).

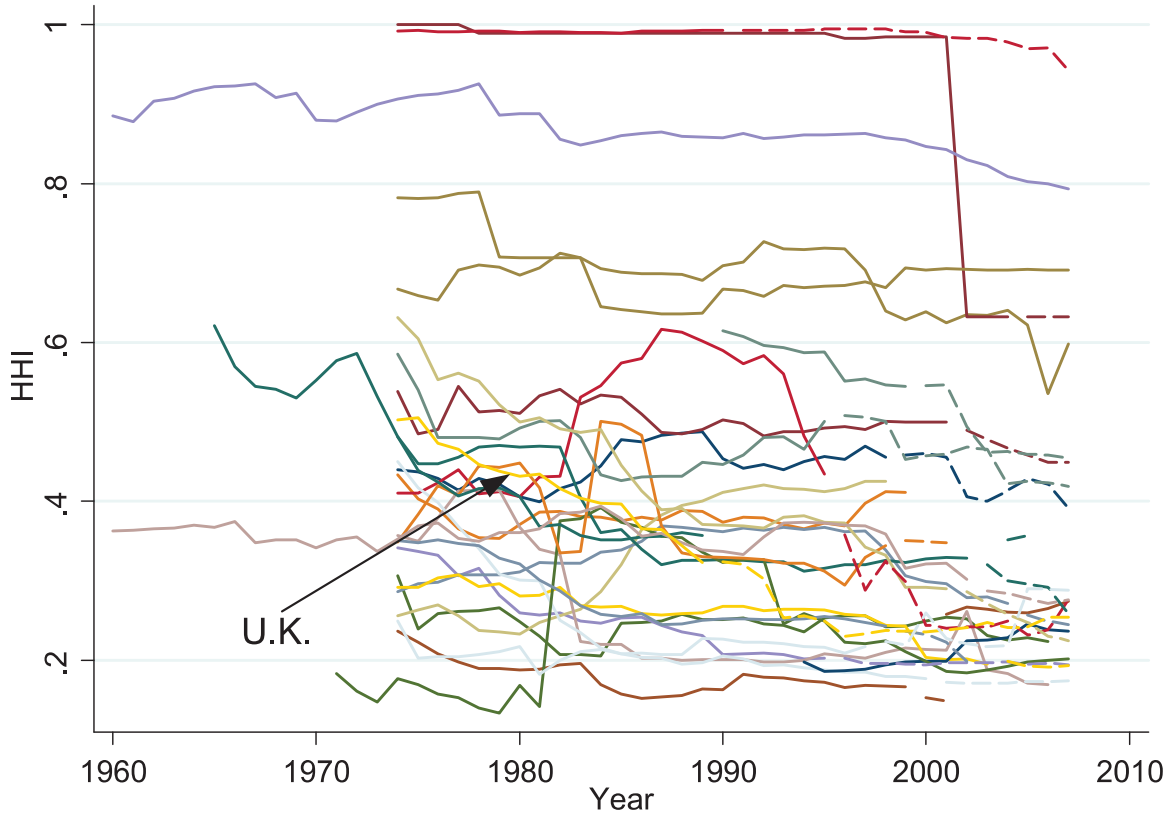


Figure 4.1: Evolution of HHI by country

4.2 A simple approach: a separate between-country analysis for each year

The simplest approach to analysing these data is to take each year separately (or to choose one particular year of interest) and perform a two-sample t-test comparing the mean of HHI in the countries that have a wholesale market / electricity pool (by that year) versus those that have not. This gives us an estimate of the difference in means (post – pre), with a positive difference indicating a higher mean HHI among countries with a pool. Clearly, this comparison can only be made in years when at least one country has established an electricity pool, and thus this analysis ignores all data before 1990 (when the UK's pool was established).

The standard two-sample t-test gives a two-sided p-value for the hypothesis that the true underlying difference in HHI between the two groups is zero, based on the assumption that HHI is normally distributed, and that the variance of HHI is the same in both groups. Under these

assumptions, the lower the p-value, the greater the evidence against this hypothesis. A high p-value can arise either when the hypothesis of no difference is true, or when the analysis lacks the necessary power to detect the difference; the smaller the sample size, and the smaller the true (absolute) magnitude of the difference, the lower the power.

As well as obtaining the p-value, we can estimate the standard error of the difference in the two means, and thus a 95% confidence interval for this difference.

4.2.1 Results

The difference in mean HHI between the groups with and without the wholesale market and the corresponding p-values, obtained from the two-sample t-tests, are shown in Table 4.1. Note the numbers of countries in each group for each year shown in the 2nd and 3rd columns. For example, the comparison in 1990 involves only one privatised country (the UK) versus 26 others. We also note that none of the p-values is less than 0.1, and thus there is insufficient evidence from this analysis to conclude that there is a difference in mean HHI between the two groups in any of the 18 years considered. The differences and their 95% CIs are shown in Figure 4.2; we note that there appears to be a slight downward trend in this difference over time.

4.2.2 Limitations of this approach

In terms of this particular application of this approach, there are clearly limitations, particularly towards the beginning and end of the 18-year period considered, due to the small number of countries in one or other of the groups. Indeed, a maximum total N of 28 is in any case too low for these tests to have sufficient power to detect a difference of realistic magnitude. More generally, however, even if we had data on more countries, the approach remains highly limited.

First, there is the problem of how to interpret the p-values when 18 separate tests have been carried out. Furthermore, even if we were able to interpret the results and make a reliable statement about the comparison of the mean HHI in the two groups over the 18 years in question, this statement would shed very little light on our question of interest. We are interested in whether or not establishing a wholesale market causes a change in a country's HHI, and a naïve analysis of the crude differences between privatised and non-privatised countries in any given year cannot plausibly address this. We expect countries to have characteristics that mean that

Table 4.1: Two-sided p-values from a series of two-sample t-tests, comparing the mean HHI in privatised and unprivatised countries for each year from 1990 to 2007.

Year	No. of countries		Difference in means (post – pre)	p-values
	post-privatisation	pre-privatisation		
1990	1	26	−0.115	0.638
1991	2	25	0.240	0.166
1992	2	25	0.230	0.188
1993	2	25	0.209	0.240
1994	2	26	0.223	0.204
1995	2	26	0.221	0.210
1996	5	23	0.060	0.621
1997	5	23	0.043	0.721
1998	6	22	0.008	0.940
1999	9	18	−0.024	0.811
2000	11	15	−0.034	0.734
2001	12	15	−0.060	0.540
2002	12	13	−0.025	0.784
2003	13	11	−0.031	0.744
2004	15	10	−0.066	0.471
2005	17	8	−0.041	0.662
2006	16	8	−0.031	0.745
2007	17	6	−0.122	0.243

their HHI differs from that of other countries, irrespective of privatisation or liberalisation. This is evident from Figure 4.1, where countries start and tend to remain at different levels, with relatively few lines "crossing". Thus, by making comparisons across countries in this simple approach, we are likely to fall into the trap of "comparing apples with oranges". If, in 2007, we could conclude that mean HHI is lower for privatised countries, this would not necessarily be due to the effect of privatisation; it could be that the two groups are inherently different in other ways, with these differences affecting both the propensity to privatise and the mean HHI.

Also, the comparison pertains to different countries at different times. Thus, the apparent downward trend seen in Figure 4.2 is – rather than indicating that the effect of privatisation on HHI changes over time – just as compatible with the explanation that, over time, more of the countries with a relatively low HHI are becoming privatised. Indeed, it can be seen in Figure 4.1, that one of the countries with a very high HHI throughout forms an electricity pool early (in 1991). This country is Norway. If we repeat this simple approach excluding Norway, we see

quite a different picture, as is shown in Figure 4.3. When an analysis is clearly highly influenced by one country, it is unwise to draw any firm conclusions.

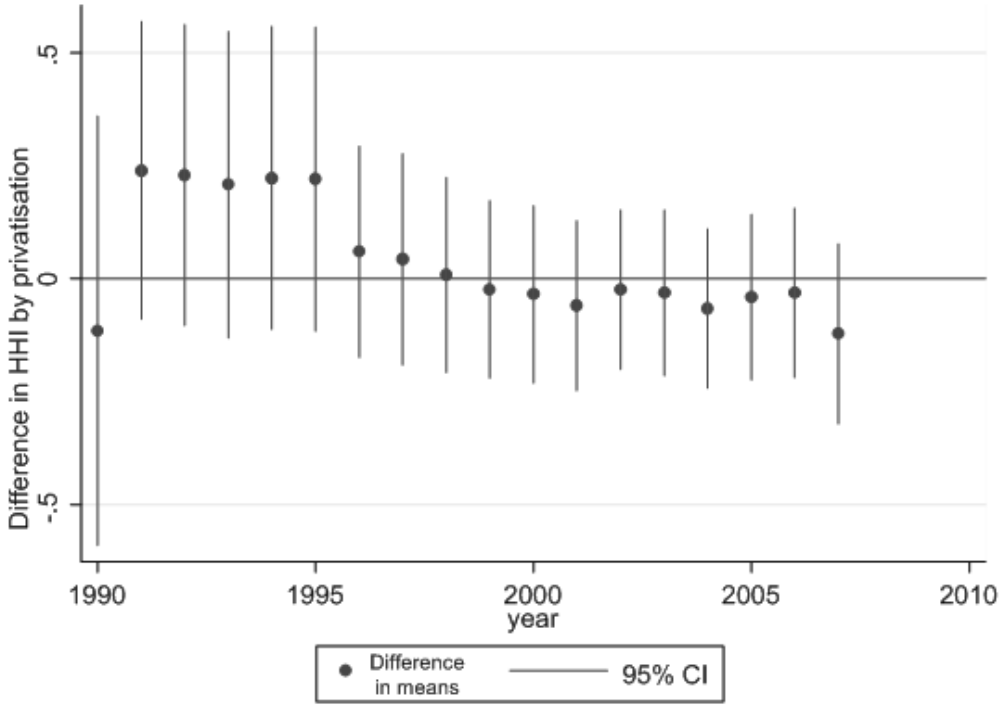


Figure 4.2: The difference in mean HHI between the two groups (privatised and unprivatised), and its 95% confidence interval, calculated separately for each year.

A between-country analysis such as this one is highly limited given that the causal question of interest looks inherently within-country. In other words, the causal effect of privatisation on HHI is concerned with what would have happened to HHI in the UK, say, if, contrary to fact, the UK had not privatised in 1990; and similarly for the other countries. There is an implicit assumption here that "all other factors (not affected by privatisation) should remain constant" across the two worlds that we wish to compare (the world in which the UK privatises in 1990, and the world in which it doesn't). Comparing different countries constitutes a very poor attempt at keeping "all other factors constant". Given that we have data on countries before and after privatisation, the obvious next step would be to incorporate this feature into the analysis.

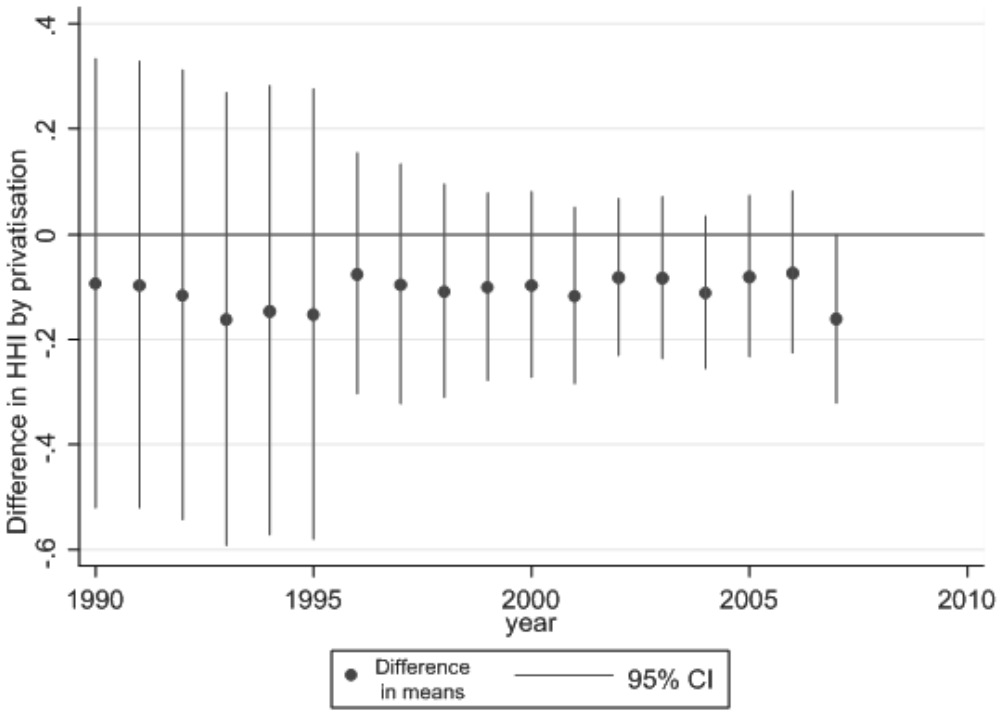


Figure 4.3: Identical to Figure 4.2, but excluding Norway.

4.3 Another simple approach: looking within countries at the point of privatisation

The simplest approach to comparing HHI in countries before and after privatisation is to discard all data except for those arising immediately before and immediately after privatisation. Then, a paired t-test comparing HHI pre- and post-privatisation can be made. This comparison is based entirely on the within-country differences in HHI before and after privatisation, and thus does not suffer from the "comparing apples and oranges" problem described above.

4.3.1 Results

Table 4.2 shows the 20 countries contributing to this analysis, together with the HHI directly before and after privatisation for these countries. A paired t-test gave a mean difference (post – pre) of -0.006, with a two-sided p-value of 0.129. Again, this provides little evidence against the null hypothesis of no difference.

4.3.2 Limitations of this approach

In carrying out this particular within-country analysis, we have used less than 5% of the collected data on HHI, and thus we are clearly not using the data to their full capacity. Also, we have looked only for a step change in HHI at the point of privatisation, and this is unlikely to capture the more complex and long-term nature of any potential impact of privatisation.

Table 4.2: The data for the countries contributing to this analysis.

	HHI	
Country	Pre-privatisation	Post-privatisation
Australia	0.456	0.459
Austria	0.499	0.49
Czech Republic	0.545	0.546
Denmark	0.434	0.358
Finland	0.202	0.202
Germany	0.166	0.153
Greece	0.271	0.257
Hungary	0.328	0.32
Ireland	0.169	0.168
Italy	0.195	0.198
Japan	0.177	0.172
Luxembourg	0.632	0.632
Netherlands	0.344	0.35
New Zealand	0.501	0.508
Norway	0.993	0.993
Portugal	0.29	0.286
Spain	0.243	0.236
Turkey	0.302	0.287
United Kingdom	0.323	0.324
United States	0.217	0.223

4.4 A more sophisticated approach: panel data analysis

4.4.1 Fixed effects model

We now turn to an approach which has been advocated for use in this and other similar settings (Allison, 2005), which is somewhat more principled than the approaches discussed thus far and

uses all collected data on HHI.

Let Y_{ij} be the value of HHI in country i in year j and let X_{ij} be a dummy indicator taking the value 1 if country i's electricity system is privatised in year j and 0 otherwise. We propose the following model:

$$Y_{ij} = \alpha_i + \beta_j + \gamma X_{ij} + \varepsilon_{ij} \tag{4.4.1}$$

where $\{\alpha_i : i = 1, \ldots, 30\}$, $\{\beta_j : j = 1961, \ldots, 2007\}$ and γ are fixed parameters to be estimated, β_{1960} is set to 0, and $\{\varepsilon_{ij} : i = 1, \ldots, 30; j = 1960, \ldots, 2007\}$ are independent identically distributed normal random variables with mean 0 and variance σ^2, where σ^2 is also a fixed parameter to be estimated.

γ is our parameter of interest, since it represents the effect of privatisation on HHI, controlling for country and year. The fact that a separate parameter is fitted for each year (as opposed to, say, one parameter for the intercept and one for the slope) means that no assumption is being made about the way HHI evolves over time. However, the fact that the model does not include a different parameter for each country in each year (ie there is no interaction between country and year in our model) means that we assume that (apart from the effect of privatisation and random fluctuation), the evolution of HHI over time is the same in each country. Indeed, if we specified a separate parameter for each country in each year, this model would fit the data perfectly and there would be no way of estimating the parameter of interest, γ.

Results

This analysis gives an estimate for γ of -0.029, and the p-value from a Wald test for the null hypothesis that γ=0 (i.e. no effect of privatisation) is < 0.001. That is, this analysis points towards there being strong evidence against the null hypothesis of no difference due to privatisation, with privatisation leading to to an average drop of 0.029 in HHI. First, of course, we note that -0.029, irrespective of its statistical significance, is not a substantively large change in HHI. Furthermore, there are strong reasons to believe that the assumptions made by this analysis are not plausible, as we discuss in the next section.

Are the assumptions made by this model plausible?

One way of assessing the plausibility of the assumptions made is to compare the observed values of HHI with the corresponding fitted ones (i.e. those predicted by the model). A country with a

reasonably good fit, is Poland (shown in Figure 4.4), whereas the fit for Denmark is particularly bad (see Figure 4.5).

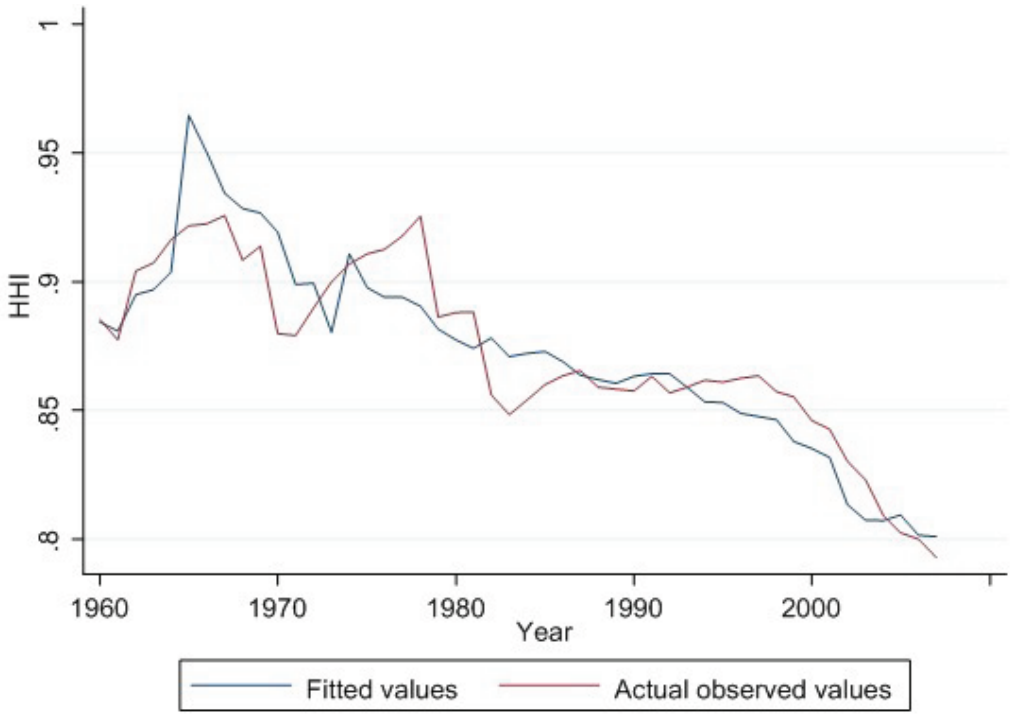


Figure 4.4: The observed and fitted profiles for Poland (which remained nationalised throughout).

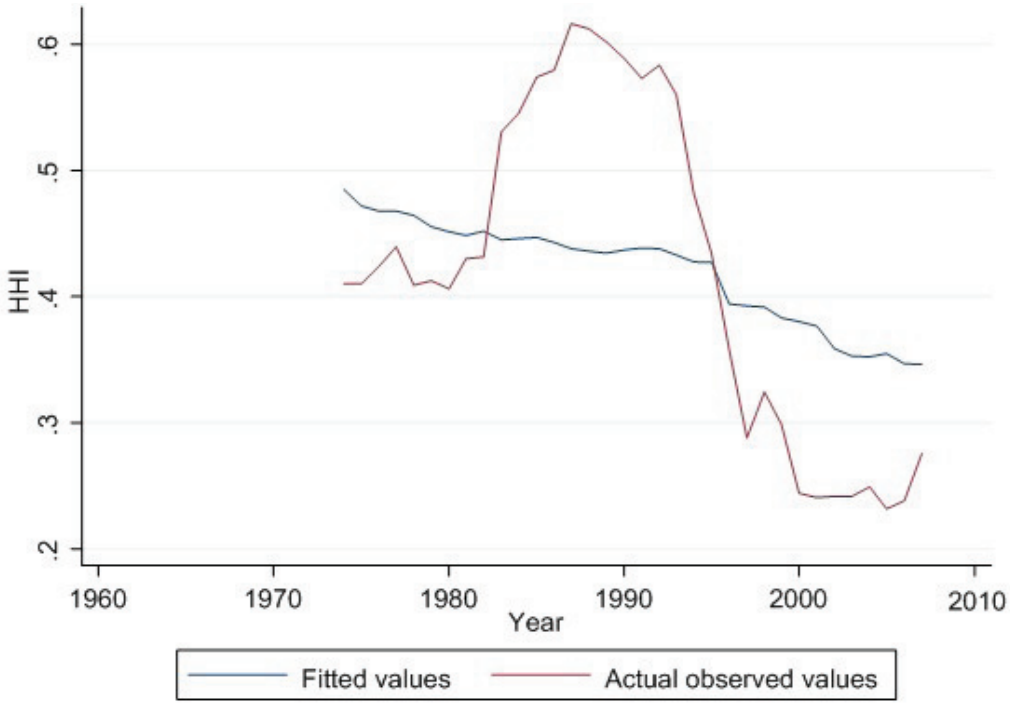


Figure 4.5: The observed and fitted profiles for Denmark (which privatised in 1996).

The first issue raised by these plots is clearly the plausibility of the assumption that there is no year-by-country interaction, i.e. that the yearly changes in HHI are the same across countries. In other words, it seems as if the shape of the trajectory for Denmark is quite different from Poland's, and that this difference in shape is not explained by a difference in privatisation indicator. Furthermore, even for Poland, where the fit is good (i.e. where the fitted trajectory is close to the observed trajectory), the assumption that the residuals (i.e. the deviations of the actual trajectory from the fitted trajectory) are independent does not seem to be satisfied. As we would expect, there is strong correlation in time, with residuals close together in time more similar than those further apart (this is often called auto-correlation). To confirm that this is the case, we looked at the pairwise correlations between estimated residuals. Table 4.3 gives these for the years 1990-1995. If the assumption of independent residuals were true, we would expect to see correlations close to zero for all off-diagonal elements of this matrix. Clearly, this assumption is seriously violated by these data. This is often the case in longitudinal data such as these, and a method that acknowledges this auto-correlation is needed.

Table 4.3: The pairwise correlations between the estimated residuals in the years 1990-1995.

Year	1990	1991	1992	1993	1994	1995
1990	1	0.98	0.96	0.86	0.79	0.61
1991	0.98	1	0.98	0.88	0.82	0.67
1992	0.96	0.98	1	0.92	0.87	0.73
1993	0.86	0.88	0.92	1	0.94	0.83
1994	0.79	0.82	0.87	0.94	1	0.95
1995	0.61	0.67	0.73	0.83	0.95	1

4.4.2 Mixed effects model

Our next aim is to relax the assumption that the residuals, ε_{ij}, in equation 4.4.1 are independent. In order to do so, and in order for the model parameters to remain identifiable, we must make one additional assumption, that the country-level parameters $\{\alpha_i : i = 1, \ldots, 30\}$ in equation 4.4.1 come from a normal distribution with some mean and variance to be estimated from the data. The country effect is then called a random effect and the model is now a mixed effects model since it includes both fixed and random effects. The plausibility of this assumption will be considered later, but the advantage of making such an assumption is that information can now be shared across countries, gaining statistical power. The mixed effects model can be thought of as the principled way of combining between- and within-country comparisons (Rabe-Hesketh and Skrondal, 2008). It also allows us to fit a different structure to the residuals (ε_{ij}), and the one we consider is auto-regressive level 1. This assumes that the correlation between ε_{ij} and ε_{ij} is given by $\rho^{|j-k|}$, where ρ is to be estimated from the data. This means that the correlation between two observations from the same country decreases as the time between those two observations increases.

Results

This analysis gives an estimate for γ of -0.0009, and the p-value from a Wald test for the null hypothesis that γ=0 (i.e. no effect of privatisation) is 0.867. That is, this analysis points towards there being very little evidence against the null hypothesis of no difference due to privatisation, in contrast with what was found from the fixed effects model. This is consistent with the violation of the independence assumption discussed for the fixed effects model. If observations are assumed to be independent when they are not, this results in an overestimation of precision (i.e. it is as if we pretend to have more information than we really have) and this leads to exaggerated claims of statistical significance. When the dependence in the data is acknowledged, we expect the

significance to decrease. However, there are still plausibility issues concerning the assumptions made by this model, as we discuss in the next section.

Are the assumptions made by this model plausible?

First, although we have relaxed the assumption that the residuals are independent, we are still making the assumption that the trajectories differ only by a constant between countries. Ideally, we would relax this assumption by allowing the $\{\beta_j : j = 1961, \ldots, 2007\}$ parameters to differ by country, using further random effects. However, we have insufficient data for such a model to be identifiable using these limited data.

We must also assess the plausibility of the normal assumption for the random country effects. This can be done using a quantile plot, in which the quantiles of the observed distribution of the random effect is plotted against the quantiles of the normal distribution with the same mean and variance. If the normality assumption holds, the plot should be a straight line at 45 degrees. This plot is shown in Figure 4.6. The plot shows some departure from the normality assumption, with the "cup" shape indicating some skewness in the distribution of the random effects.

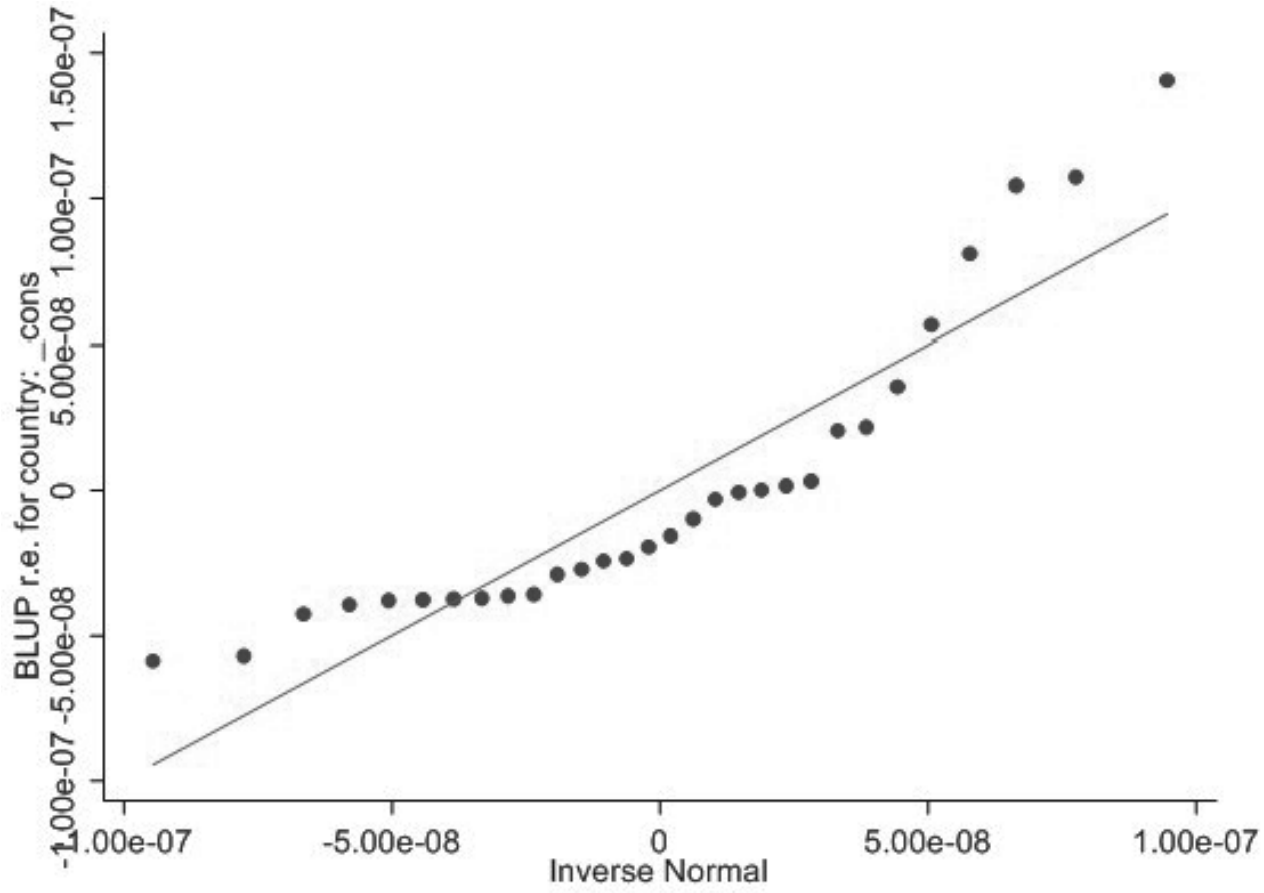


Figure 4.6: The Qnorm plot for the country-level random effects

Finally, we should assess the plausibility of our auto-regressive level 1 (AR1) assumption for the correlation structure of the residuals. A likelihood ratio test comparing this model with one in which an AR2 structure is instead fitted shows borderline improvement (p=0.05) in the fit of AR2 compared with AR1, suggesting that this should be considered as a superior model. However, there was very little change in the estimate of γ nor the associated p-value between the two models.

5

Generation System Margins

This chapter addresses the first of the resilience indicators described above: 'generation system margins'. 'System margin' is the level of generation capacity available on the system in addition to that required to meet the expected peak power demand in a given year. The purpose of this chapter is to review the evidence available on the UK electricity system margin, to ask what level of margin is 'acceptable' for resilient system function, and to understand the difficulties associated with forecasting system evolution under the UK market structure.

The requirement for system margin can be assessed statistically, taking into account factors such as generation plant reliability and demand prediction error (Gross *et al.*, 2006; Ilex Consulting, 2002). A common measure of reliability is the Loss of Load Probability (LOLP), which "expresses how likely it is that a load will need to be shed (forced to disconnect from the system) because insufficient generation is present. This is expressed as a percentage that is the number of years per

century in which load shedding will occur." Historically, under the pre-privatisation centrally planned system, the UK's LOLP was planned to remain below 9%, which corresponded to a system margin of around 20%. Post-privatisation, no explicit LOLP target is set, so the market is expected to find the appropriate level of system security. An indicative system margin of 20% is, however, still used by the British TSO, National Grid (Gross *et al.*, 2007b).

If there is insufficient generation capacity installed or operational on an electricity system, the occurrence of an adverse event is more likely to result in electricity demand not being met. Capacity shortages can occur as a result of under-investment in new generation capacity, unexpectedly high demand for electricity, or unexpectedly high levels of plant unavailability, for example as a result of a 'common mode' fault affecting several power stations simultaneously.

A number of authors have expressed concern that in the coming decade the system margin will erode to such a level that electricity supply system will be at risk of being unable to meet demand in the event of a demand surge or a generator failure (Brinckerhoff, 2007; BWEA, 2007; Lodge, 2008; Logica, 2006). Such concerns have been driven largely by the expected closure of a number of coal-fired and nuclear power stations (BERR, 2007b), and uncertainty surrounding the effectiveness of the UK's liberalised market in delivering timely investment (BERR, 2007b; Redpoint, 2007). Such warnings form the basis of claims, respectively, for increased government action, for reduced government meddling, and both for and against the construction of a new generation of nuclear power stations (BERR, 2007a; EDF Energy, 2007; Greenpeace, 2008b,a; Scott and Watson, 2006; WWF, 2006). The UK Government has frequently re-stated its position that it is for the market to decide when to build new generating capacity (DTI, 2007). Notwithstanding this, due to the strategic importance of energy supply, some argue that irrespective of ownership arrangements, the final responsibility for the provision of electricity ultimately lies with the Government. As Walt Patterson puts it, "if the lights go out, the government is in the front line, no matter who else may be nominally responsible" (Patterson, 2007).

Supply shortages have occurred on a number of occasions internationally, either as a result of environmental or technical problems, or because of regulatory changes. For example, Norway's high dependence on hydroelectricity made it highly susceptible to the drought that occurred in 2002 (IEA, 2005a); Tokyo suffered a capacity shortage in 2003 as security concerns resulted in the closure of a number of nuclear power stations (ESMAP, 2005); California suffered high electricity prices and blackouts as a result of a number of factors, including the impacts of partial liberalisation, unexpected generator unavailability, a drought and a gas shortage (ESMAP, 2005; IEA, 2005a). Such cases demonstrate the range of adverse events that can lead to a shortage of

electricity provision.

The effect of the liberalisation of energy markets on supply security has been subject of a wide range of analyses (de Bruijne and van Eeten, 2007; DTI, 2006a; PIU, 2002; Select Committee on EU, 2002). The House of Lords Select Committee on European Union concluded in 2002 that some risks can be identified and managed directly, but that "more commonly, the nature and scale of the risks will be uncertain" (Select Committee on EU, 2002). To protect against such uncertainty, the report suggests that "the main tools should be diversity, flexibility and availability of backup". It expands on these terms as follows:

1. "diversity: of fuels, of the sources of those fuels, and of the transit routes, to avoid over-dependence on any particular source;
2. flexibility: so that the system can respond quickly to any disruption;
3. back-up: via the existence of stocks, alternative sources which can be expanded in an emergency, and so on." (Select Committee on EU, 2002)

5.1 Capacity Gap

A 'capacity gap' would arise if installed electricity generation capacity were not large enough to meet peak electricity demands reliably. The terminology can differ, but here the 'installed capacity' refers to the sum total of the rated capacities of each operational generator that is connected to the electricity grid (Gross *et al.*, 2006). Power system engineers refer to the need for a 'system margin' on an electricity system in order to ensure that standards of reliability can be met. 'System margin' is the level of generation capacity available on the system in addition to that required to meet the expected peak power demand in a given year (Gross *et al.*, 2006).

The larger the system margin, the more able a system is to cope with a demand- or supply-side shock. More accurately, the ability of a system to cope with short-term shocks is dependent on its 'operating margin', which is a function of both the system margin and the proportion of that spare capacity that can be brought online at the moment of the shock and within the required timescale. This second component of resilient response depends on the contractual arrangements for ancillary service provision, which is discussed elsewhere.

5.1.1 Historic Trends

This research aims to determine the effect of the UK's liberalisation on the resilience of its electricity system. The approach to be taken to answer this question relies on analysing the historic time series data, such as that shown in Figure 5.1.

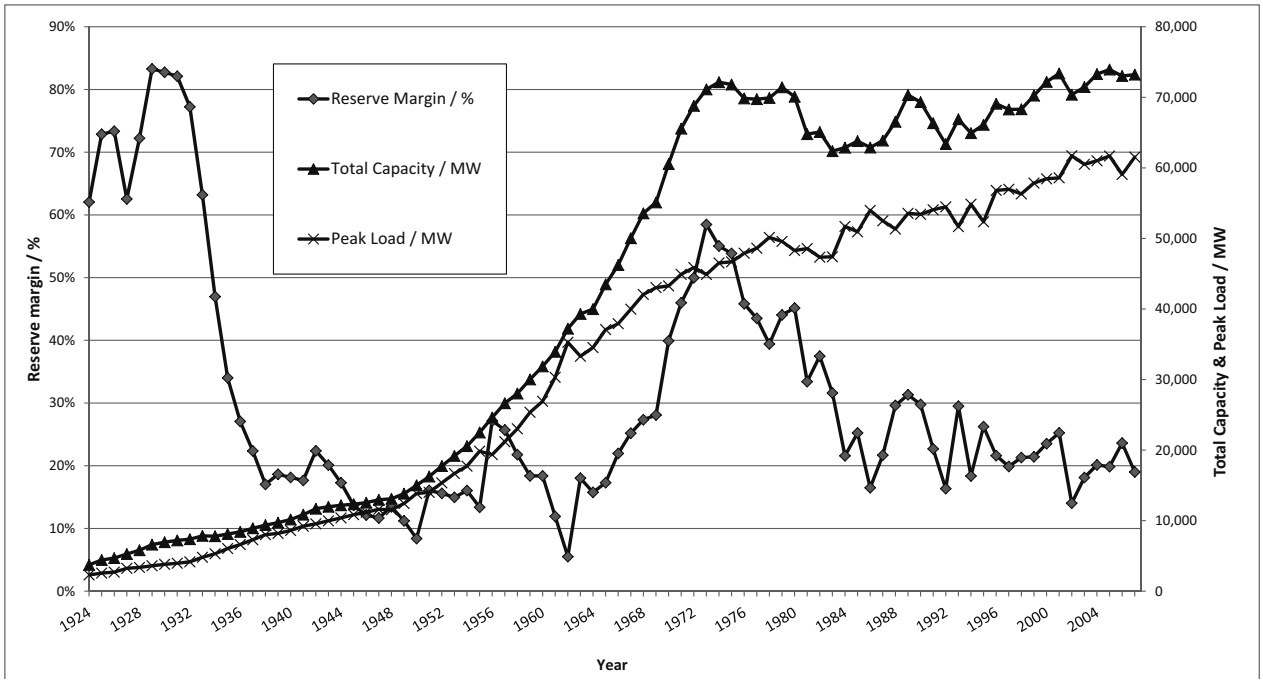


Figure 5.1: UK Reserve Margins 1924 – 2007

As discussed in the Methodology section (Section 2), the above time series data is to be analysed using multivariate statistical methods, drawing on the time series data from a number of different countries concurrently to maximise the probability of seeing any real effect of liberalisation on resilience. This will be conducted in a later chapter, but this statistical approach can be supported by a review and synthesis of modelling work done for the UK electricity system that attempts to predict future trends. In particular, much of this work has been done to investigate the possibility of the UK experiencing a 'capacity gap', in which generation capacity becomes inadequate to meet the future demand for electricity.

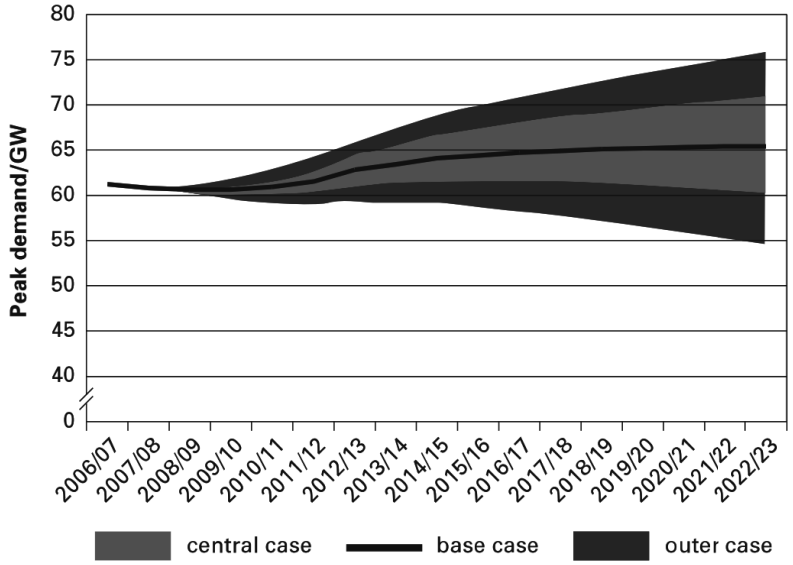
Crucially, the notion of an emerging 'capacity gap', and the associated decline in system resilience, is inherently prospective, and is therefore subject to the potentially large uncertainty associated with forecasting. In order to anticipate a capacity gap in a given period we need to be able to estimate the expected peak electricity demand and the expected installed capacity available in

that period. The following questions are addressed in the next three sections:

1. What is the *expected change in demand* between now and the period in question?
2. What is the *expected closure of generation capacity* between now and the period in question?
3. What is the *expected level of new capacity* construction between now and the period in question?

5.1.2 Expected Change in Demand

National Grid's Seven Year Statement for 2008 estimates that peak demand for electricity could rise from 61 GW in 2007/08 to 67 GW by 2014/15 (National Grid, 2008a). Analysis by independent consultants (Redpoint, 2007), which informed the UK Government's 2007 Energy White Paper, anticipates demand for electricity to be between 69 GW ("base case") and 73 GW ("challenging case") in 2015. By 2020 this is forecast to increase to 73 GW and 77 GW, respectively. The use of such projections in scenario building disguises to some extent the degree of uncertainty involved. A distribution of possible future demand levels is given by the BERR Energy Markets Outlook report (BERR, 2007b), shown in Figure 5.2.



Source: National Grid

Figure 5.2: Forecast of future peak demand on the UK electricity system

Figure 5.2 is consistent with both National Grid and Redpoint estimates, but it indicates that future demand is uncertain, and that projections lie within a considerable range. Crucially, the Energy Market Outlook notes that the highest levels of demand shown would only occur if all the relevant factors (e.g. low fuel prices, high energy intensity, low uptake of efficient technologies) converged to drive demand up and nothing was serving to suppress demand. "In practice," the report argues, "these variables are not mutually exclusive and it is unlikely that they would all combine to push electricity demand in one direction" (BERR, 2007b). Short-term trends should only be used tentatively to make long-term forecasts. For example the economic downturn that began in 2008 is not factored into any of the above forecasts and economic factors have a significant impact on demand growth. Similarly, any new policies developed in response to the proposed EU Climate and Energy Directive (Commission of the European Communities, 2008) have yet to be factored into the above projections.

The forecasts provided by National Grid are "unrestricted", "[taking] no account of demand response/management by customers" (National Grid, 2008a). This conservative forecasting method is adopted because "demand response/management by customers cannot be fully relied upon to be enacted at peak times" (National Grid, 2008a). Currently, only very large energy consumers hold contracts with the National Grid for demand-side management (DSM). Control and communication technologies are beginning to emerge, however, that could make DSM technically and economically feasible for smaller-scale consumers, perhaps even down to the level of individual households. For example, smart meters, in their most sophisticated form, could be used to disconnect certain domestic appliances at times of constrained supply; this has been proposed in South Africa (Department of Minerals and Energy, 2008).

5.1.3 Expected Generator Closure

A number of power stations are set to close in the coming decade. The majority of these are either nuclear power stations that have come to the end of their working life, or fossil fired power stations (coal and oil) that will not comply with the provisions of the latest phase of the European Union Large Combustion Plant Directive (LCPD) (National Grid, 2008a).

Non-LCPD-compliant coal- and oil-fired power stations will have to shut down by the end of 2015, or after 20,000 hours of operation from 1st January 2008, whichever is sooner (BERR, 2007b). Nine power stations, totalling 12 GW of capacity, have opted out of the LCPD and will have to close by 2015 (BERR, 2007b). This represents a reduction of 15% of the current

generation capacity. A number of these plants may close prior to 2015. BERR estimates that 2 GW of capacity will have shut down by 2012, and a total of 6 GW may have left the system by the end of 2013 (BERR, 2007b).

A number of nuclear power stations are scheduled to close as they reach the end of their operating lives. The Energy Markets Outlook report estimates that 6.3 GW of nuclear capacity will be retired by 2014, rising to 7.4 GW by 2020 (BERR, 2007b). However, in December 2007 British Energy announced that it would be extending the lives of their Hinkley Point B and Hunterston B power stations by five years (British Energy, 2007). This would defer the loss of 2.5 GW of nuclear capacity from 2011 to 2016. The largest loss to be expected from nuclear closures by 2015 is therefore 3.8 GW. British Energy also says it is planning to consider applying for extensions for its other nuclear power stations, and may extend the lives of Hinkley Point B and Hunterston B beyond 2016 if further studies show that it is feasible on technical, safety and economic grounds (British Energy, 2007). A high price of electricity would encourage further applications for lifetime extensions provided that any technical and safety requirement could be met. This would suggest that 3.8 GW is a realistic estimate of an upper limit for 2015, and that the reduction in nuclear capacity could be lower if further lifetime extensions are secured.

Other than the old nuclear and non-LCPD-compliant thermal plants, the rate of plant closure is uncertain, and depends on a number of factors. National Grid notes that six months' notice must be given before a power plant can decommission (National Grid, 2008a). It also says that such notices are not irreversible. Over the next ten years, therefore, generators can either be decommissioned or mothballed, allowing for reversal should the economic or political incentives change. These decisions will be based on the price of electricity, the price of fuel, the price of carbon and constraints imposed by policy decisions.

5.1.4 Expected Capacity Additions

The uncertainty surrounding the addition of new capacity following the closure of old or non-LCPD-compliant plant is central to the question of how the UK's liberalisation is expected to affect capacity margins. In a system where generation capacity is constructed in response to market forces, a reduction in capacity system margins (whether actual or anticipated) may be necessary to provide the price signals that lead investors to build more generators. In a perfectly-functioning market, these oscillations in capacity would be small. In reality, however, larger oscillations are typical because a variety of market imperfections lead investors to delay

investment, and indeed encourage periods when new plants are built in large numbers (Gross *et al.*, 2007a; White, 2006). The 'lumpiness' of investment in electricity generation is one reason for this, contributing to more extreme oscillations than would be the case if new plant could be provided in smaller units. Even if such oscillations in capacity construction are 'natural' under market driven conditions, the periods of constrained margins that have the potential to emerge from these conditions are at the heart of concerns about a 'capacity gap'.

BERR states that fourteen new conventional power stations amounting to 14 GW of capacity have been announced, the majority of which are Combined Cycle Gas Turbine (CCGT) generators (BERR, 2007b). Of this 14 GW, 7.5 GW has received Section 36 approval, and 4.5 GW of this is at, or near, the construction phase.* Of the remainder, some might not go to completion due to local opposition or because of restrictions imposed by the grid operator. Because the decision to build new capacity is based on expectations about generators' future profitability, which in turn depends on a number of uncertain factors (e.g. supply-demand balance, capital costs, fuel costs, government policy), the "type and total amount of new build could outturn higher or lower" (BERR, 2007b).

The National Grid forecast includes all types of large-scale generation, and offers a range of values under different assumptions. Including only those units that currently exist or are under construction, National Grid estimates that 5.2 GW of new capacity would be built by 2014/15. If it uses as a guide those plants that have consent, this forecast rises to 6.5 GW by 2014/15. These estimates ignore the likely addition of new generation that has yet to apply for grid connection. It does, however, also ignore the possibility that plants under construction or holding planning and connection permission may not go to completion.

There is an important point of interpretation here: the Seven Year Statement (SYS) provided by National Grid is not a prediction of the future. The company states that "none of the plant margins presented... is intended to represent our forecast or prediction of the future position." Rather, the SYS is intended to provide a signal to the market to facilitate investment in new generation. Crucially, it makes no assumptions about the ability of the market to deliver this new generation in a timely manner.

One significant source of uncertainty surrounding the UK electricity generation mix is the contribution that nuclear power could make. A range of estimates exist for the length of time required

*Section 36 of the Electricity Act 1989 is the legislative provision under which the Secretary of State grants development consents for generating stations above 50 MW, and is used by National Grid as one indicator of new capacity additions.

to build a new nuclear power station (BERR, 2007a). The UK government has expressed its support for new nuclear, and has introduced provisions intended to facilitate the process for investors (House of Lords, 2008). Even so, the government does not expect construction of new nuclear power stations to begin until 2013 at the earliest, with the first plant becoming operational between 2017 and 2020 (BERR, 2007a).

The cost of a new nuclear programme is similarly faced with a large amount of uncertainty, and in particular the cost of construction and decommissioning. The government has stated that it will not offer financial support (BERR, 2008a), so a new nuclear programme must be wholly privately funded. There have been suggestions that a number of power companies are willing to make such an investment (British Energy, 2008), but to date no new nuclear projects have been announced

Interconnectors may be able to provide the UK with power that complements indigenous generation during peak periods. The England-France Interconnector has a capacity of 2,000 MW and has had an availability of 97%. The Moyle interconnector has a capacity of 500 MW, but is mainly used to export electricity from Scotland to Northern Ireland, and is therefore unlikely to contribute to meeting peak electricity demand on the British mainland (BERR, 2007b). In addition to these, two more interconnectors are planned: the EirGrid 500 MW Britain-Ireland interconnector has planning permission and grid access rights, and is expected to be operational by 2012 (EirGrid, 2008); the BritNed interconnector between Britain and the Netherlands will have a capacity of 1000 MW and is expected to be operational by 2010 (National Grid, 2008b). These interconnectors are not strictly defined as generation, but they nonetheless have the potential to deliver up to 3.5 GW of electrical power during peak periods, provided other European transmission operators are able and willing to export electricity to the UK at that time.

5.1.5 Forecasting a 'Capacity Gap'

The uncertainties surrounding estimates of future demand, plant closure rates, and the rate at which new capacity will be added to the system result in a range of projected system margins. UK peak demand in 2007 was 61 GW and forecasts for 2015 range from 57 GW (4 GW reduction) to 73 GW (12 GW increase). 12 GW of coal plant is expected to close by 2015, as well as approximately 4 GW of nuclear plant (depending on life extension plans). The combined effect of changing demand and plant closures puts the new capacity required to maintain existing margins between 12 GW and 28 GW. This large range demonstrates the difficulty in making

such forecasts.

The forecast for capacity additions is similarly uncertain. The range for additions runs from around 7 GW, if the new interconnectors are built but only those power stations currently under construction are ultimately built, to around 15 GW if the new interconnectors are built and all existing power station applications result in completed projects. The range could be larger, since construction projects can be halted, and additional power stations could be applied for, approved and constructed by 2015.

However, using the ranges given above, the current system margin of 19 GW could drop to *minus 2 GW*, or it could rise to *22 GW*. It is important to stress that the margin is unlikely to reach either of these outermost values. As the 2007 Energy Markets Outlook report observes, "the theoretical range of possible future effective capacity margins is very wide [but] we are unlikely to see such a wide range... because the supply of and demand for electricity... are related to each other through price" (BERR, 2007b).

It is of limited value, therefore, to look at forecasts of demand, plant closures and capacity additions in isolation. Instead, an integrated approach is needed, that can take into account the effect of these factors on each other. It is important to note that scenarios are *not* forecasts, rather they are self-consistent descriptions of the future that allow the implications of different assumptions about factors such as fuel prices, electricity prices, carbon prices, incentives and political constraints to be assessed (Hughes, 2003). At least some of the scenarios developed by, or for, the British government represent the analysts 'best guess' about what the future is likely to hold. Others seek to represent a 'worse case' or to present an 'optimistic' view of the future. Scenarios are decision making tools that allow policymakers to test the implications of different policy choices and assess the range of risks attached to policy.

5.2 Recent Scenarios

This section examines seven scenarios, three of which come from BERR's 2007 Energy Markets Outlook (EMO) report (BERR, 2007b), and four of which were developed for the UK government by electricity market analysts (Redpoint, 2007). The range of values that emerges from these scenarios illustrates the challenge of making reliable projections of system margins.

Redpoint's scenarios assume that Britain's electricity market is either "well-functioning" or "im-

perfect", and for each of these produces a "base case" and a "challenging case" projection. The assumptions underlying the three EMO scenarios vary according to the future carbon price, which is assumed to affect both consumption levels and the future generating mix; these scenarios are classified as "Tough Carbon" in which the carbon price is high, "Easy Carbon" in which the price is low, and a "Central" case. These seven scenarios are collated in Figure 5.3.†

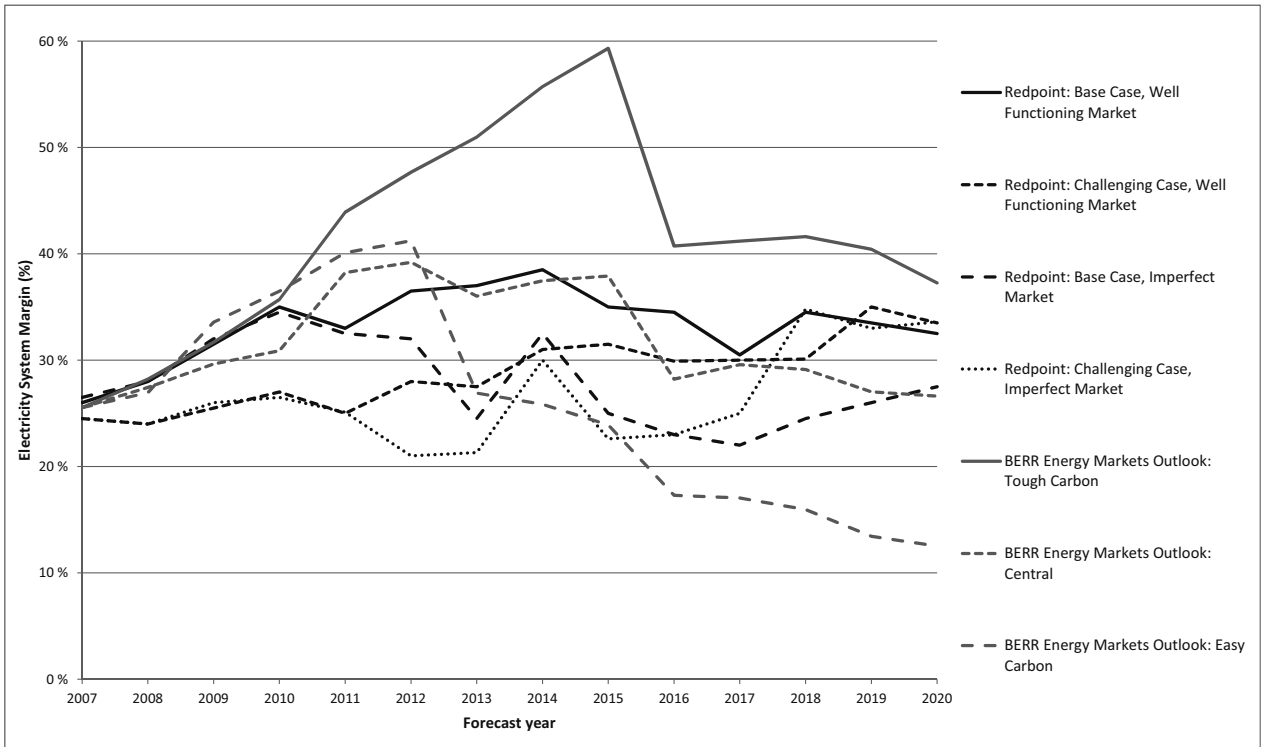


Figure 5.3: Forecasts of the future UK system margin

The specific features of each scenario are discussed in detail in their respective sources (BERR, 2007b; Redpoint, 2007), but some broad observations can be made that are of relevance here.

First, the range of future system margins presented by these scenarios is wide, even projecting only out to 2010. By 2015 and 2020 this range has widened further still. These scenarios are not predictions of the future, but they do highlight the sensitivity of trends in system margins to underlying assumptions, each of which is difficult to predict.

Second, each of the scenarios in Figure 5.3 shows system margins that vary over time, resulting in

† Note: the Energy Markets Outlook report presented the "effective capacity margin", which reduced the installed capacity margin according to the expected availability of each generator type. In order to quote these figures in terms of the installed capacity margin, Figure 5.3 uses the raw demand and installed capacity projections, which can be found at www.berr.gov.uk/files/file41824.xls

peaks and troughs of different sizes. This is particularly distinctive in Redpoint's two "imperfect market" cases, which is to be expected as investors delay construction of new generating plant until they are confident that a profit can be made. These cycles of investment are a feature of any market. The difficulty for regulators and policymakers is in distinguishing between an investment-driving dip in the system margin, and the beginnings of an inexorable decline.

Third, and perhaps most important for this discussion, is the fundamental difference between the Redpoint and the EMO scenarios. All three EMO scenarios exhibit a sharp decline in system margins at some point between 2012 and 2015: these correspond to the closure of nuclear power stations and non-LCPD-compliant thermal plant. The Redpoint scenarios also account for the closure of these generators, but the system margins do not exhibit a corresponding decline. This discrepancy arises because the Redpoint analysis assumes that there will be some investor response to capacity scarcity, whereas the EMO report makes its forecasts "in the absence of any new investment" (BERR, 2007b).

5.3 UK Liberalisation and Capacity Margins

The creation of scenarios illustrates the range of uncertainty associated with forecasting a change in an electricity system's capacity margin. The largest source of uncertainty comes from a lack of understanding of the way in which investors will behave in the liberalised market. The initial impact of the LCPD is fairly clearly defined, and the closure of the older nuclear power stations, while not entirely fixed in time, is reasonably well understood. The fundamental question for policymakers is whether or not the UK market is functioning sufficiently well to respond to these planned closures in a timely manner. As the Redpoint report observes, the UK market is relatively new, and its behaviour in response to plant closures has yet to be observed:

> In the absence of a clear cost advantage of new technologies over existing technologies, new investment must be driven largely by investors' expectations of future scarcity. The dynamics of the market have not been tested under these conditions until now (Redpoint, 2007).

The Redpoint report, which provides the only analysis of those discussed above that considers the effect of scarcity on investor behaviour, provides scenarios under differing assumptions but does not posit which of those is likely to materialise. The impact of regulatory interventions

such as the LCPD undoubtedly have an impact on future levels of capacity margins, but the trajectory of those margins ultimately depends on the decisions of investors and the market context in which those decisions are made. Further analysis is therefore required to determine under what regulatory regimes forced capacity closures can and cannot be adequately offset by new plant construction.

5.4 Panel Data Analysis

This section describes the outcome of conducting a panel data analysis using mixed effects modelling. As described in chapter 4, this chapter uses the historic data from 30 different countries to determine what, if any, evidence exists to suggest that liberalisation and the subsequent regulation that occurred has had an effect on the level of system margin.

The explanatory variables of interest here can be placed into one of two categories:

1. Liberalisation indicators: These indicators describe different aspects of electricity liberalisation and privatisation

    - ***overall_lib***:What is the overall level of liberalisation (this is a function of the following six indicators)
    - ***tpa***:How are the terms and conditions of third party access (TPA) to the electricity transmission grid determined?
    - ***liberalisedpool***:Is there a liberalised wholesale market for electricity (a wholesale pool)? ***liberalised*** is a binary variable generated from ***liberalisedpool***.
    - ***supplychoice***:What is the minimum consumption threshold that consumers must exceed in order to be able to choose their electricity supplier?
    - ***ownercode***:What is the ownership structure of the largest companies in the generation, transmission, distribution, and supply segments of the electricity industry? ***privatised*** is a binary variable generated from ***ownercode***.
    - ***transgensep***:What is the degree of vertical separation between the transmission and generation segments of the electricity industry? ***transgen_unbundling*** is a binary variable generated from ***transgensep***.

- ***vertsepoverall***:What is the overall degree of vertical separation in the electricity industry? ***overall_unbundling*** is a binary variable generated from ***vertsepoverall***.

2. Low-carbon policies: These explanatory variables indicate the type of policies put in place by governments to encourage the increased contribution of new renewables to the electricity mix

   - ***renew_support_binary***:Is there any form of renewables policy in place?
   - ***newrenewable_proportion***:What proportion of installed capacity is made up of new renewable technologies?
   - ***fit***, ***tgc***, ***tender***, ***tax***: Is there a Feed-In Tariff, Tradeable Green Certificate, Tendering or Tax/Incentive scheme in place for renewable generation?

The margins used for this analysis are calculated using the IEA Electricity Data. These data provide installed capacities and peak load values for two different generator categories (OECD, 2010):

- **Main activity producers** generate electricity for sale to third parties as their primary activity.
- **Autoproducers** generate electricity wholly or partly for their own use as an activity which supports their primary activity.

The BERR margin data that gave rise to Figure 5.4 uses the “Main activity producers” data, as can be seen by comparing figures 5.4 and 5.5.

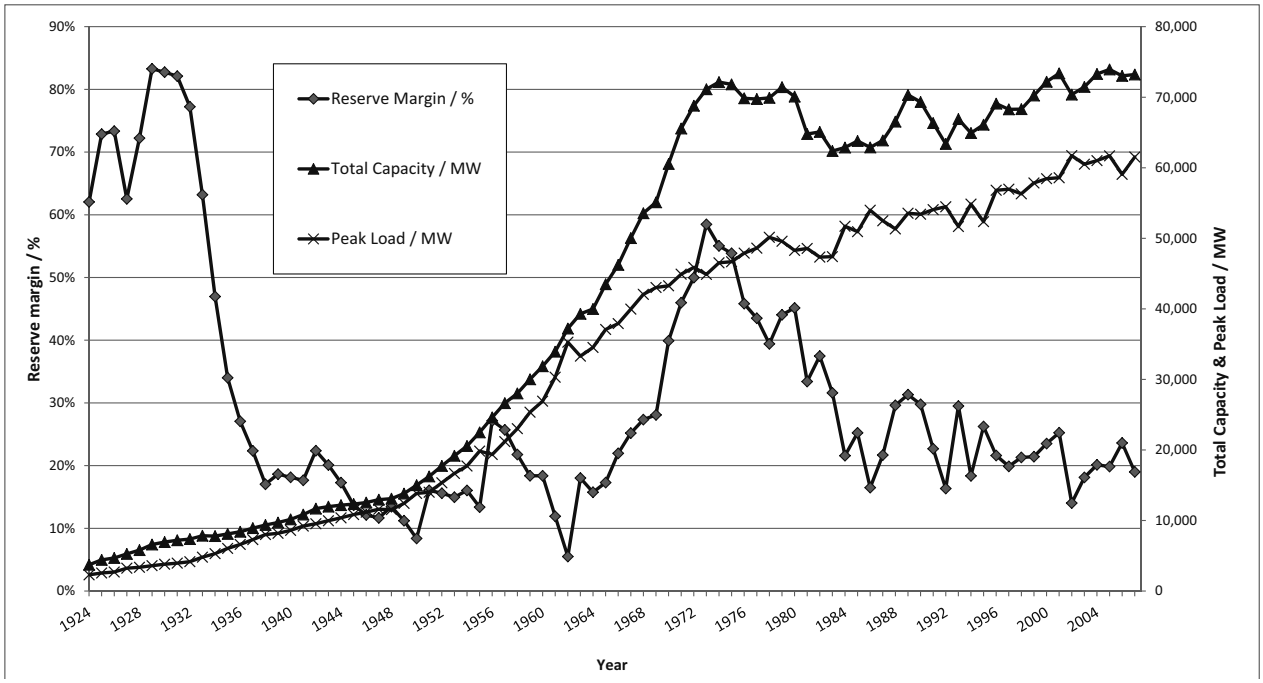


Figure 5.4: UK Reserve Margins 1924 – 2007

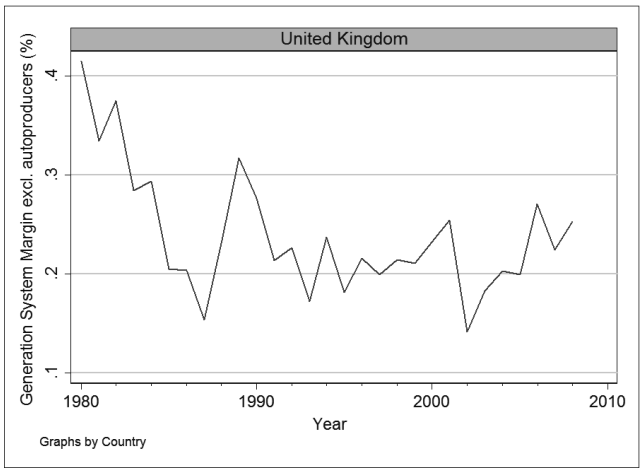


Figure 5.5: Generation system margin of the UK, excluding autoproducers

In the case of the UK, none of the new renewables capacity is included in these data. Prior to 1989 almost no new renewable generation was installed in the UK, so this omission would have made a negligible difference to the calculation of system margin. As the levels of renewables increases their contribution to the system margin becomes significant.

Internationally, the classification of renewable generation is inconsistent. For example, in the

United States the declared "autoproducer" wind capacity was 1,690MWe in 1998 but by the following year it had gone down to just 1MWe. In the same period the "main activity" wind went from 9MWe to 2,251MWe. This results from a redesignation of existing wind farms, but there is no rationale for saying that the resilience offered by the margin has changed as a result.

An alternative to using the "main activity" values would be to use the total of the main and autoproducer capacities. This approach would show a noticeably different trend for the UK margin (Figure 5.6). The decline in margin shown in Figure 5.5 is markedly less pronounced in Figure 5.6.

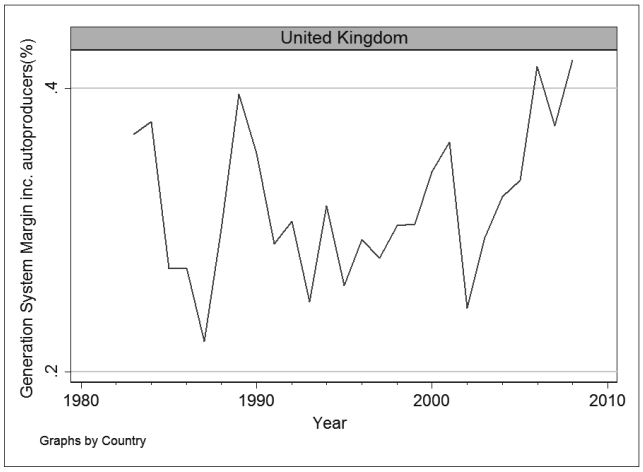


Figure 5.6: Total generation system margin of the UK

For low levels of renewables penetration, "margin" provides a consistent indicator of system security. Renewables are, by their nature, non-dispatchable and intermittent. As the National Grid Winter Outlook report shows in Figure 5.7, the ratio of expected output to nameplate capacity for renewable energy technologies such as wind are lower than for dispatchable generation technologies.

Power Station Type	Full Metered Capacity (GW)	Assumed Availability	Assumed Availability (GW)
Nuclear	10.4	80%	8.4
French Interconnector	2.0	100%	2.0
Hydro generation	1.1	80%	0.9
Wind generation	1.6	27%	0.4
Coal	28.1	85%	23.9
Oil	3.5	95%	3.3
Pumped storage	2.7	95%	2.6
OCGT	1.3	80%	1.0
CCGT	26.3	90%	23.6
Total	**77.0**		**66.1**
Overall availability		**86%**	

Figure 5.7: Generation Availability Assumptions Made For Winter 2009/10

As well as making a smaller contribution to electricity supply for each unit of installed capacity, renewables are intermittent in nature (UKERC, 2006). To accommodate this additional variability, some additional conventional plant needs to be added to the system to maintain a constant Loss of Load Probability (LOLP). The amount of additional conventional plant required depends on the variability of the renewable resource (wind, sun, tide, etc.), the geographic spread of those technologies (the more dispersed across the country wind farms are, the less their variability is correlated), and the degree of correlation between renewable technologies (e.g. wind speeds and insolation levels are negatively correlated (Sinden, 2006)).

To describe the amount of demand that is displaced by a unit of renewable capacity, the notion of a 'capacity credit' has been conceived (UKERC, 2006). If 1GW of wind has a 30% capacity credit, it can displace 300MW of conventional generation without changing the LOLP. The capacity credit of a given renewable technology is a function of the resource variability and the geographic spread. Most important, however, is that the capacity credit is a function of the level of penetration of the intermittent generating technology. For example, National Grid (2009b) has made some planning estimates that show how the capacity credit of wind is expected to decrease as the amount of wind on the system increases (see Figure 5.8).

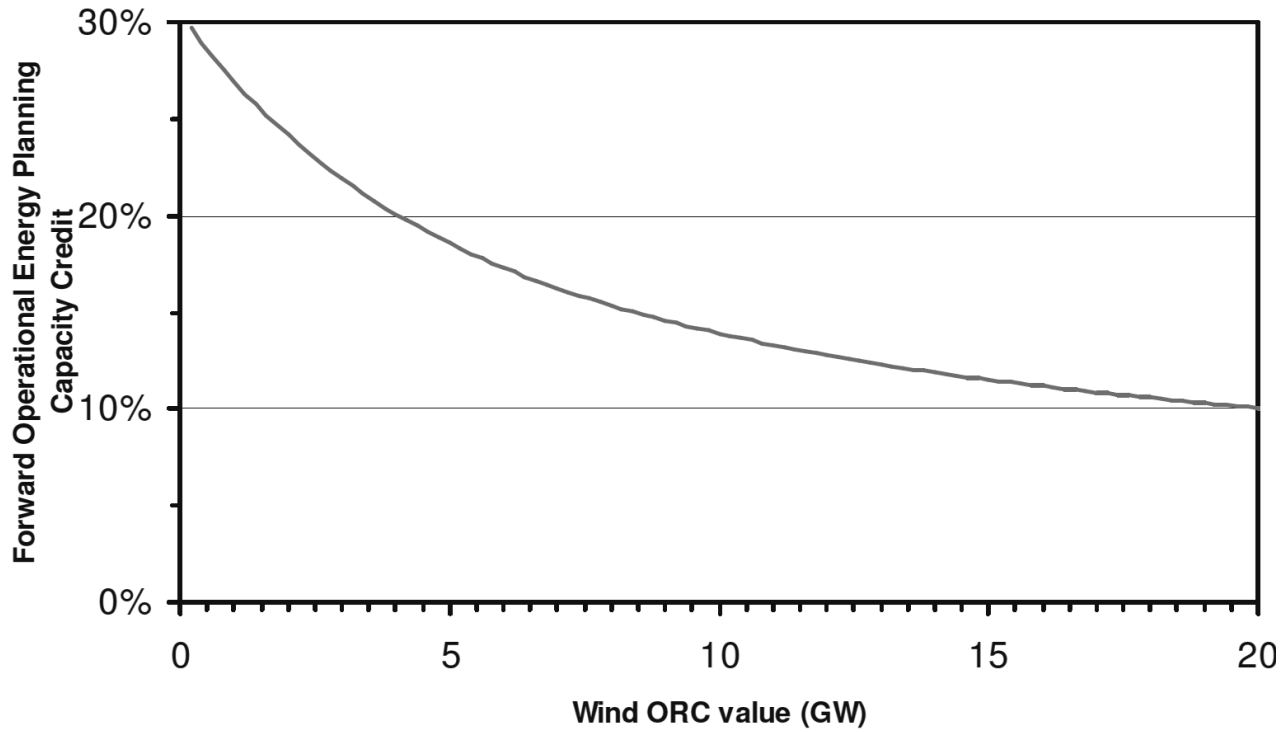


Figure 5.8: Forward Operational Energy Planning Wind Capacity Credit

The relationship between capacity credit and renewables penetration is part of ongoing research in literature and will, once defined, differ from region to region depending on the pre-existing generation mix, local climate and the geographical dispersion of renewable generators. For the purposes of this thesis, a simplified approach is needed to be able to conduct a comparative analysis between countries and over time. In order to do this, the work of Voorspools and D'haeseleer (2006) has been used. In their paper, "An analytical formula for the capacity credit of wind power", they propose an equation to calculate the capacity credit, CC, of wind as a function of penetration, x, the capacity factor of wind, CF_{wind}, the reliability of conventional plant, R_{system}, and the coefficient of wind dispersion, δ.

$$\text{CC} = \frac{U}{V+\delta}\frac{CF_{\text{wind}}}{R_{\text{system}}}\left\{1 + W\delta e^{-Y(V+\delta)(x-1)}\right\} \text{ for } x > 1\% \tag{5.4.1}$$

$$\text{CC} = \frac{U}{V+\delta} \cdot \frac{CF_{\text{wind}}}{R_{\text{system}}}(1+W) \text{ for } x < 1\% \tag{5.4.2}$$

where U, V, W and Y equal 32.8, 0.306, 3.26 and 0.1077, respectively.

By replacing the installed capacity of renewable generation with this concept of a 'capacity credit', the traditional measure of 'system margin' is converted into a 'derated margin'.

Whereas the system margin, M is defined as:

$$M = \frac{\text{Total Capacity} - \text{Peak Load}}{\text{Peak Load}} \tag{5.4.3}$$

Derated margin, DM, is defined as:

$$\text{DM} = \frac{C_I - C_R + C_R CC - L_P}{L_P} \tag{5.4.4}$$

where C_I is the total installed capacity, C_R is the renewable capacity, CC is the Capacity Credit for those renewables and L_P is the peak load.

Some additional assumptions are made. First, whereas the Voorspools and D'haeseleer (2006) analysis is concerned with wind, this analysis assumes that it is reasonable to extended the formula to cover solar, wave and tidal generation. Second, the availability of conventional plant is assumed to be 85% in line with the National Grid data; the exact figure will depend on the generation mix and specifics of the generation technology within each country (such as generator age and system operation). Third, the dispersion coefficient, δ is assumed to be equal to 0.8, where 0 would mean the renewable generators were entirely uncorrelated and 1 would mean perfect correlation. The value of 0.8 produces a relationship between capacity credit and renewables penetration similar in form to that produced by the National Grid, as shown in Figure 5.9.

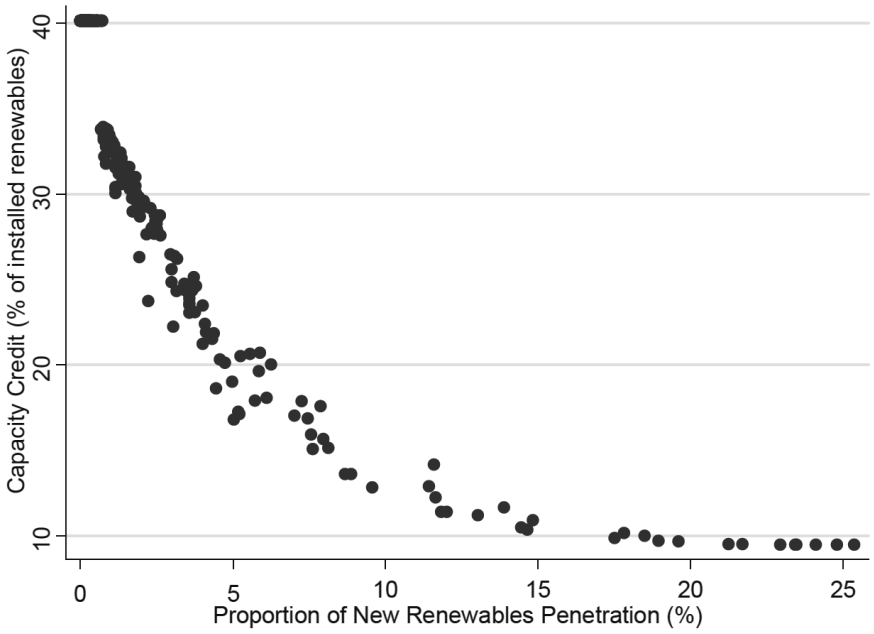


Figure 5.9: Capacity Credit vs Renewables Penetration using Voorspools (2005) formula

In the remainder of this chapter, the focus will be on the derated margin as this is the best reflection of the security of the system in terms of the associated Loss of Load Probability (LOLP). The derated margin across the OECD countries is shown in Figure 5.10.

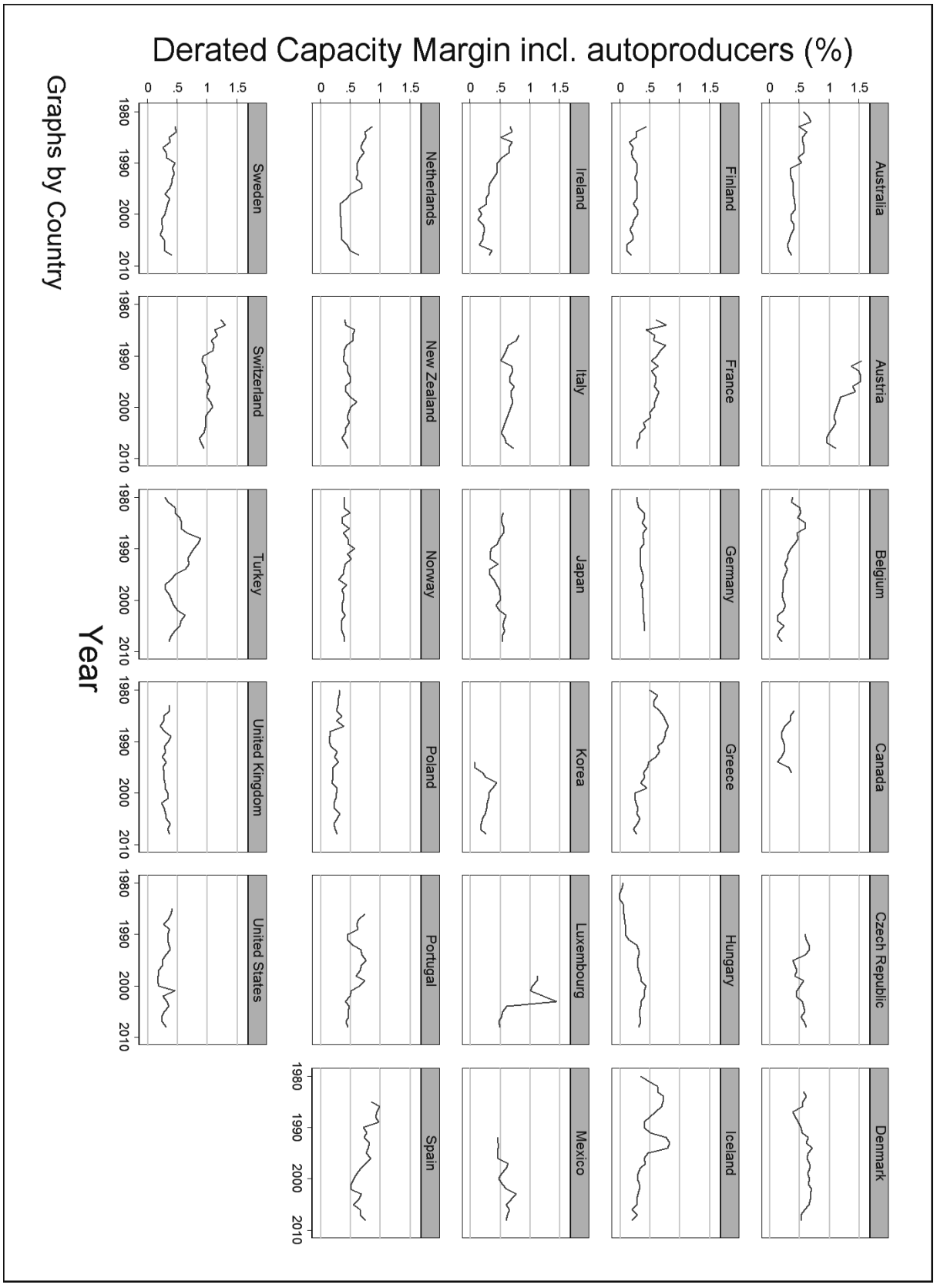


Figure 5.10: Derated margin for the OECD countries

5.4.1 Liberalisation Indicators

This section asks whether different liberalisation measures are causally associated with a change in the derated system margin.

5.4.1.1 The effect of overall liberalisation on the derated system margin

As Figure 5.11 shows, there is a correlation between increasing liberalisation and decreasing derated margin. The effect, however is neither strong nor consistent. This representation of the data simply plots the margin against the overall level of liberalisation for all country-years, and does not reveal whether this trend occurs as a result of differences between countries or whether those differences arise within countries over time.

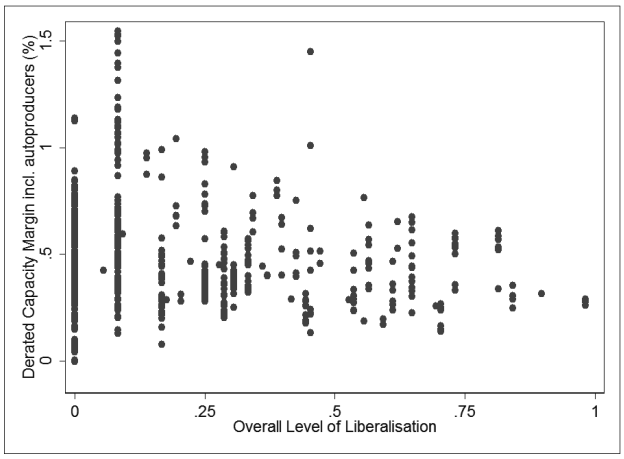


Figure 5.11: Derated margin (all county-years) vs overall liberalisation

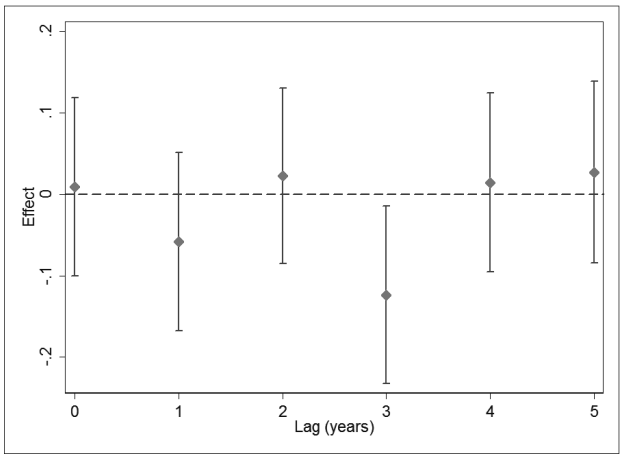


Figure 5.12: Lagged effect of overall liberalisation on derated margin

The question of interest is whether an increase in overall liberalisation is associated with a change in the margin. The panel data analysis described above was used to test this question, looking for a relationship between a change in overall liberalisation and a change in derated margin from between zero and 5 years into the future.

Figure 5.12 shows the results of this analysis. There is little support for the notion that a change in the overall level of liberalisation has an effect on the derated margin. There is a negative effect of 0.12, which is significant at the 5% confidence level. If this effect were real, and held over all ranges of the explanatory variable, this would mean that a shift from a system fully owned

by a nationalised monopoly to one that was fully privatised and liberalised, the margin would decrease by 12% after three years.

Again, this finding is not supported at any other time lag, so it seems more reasonable to conclude that this particular result is an artefact of the limited number of data, rather than an underlying effect. This conclusion is discussed further in the following sections, which look at some of the underlying liberalisation indicators that constitute the "overall liberalisation" measure.

5.4.1.2 The effect of the creation of a liberalised pool on derated margin

The measure of overall liberalisation (overall_lib) is a composite of a number of different liberalisation indicators defined by the OECD. One of these is a binary indicator that measures whether there is a liberalised pool in operation. As with all the indicator variables used in this research, this has been coded to take a value of 1 if the liberalised pool exists and 0 if it does not.

As can be seen from Figure 5.13, the derated margins in countries that have a liberalised electricity pool tend to be slightly lower than those that do not. This difference, however, is well within the 95% confidence intervals.

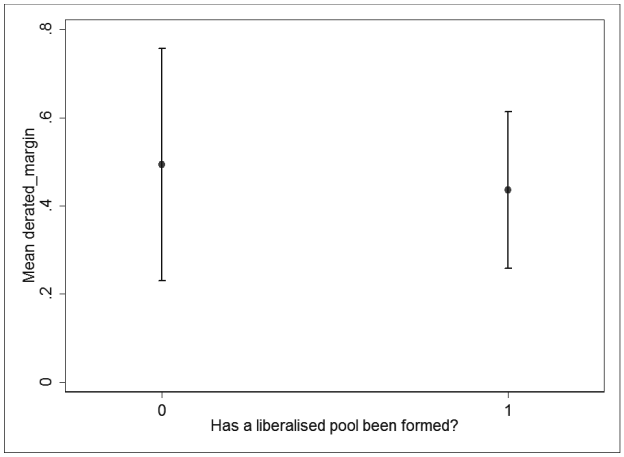


Figure 5.13: Overall mean derated margin with and without a liberalised pool

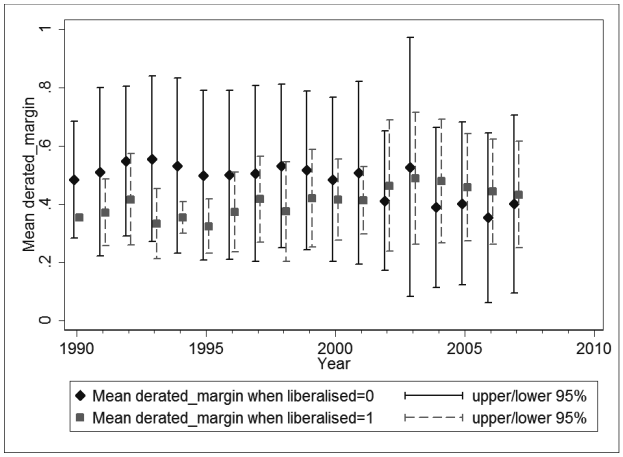


Figure 5.14: Mean derated margin by year, with and without a liberalised pool

The relationship is better shown by looking at individual years. Figure 5.14 illustrates this, and reveals that from 1990-2001 the countries with liberalised pools tended to have a lower margin than those without. As more countries liberalised this difference narrowed and eventually reversed, so that the countries that remain without a liberalised pool now have a slightly lower

mean derated margin than those that have liberalised. In all years the difference between the means is much less than the confidence intervals.

Again, the causal question is whether creating a liberalised pool caused a change in the level of the derated margin. Figure 5.15 shows the result of this analysis. At all lags there is no statistically-significant effect.

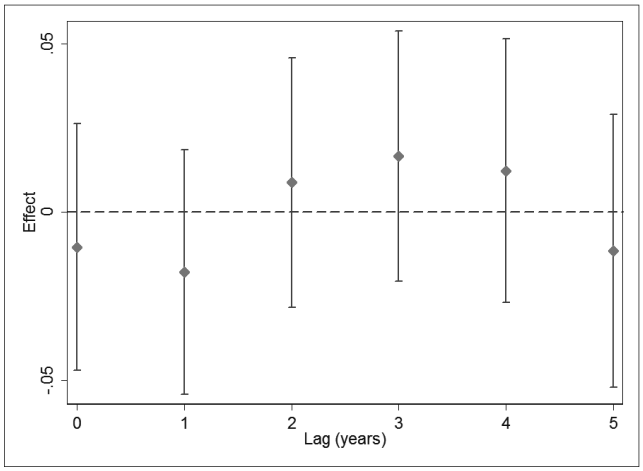


Figure 5.15: Effect of the creation of a liberalised pool on generation margin

5.4.1.3 The effect of the ownership arrangements on generation margin

The ownership arrangements variables describe the extent to which the largest generation, transmission, distribution and supply companies have been privatised in a given country. The 'ownercode' variable takes a value of 0, 0.25, 0.5, 0.75 or 1 depending on whether a country's main electricity companies are, respectively, 'public', 'mostly public', 'mixed', 'mostly private' or 'private'. Further, a binary variable 'privatised' has been generated from the ownercode and takes a value of 1 if a country's system is privatised or mostly privatised, and takes 0 otherwise.

A plot of the mean derated margin against ownercode (Figure 5.16) reveals no real trend, and any variation is within the 95% confidence intervals.

The mixed effects model shows an effect of -0.17 (p=0.001) at a lag of three years (Figure 5.17), which is similar to that observed in the overall liberalisation variable, of which ownercode is a component. Using ownercode in this way assumes that it exhibits a linear effect on derated margin. A change from 0 to 1 would, therefore, have twice the effect of a change from 0 to 0.5. This assumption is probably false, since the effect could in principle take a number of forms.

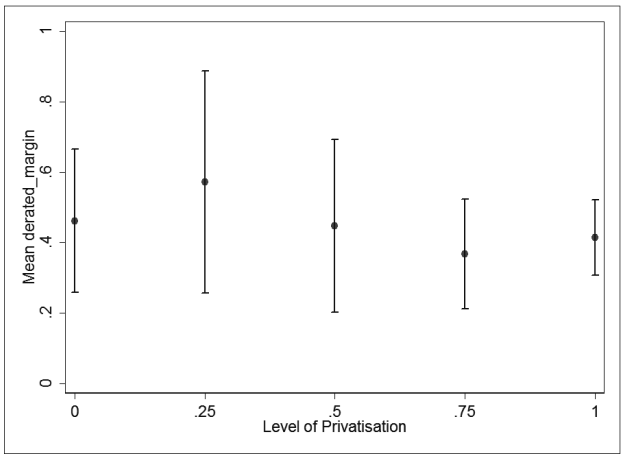


Figure 5.16: Derated margin (all county-years) against the degree of private ownership

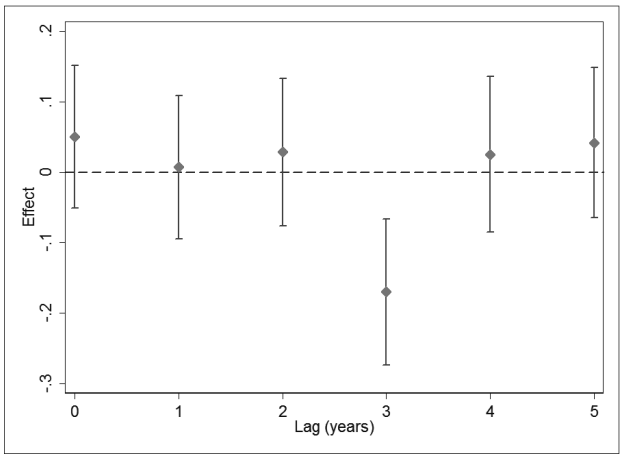


Figure 5.17: Effect of the ownership arrangements on the derated margin

An alternative would be to treat ownercode as a categorical variable. This would make no assumption about the shape of the effect. The disadvantage would be that it would assume, for example, that 'privatised' was no more similar to 'mostly privatised' than it was to 'mostly public'. This is an unreasonably assumption and is likely to seriously reduce the power of the analysis.

Instead, a binary variable was created, 'privatised'. This pooled the ownercode variable so that 'privatised' and 'mostly privatised' were considered as one category and 'mixed', 'mostly public' and 'public' were categorised as another. This approach loses the power to discern the effect of a change within these new categories.

This variable indicates that that have undergone privatisation have a smaller derated margin than those that have not, but that this difference is within the standard error (Figure 5.18).

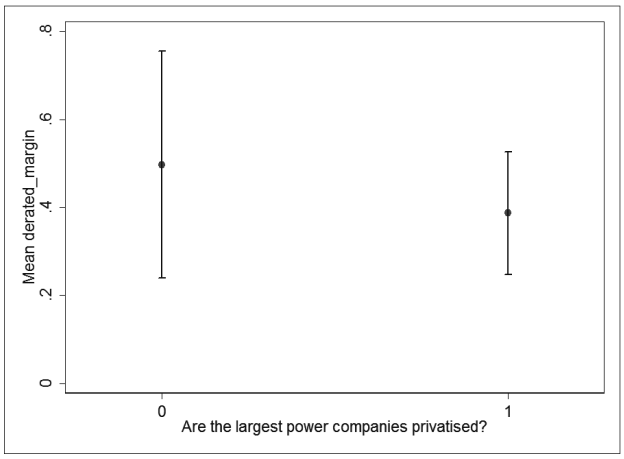


Figure 5.18: Mean derated margin by whether privatised

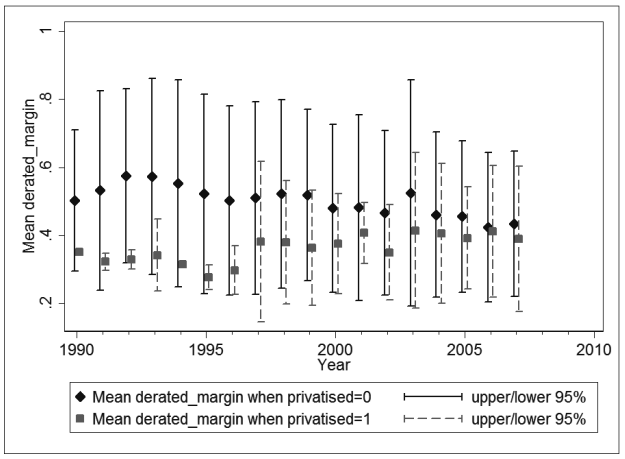


Figure 5.19: Mean derated margin by whether privatised and by year

Breaking this analysis down into separate years reveals the relationship shown in Figure 5.19. The early privatising countries tended to have lower derated margins. This remains true, although the difference between the two groups has narrowed considerably.

In terms of the actual effect that the act of transferring the electricity generation assets from public to private hands, Figure 5.20 shows that there is no association to be found from the data.

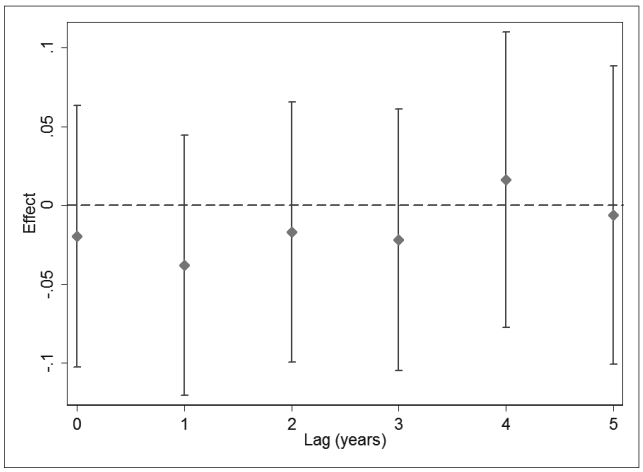


Figure 5.20: Lagged effect of undergoing privatisation on derated margin

There is certainly a difference between the margins of those countries that choose to undergo privatisation and those that do not. What this analysis shows, however, is that whatever the causal pathway may be, it is unlikely that the act of privatisation itself is a cause of a change in system margins.

5.4.1.4 Vertical Separation

Vertical separation is indicated by two variables: the degree of vertical separation between the transmission and generation segments of the electricity industry (**transgensep**, where 0=Integrated, 0.5=Accounting Separation and 1=Separate Companies) and the overall degree of vertical separation (**vertsepoverall**, where 0=Integrated, 0.5=Mixed and 1=Unbundled). As before, two corresponding binary variables were created. These are **transgen_unbundling** and **overall_unbundling**, and take a value of 0 if the system is fully vertically integrated and 1 otherwise.

Figures 5.21 and 5.22 show that systems with more separation between generation and transmission ownership have lower mean derated margins. The standard errors, however, are large in relation to the observed differences.

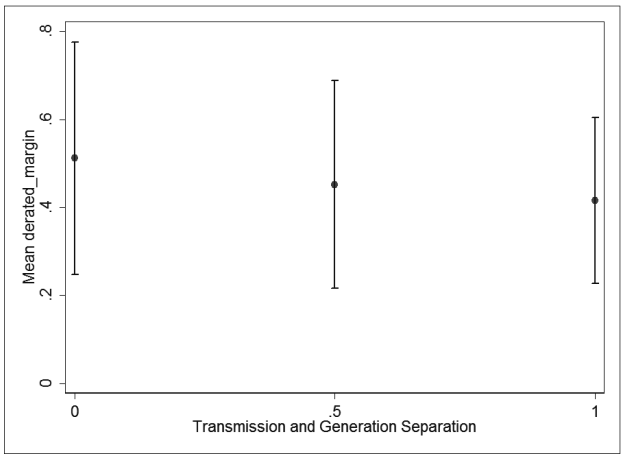


Figure 5.21: Derated margin (all county-years) against the degree of transmission-generation separation

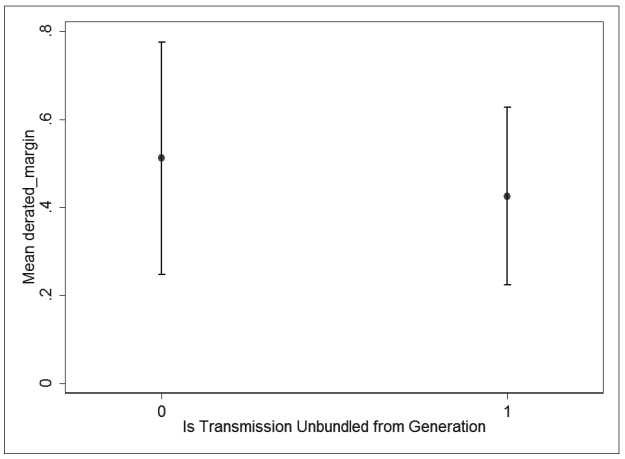


Figure 5.22: Derated margin (all county-years) against whether transmission and generation unbundling has begun

The mixed effect model shows no significant effect of separating generation from transmission (Figures 5.23 and 5.24). The only exception to this can be seen in the Figure 5.24, which corresponds to the binary **transgen_unbundling** variable, where at a lag of 4 years there is an effect that appears to be significant at the 5% level. Given this marginal nature of this finding, and the lack of an overall trend in these data, this effect is likely to have occurred by chance.

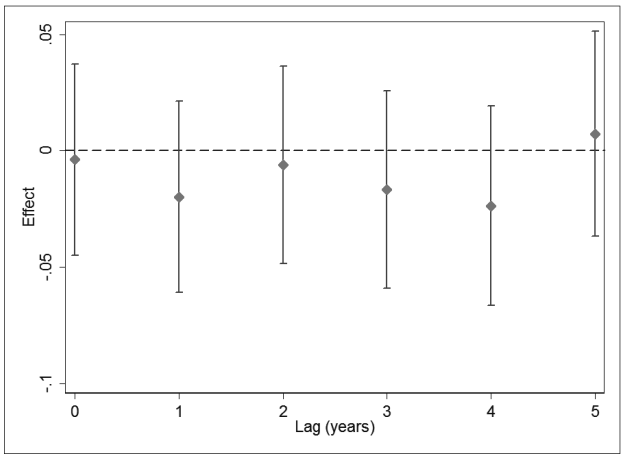


Figure 5.23: Effect of degree of transmission-generation separation on the derated margin

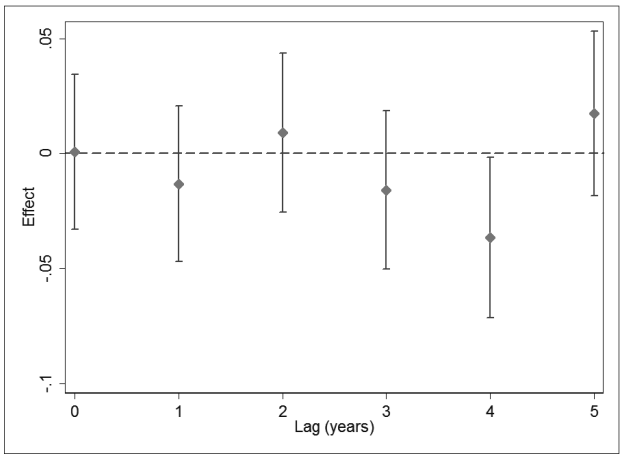


Figure 5.24: Effect of separating generation from transmission on the derated margin

By looking at the annual data (Figure 5.25), it is apparent that countries that have separated their generation and transmission sectors have, on average, lower derated margins.

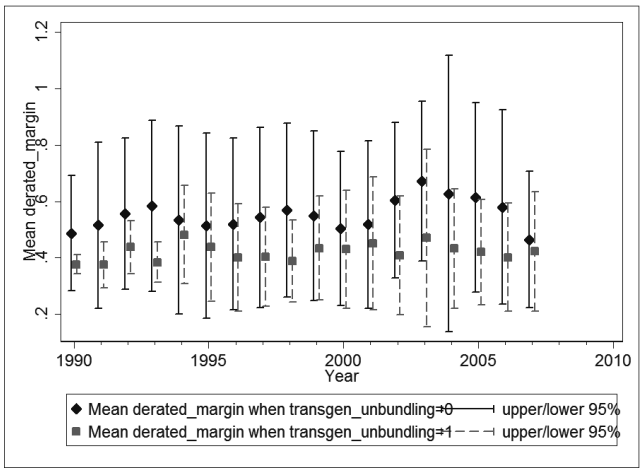


Figure 5.25: Derated margin by year against whether transmission and generation are integrated (0) or not (1)

These findings are similarly reflected in the analysis of overall vertical separation. As with the particular case of transmission-generation separation, those countries that have increased the degree of vertical separation across the generation, transmission, distribution and supply sectors tend to have lower margins (Figure 5.26) but there is no evidence of a causal relationship between the two, as shown by Figure 5.27.

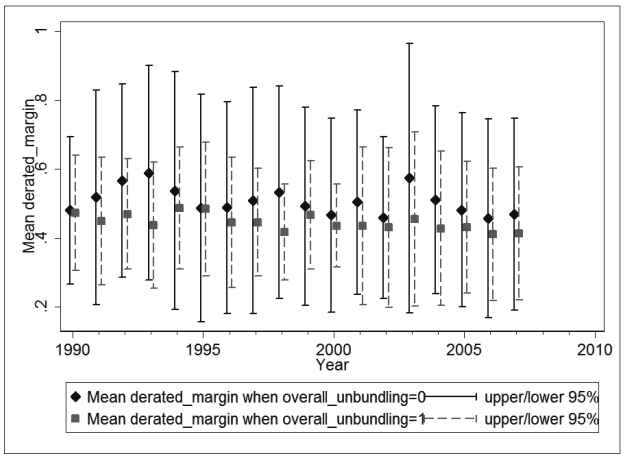


Figure 5.26: Derated margin against vertical unbundling in a given year

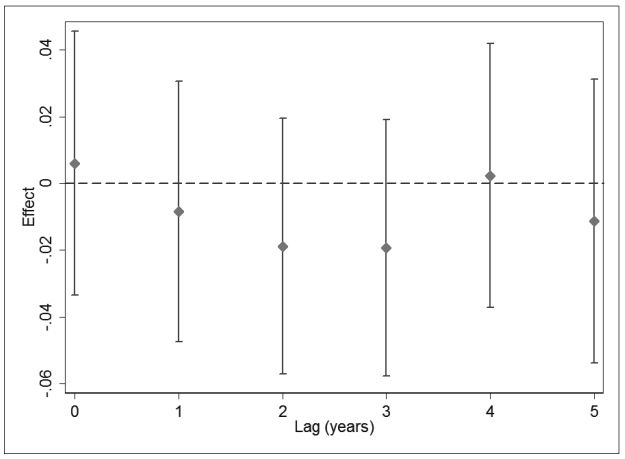


Figure 5.27: Effect of vertical unbundling on the derated margin

5.4.2 Effect of renewable generation and associated policies on system margins

As is discussed at the beginning of this chapter, privatised and liberalised systems have come under some scrutiny with regards to their ability to deliver sufficient investment in new generation. In particular, the need to decarbonise the electricity system has resulted in policies that push for the closure of some old power stations and attempt both to encourage forms of generation with lower carbon emissions, and to discourage the more polluting generation technologies.

This section, therefore, evaluates the evidence that this drive for lower-carbon generation options has affected the overall system margin. Using the same methods applied above, this section assesses the relationship between the deployment of renewable generation and the associated renewables policies on the system margin.

5.4.2.1 Installed capacity of new renewables

The most widely available and consistently reported measure of renewable generation activity in the OECD countries is the amount of renewable generation that has been installed. The first measure of interest, therefore, how an increase in the proportion of new renewable generation on a system impacts on the system margin.

Derated margin remains the best measure of system security, but it is perhaps useful to look also at the more conventional measure of the system margin. Figure 5.28 shows that there is

a positive correlation between the proportion of new renewables on a system and the overall margin of that system. The mixed model analysis shown in Figure 5.29 shows that this is a real effect. Increasing the proportion of renewable generation on the system is strongly associated with an increase in the margin.

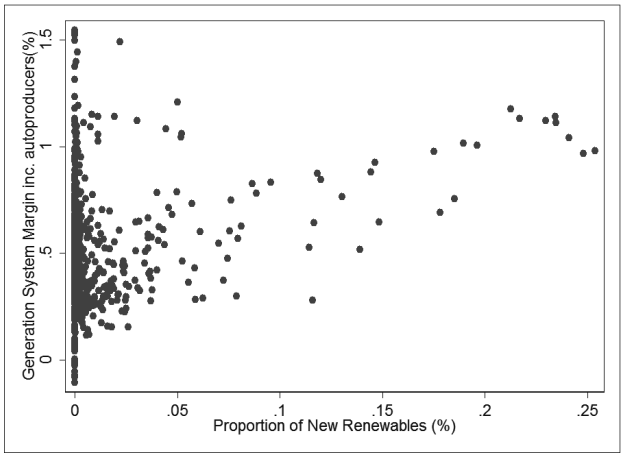


Figure 5.28: Margin (all county-years) against the proportion of new renewables on the system

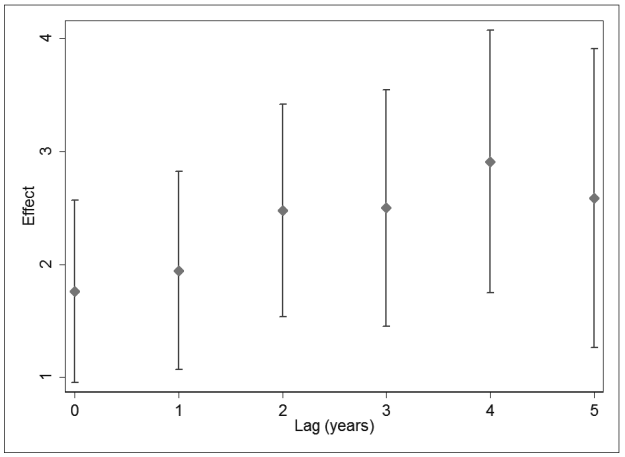


Figure 5.29: Lagged effect of increasing the new renewable proportion on margin

If however, 'derated margin' is used, the effect is far less noticeable (Figures 5.30 and 5.31). This illustrates the impact that the choice of the 'margin' measure can have on an analysis. Power systems that have a large proportion of their electricity generated by new renewable technologies have to increase the overall margin to maintain a given level of LOLP.

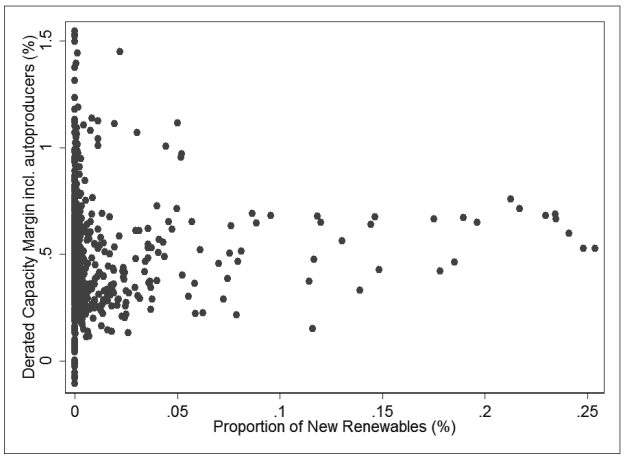


Figure 5.30: Derated margin (all county-years) against the proportion of new renewables on the system

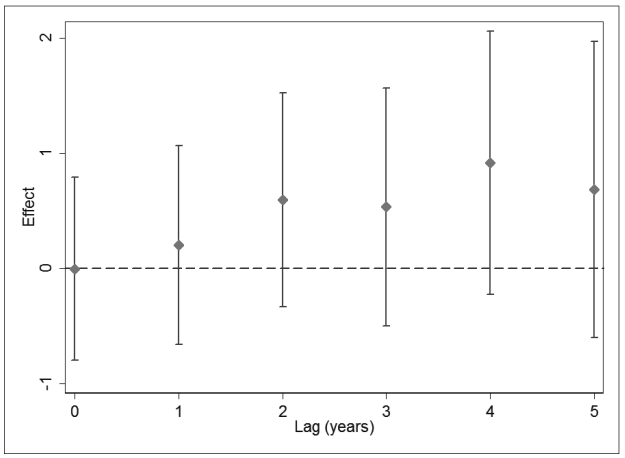


Figure 5.31: Lagged effect of increasing the new renewable proportion on the derated margin

The evidence shown in Figure 5.31 is certainly weaker than that for Figure 5.29, but the effect

is still positive for all lags. The error bars all contain zero so it is conceivable that the true effect of increasing renewables is to depress the derated margin, but it is more likely that there is no effect or that the effect is a positive one.

5.4.2.2 Renewable electricity support schemes

It may not be that the expansion of renewable generation per se is problematic for the system margin. Rather, it is conceivable that policies intended to promote renewables have an inadvertent effect on the overall level of investment that in turn could either:

1. Discourage new capacity construction by dissuading projects that otherwise might have gone ahead.
2. Encourage too much investment by keeping electricity prices artificially high.

The following sections test these hypotheses, first asking whether renewable support schemes in general affect the derated margin, and then asking whether the choice of incentive scheme has an impact.

Any renewable support scheme

As Figure 5.32 shows, there is little difference between the derated margins with and without any renewable support mechanism. Figure 5.33 shows more clearly that in most years the countries with some form of renewable support mechanism have slightly lower derated margins than those that do not.

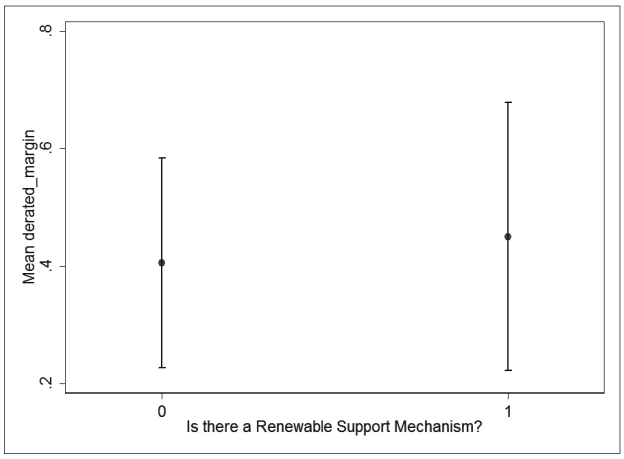


Figure 5.32: Mean derated margin by presence of renewable support mechanism

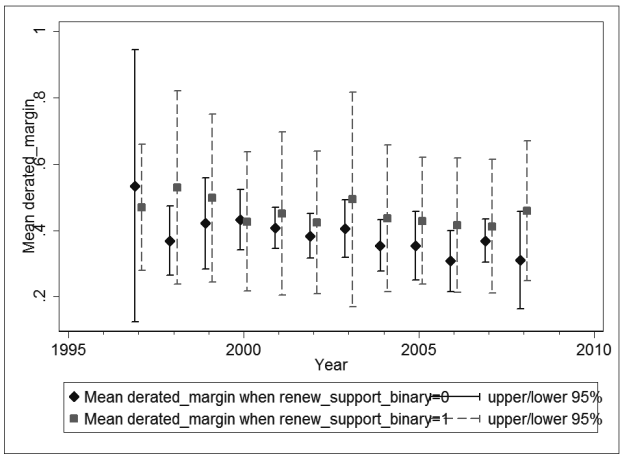


Figure 5.33: Mean derated margin by renewable support and by year

Using the mixed effects model to test this relationship, it can be seen by Figure 5.34 that introducing an unspecified renewable support mechanism has no significant effect on the derated margin.

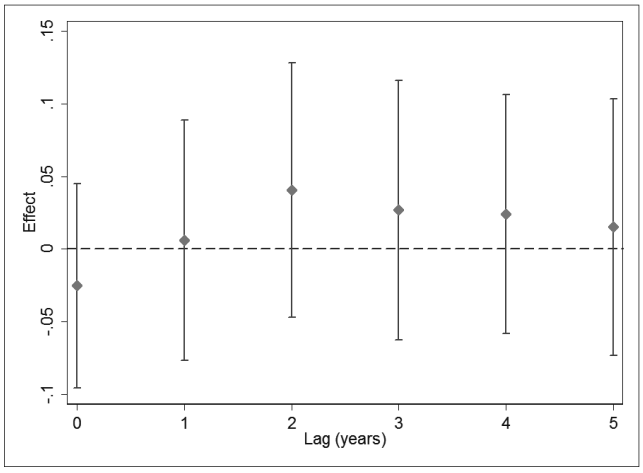


Figure 5.34: Lagged effect of introducing renewables support mechanisms on the derated margin

It is possible that some support mechanisms have an effect, while others do not, or that the effect is different in each case. Combining the mechanisms as above has the potential to hide such details, so in addition these interventions are tested independently.

Feed-in Tariff

The difference between systems that have a Feed-in Tariff (FIT) is more pronounced than in the aggregate indicator, suggesting that margins are higher where countries have a FIT. This can be

seen in Figure 5.35 for all years, and in Figure 5.36 where it is clear than those countries that implemented an FIT had higher derated margins.

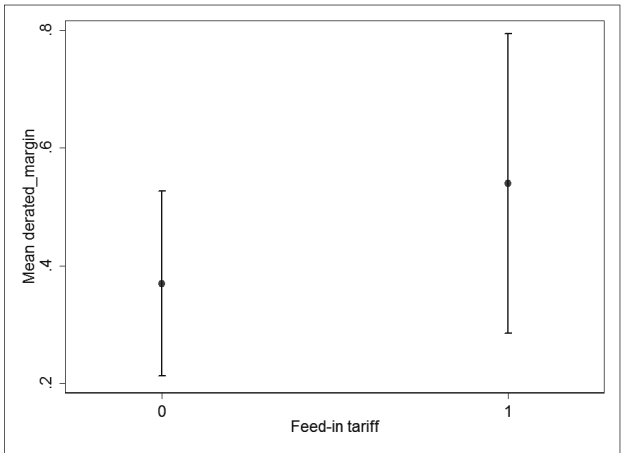


Figure 5.35: Mean derated margin in systems with (1) and without (0) Feed-in Tariff schemes

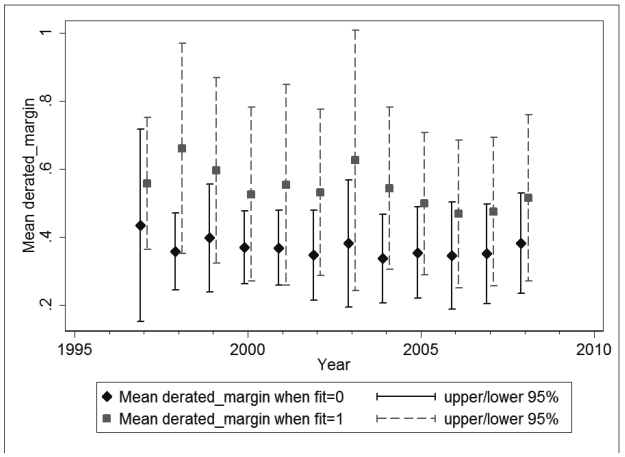


Figure 5.36: Mean derated margin by FIT and by year

As before, the observation that the FIT and non-FIT groups have different is not sufficient to conclude that the implementation of an FIT brought about a change in the margin. Figure 5.37 does, however, seem to offer some tentative support for this hypothesis. Only the 1-year lag is significant at the 5% level, but the measured effect is fairly consistent at all lags.

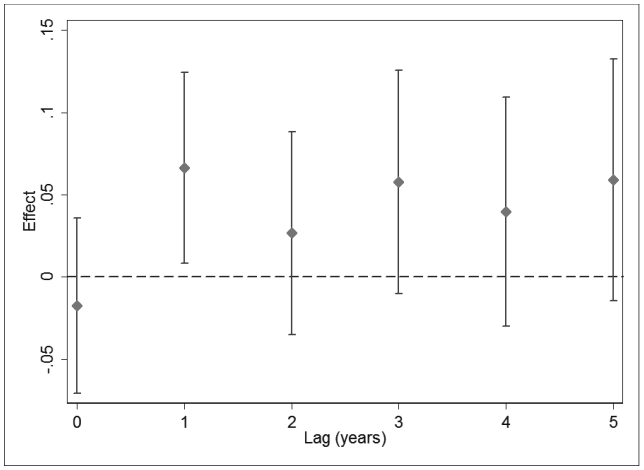


Figure 5.37: Lagged effect of introducing a feed-in tariff on the derated margin

If this analysis did indicate a real effect, the Feed-in Tariff would appear to have the effect of increasing the derated margin by around 5%. The absolute magnitude of the effect may depend on the choice of parameters in the underlying capacity credit formula, so it may be more appropriate just to make relative comparisons with the other renewable support mechanisms.

Quota / Tradeable Green Certificate / Renewables Obligation

In contrast to the FIT, countries employing Tradeable Green Certificate (TGC) schemes such as the UK's Renewables Obligation (RO) tend to have lower derated margins, as can be seen in Figure 5.38. By looking at the yearly numbers in Figure 5.39 it is apparent that in all but one year TGC countries have had lower margins.

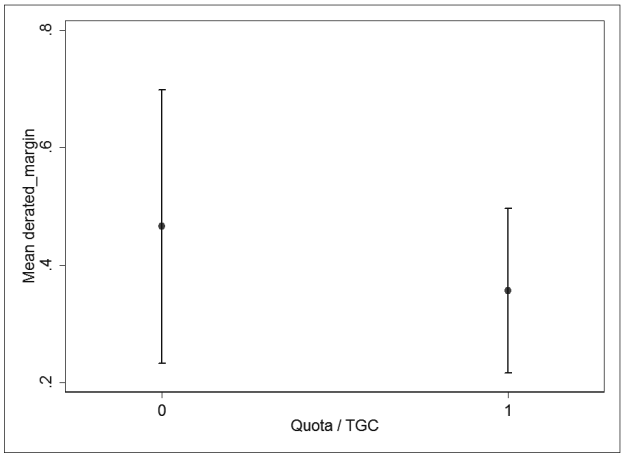


Figure 5.38: Mean derated margin in systems with (1) and without (0) Tradeable Green Certificates

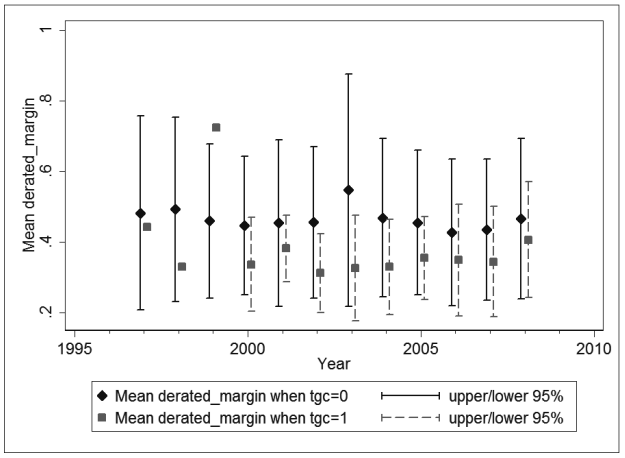


Figure 5.39: Mean derated margin by TGC scheme and by year

The mixed effects model illustrated in Figure 5.40, however, shows that there is little evidence to support the hypothesis that there is a causal link between introducing a TGC scheme and there being a change in the derated margin. Certainly, if there is a real effect to be observed, it is neither as large as that observed under the FIT scheme.

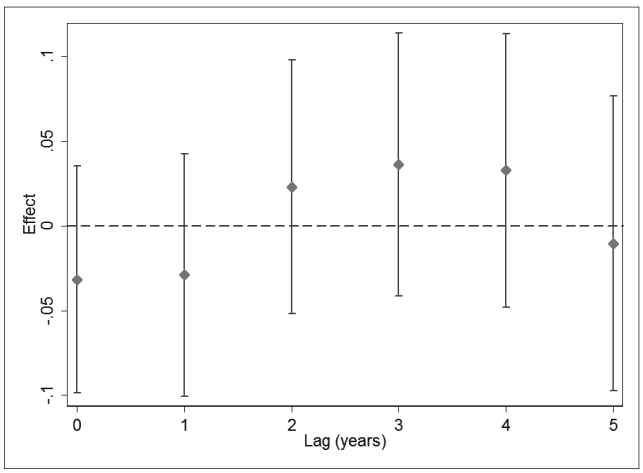


Figure 5.40: Lagged effect of introducing tradeable green certificates on the derated margin

Tendering Process

Countries with a tendering process for renewable generation have, on average, lower derated margins than those that do not (Figure 5.41. This difference has narrowed in recent years (Figure 5.42) but there are now far fewer countries using tendering processes than there were in the past. Most countries have instead adopted alternative renewable support mechanisms.

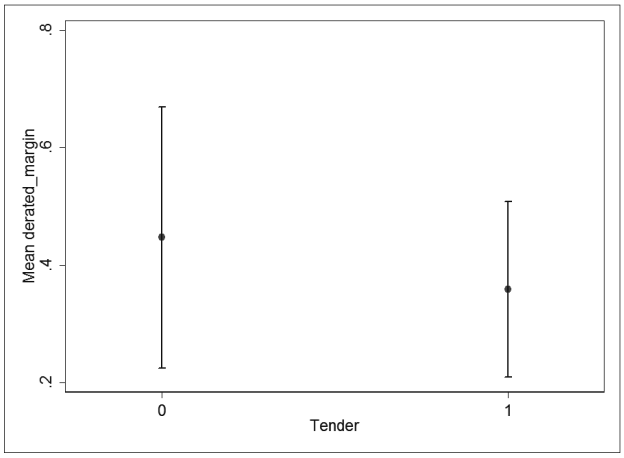


Figure 5.41: Mean derated margin by whether a renewables tendering process exists

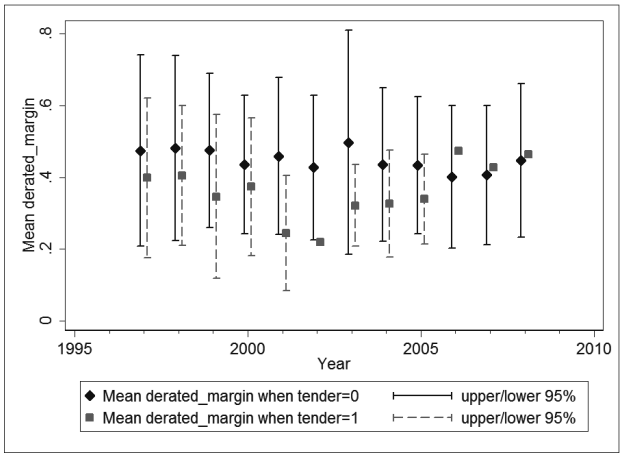


Figure 5.42: Mean derated margin by tendering process and by year

The effect of introducing a tendering scheme on the derated margin is not significantly different from zero, but it is nonetheless negative (Figure 5.43). Since the trend has been for these schemes to finish, it is perhaps more relevant to say that countries that have abandoned tendering process have seen a slight increase in their subsequent margin as a result.

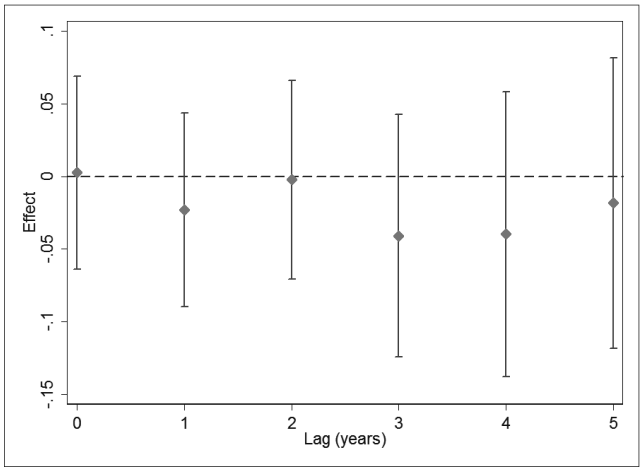


Figure 5.43: Lagged effect of introducing a tendering process on the derated margin

Renewables Tax Incentives / Investment Grants

As with TGCs and tendering processes, countries that provide tax incentives or investment grants for renewable technologies have, on average, lower derated margins than those that do not (Figure 5.44). As Figure 5.45 shows, this difference has remained fairly consistent over the period analysed.

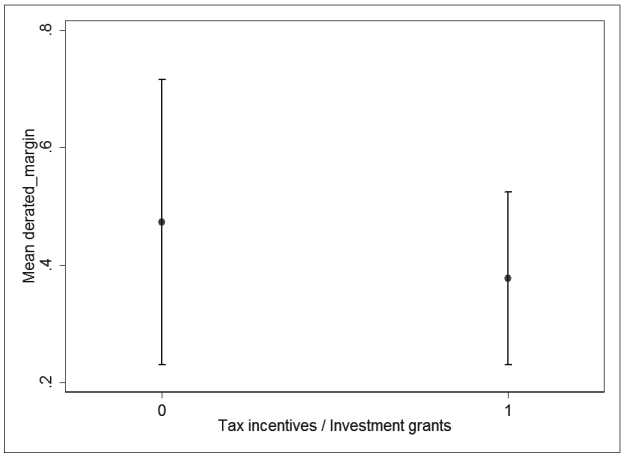


Figure 5.44: Mean derated margin by the existence of a renewables tax incentive

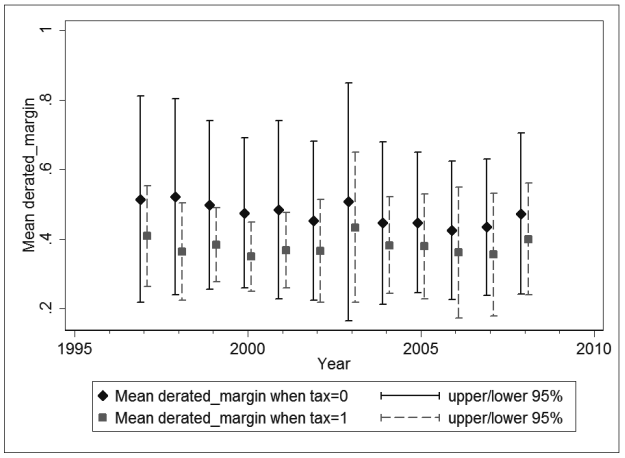


Figure 5.45: Mean derated margin by tax incentive and by year

In terms of the causal relationship, there is no significant effect that can be seen. Though it is not statistically significant, as with the tendering process, it is more likely that any true effect is negative in the sense that removing these incentives has, in the past, increased the derated margin over the subsequent years.

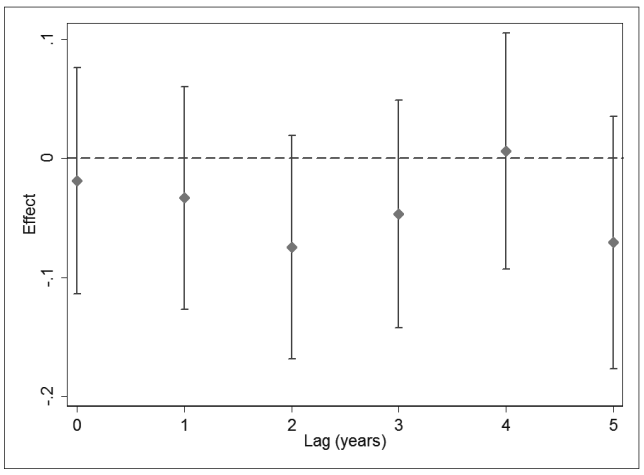


Figure 5.46: Lagged effect of introducing a renewables tax incentive on the derated margin

5.4.2.3 The impact of GDP on derated margin

The generation margin comprises two underlying measures: the installed capacity (or rather, the derated capacity) and the peak load on the system. The demand for electricity is strongly correlated with the productivity of the wider economy, as can be seen from Figure 5.47.

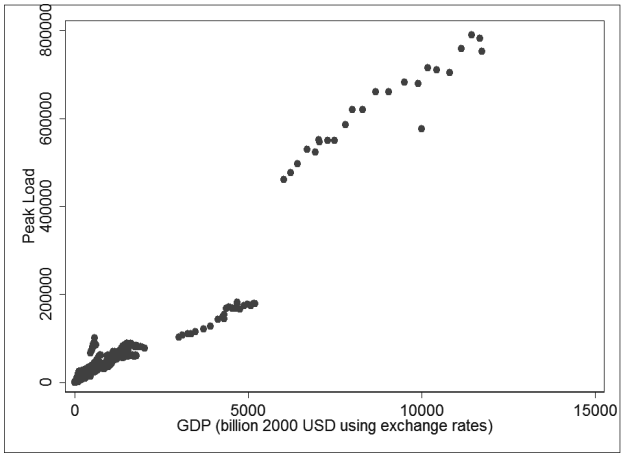


Figure 5.47: Scatter plot of peak load against GDP

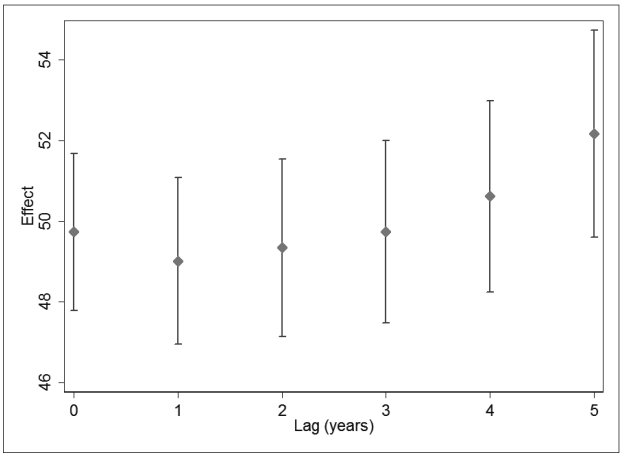


Figure 5.48: Lagged effect of GDP on peak load

Indeed, this is a causal relationship, with a rise in GDP for a given country causing a subsequent rise in the demand for electricity. This is shown clearly in Figure 5.48.

GDP is also correlated with the installed electricity generation capacity, as shown in Figure 5.49.

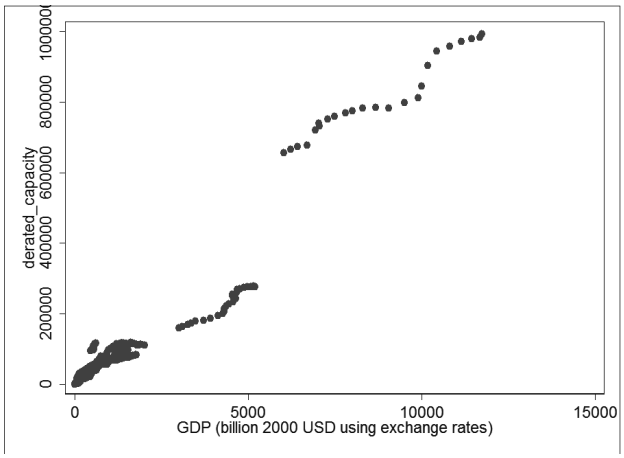


Figure 5.49: Scatter plot of derated capacity against GDP

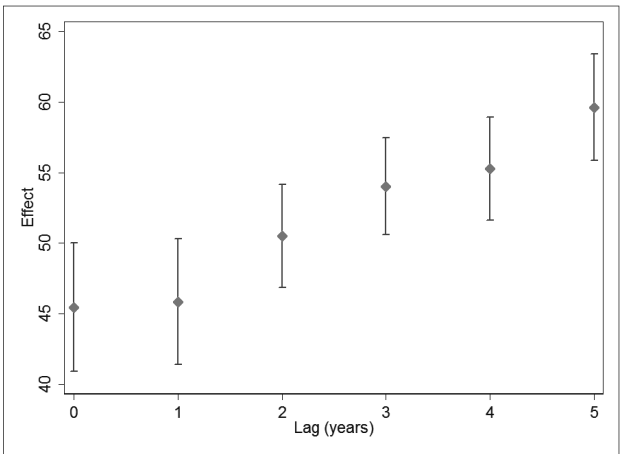


Figure 5.50: Lagged effect of GDP on derated capacity

Again, this relationship is causal, both directly in the sense that a rise in GDP enables new

electricity investment, and indirectly in that a rise in GDP causes a rise in demand, which leads to a rise in the rate of capacity expansion. Figure 5.50 shows the impact of a rise in GDP on the derated capacity.

Again, this effect is unambiguously strong, but the shape of the lagged effect is different from that exhibited by the peak load plot. Following a rise in GDP, the immediate and 1-year lag effect is to increase the peak load by more than the derated capacity. Conversely, for the lags of 3,4 and 5 years the resulting capacity increase is larger than that of the peak load. This would suggest that capacity expansion tended to lag behind demand increases, and then, after this initial delay, was prone to over-supply.

Whilst these differences are significant at the capacity and the peak load level, the resulting effect on the derated margin appears to be negligible. As Figure 5.51 shows, the overall effect is slightly negative, but is small in absolute terms.

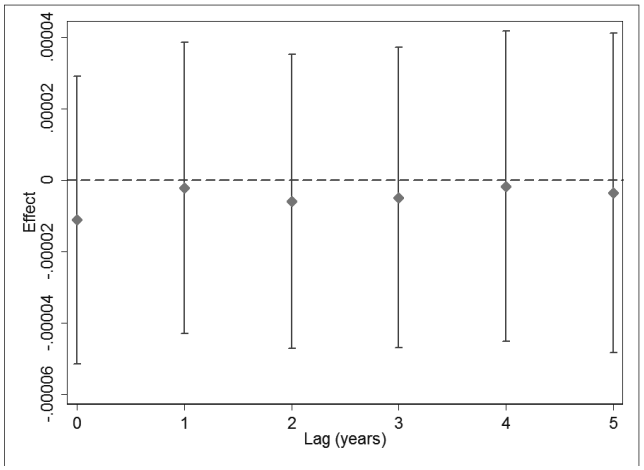


Figure 5.51: Lagged effect of GDP on derated margin

5.4.2.4 The impact of electricity price on derated margin

The analysis of electricity prices suggests that, unlike GDP, there is no significant relationship with either peak load or the derated generation capacity.

Figures 5.52 and 5.54 show no consistent overall correlation between electricity price and peak load, and Figures 5.53 and 5.55 suggest no significant effect of a change in price.

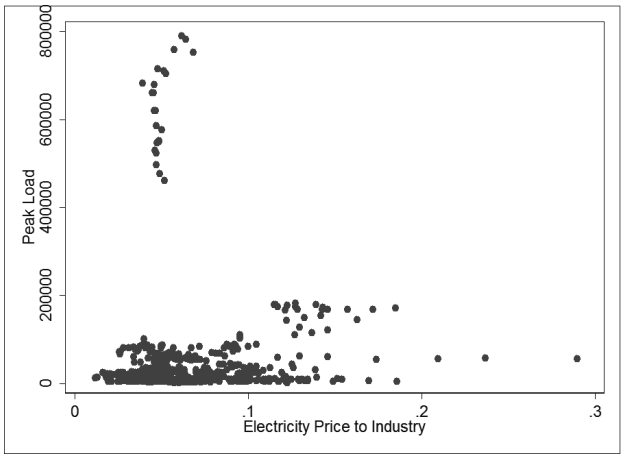


Figure 5.52: Scatter plot of peak load against industrial electricity prices

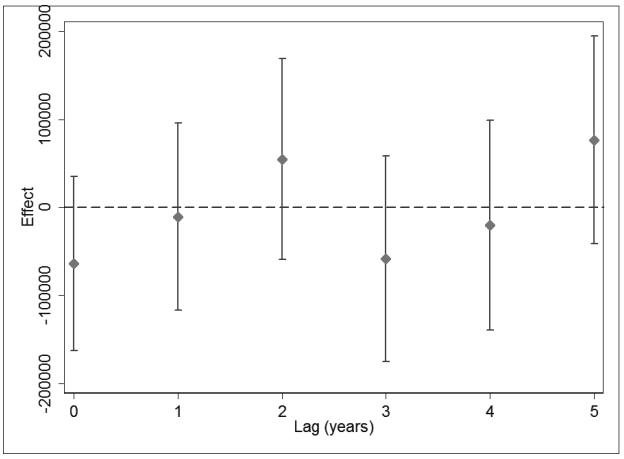


Figure 5.53: Lagged effect of industrial electricity price on peak load

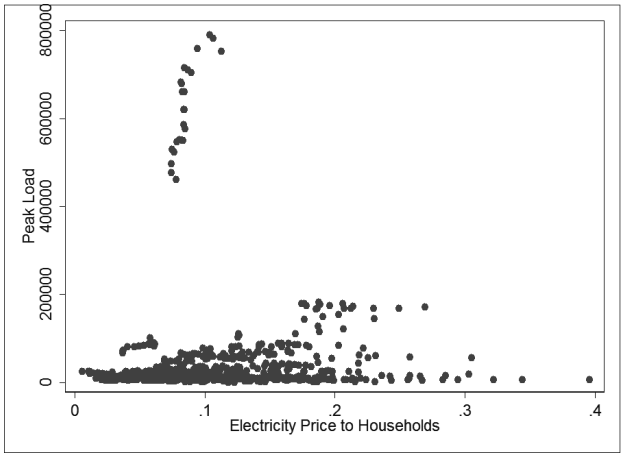


Figure 5.54: Scatter plot of peak load against household electricity prices

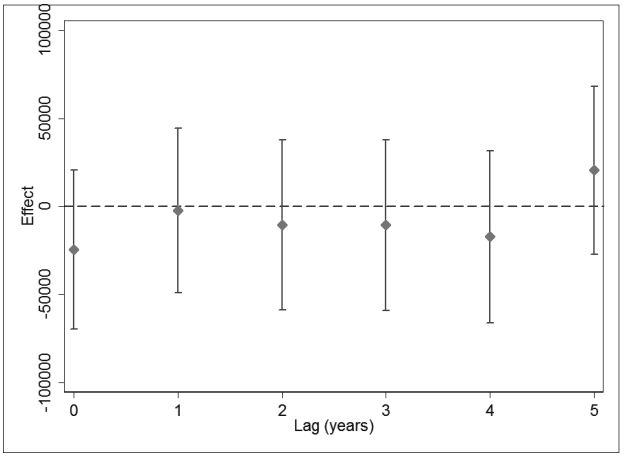


Figure 5.55: Lagged effect of household electricity price on peak load

Similarly for the derated generation capacity, there appears to be little overall correlation (Figures 5.56 and 5.58), and there is no significant effect of electricity prices, as shown in Figures 5.57 and 5.59.

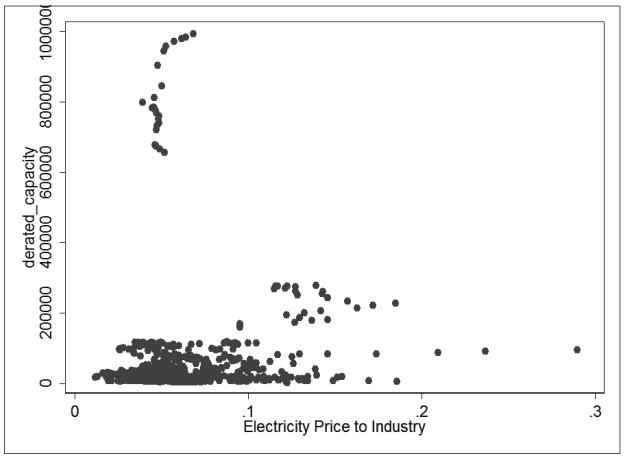


Figure 5.56: Scatter plot of derated capacity against industrial electricity price

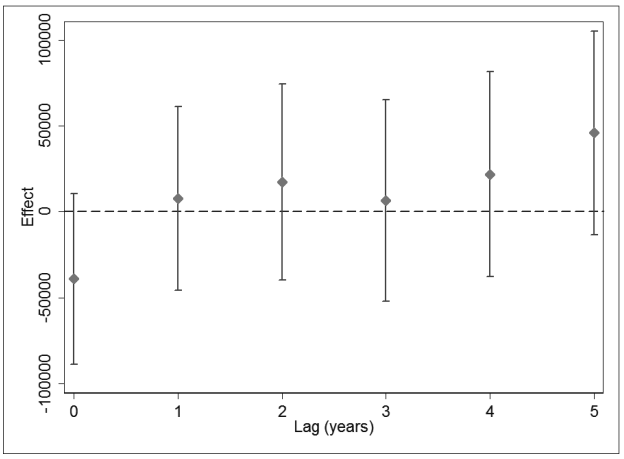


Figure 5.57: Lagged effect of industrial electricity price on derated capacity

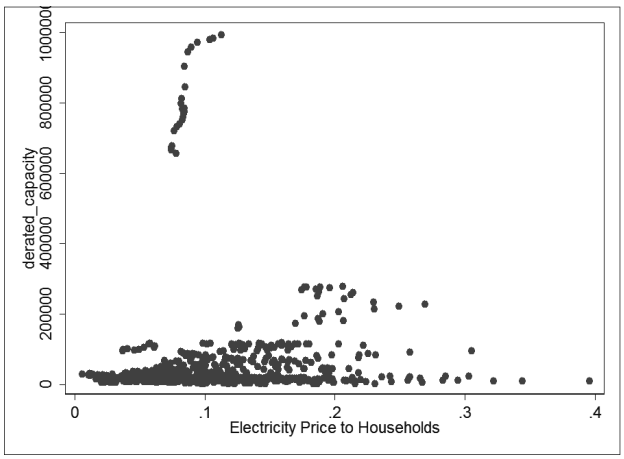


Figure 5.58: Scatter plot of derated capacity against household electricity price

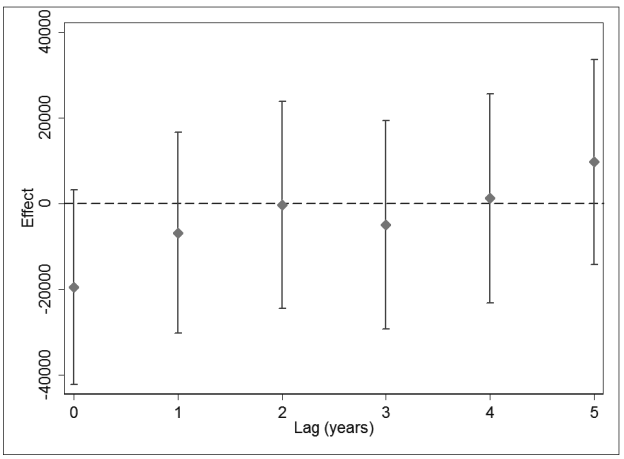


Figure 5.59: Lagged effect of household electricity price on derated capacity

Although electricity prices do not have a strong effect on either peak load or derated generation capacity, the overall derated margin is sensitive to small differences between these two measures. Indeed, Figures 5.60 and 5.61 show that over all lags the impact of an increase in industrial and household electricity prices is to increase the overall margin. Although the largest effect for household and industrial prices occurs at different lags, the effect has a magnitude of 1, meaning that an increase of 1 cent is associated with an increase of 1% in the margin.

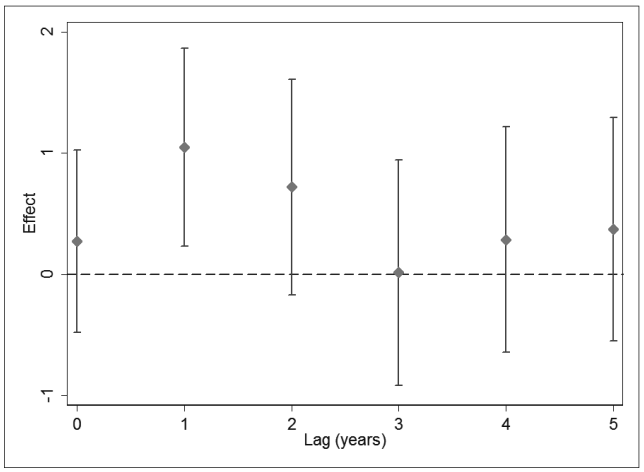


Figure 5.60: Lagged effect of industrial electricity price on derated margin

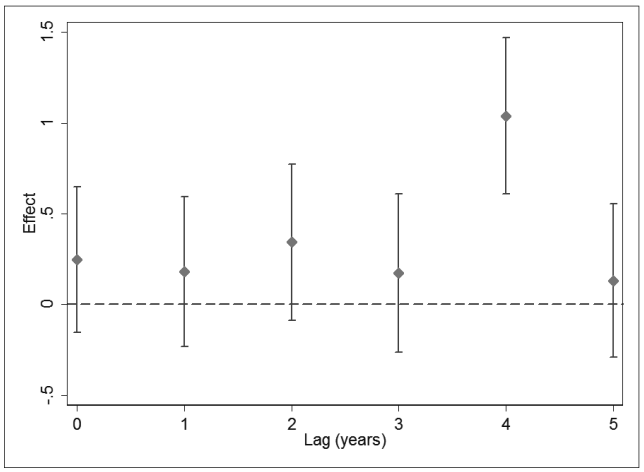


Figure 5.61: Lagged effect of household electricity price on derated margin

The conclusions that can be drawn here are twofold. First, GDP is a strong driver of both peak load and the installed capacity, but despite this it has little effect on the difference between the two - i.e. the margin. Conversely, the price of electricity has only a small bearing on either the demand for, or the capacity to supply, electricity in absolute terms. What small effect there is, however, serves to reduce demand whilst either retaining or increasing the levels of installed capacity. The overall effect on margin is, therefore, an increase.

5.4.3 Conclusions about the effect of liberalisation and low-carbon policies on margins

The findings of this analysis reveal that the majority of the difference in system margins between countries exists prior to the decision to liberalise the electricity system. There is a clear difference in the generation margin between those countries that have undergone a process of liberalisation & privatisation and those that have not. Under most measures of liberalisation, the difference between liberalised and non-liberalised countries has narrowed over time as more countries undergo this process.

Overall, there is a negative correlation between the margin and the degree of liberalisation and privatisation. The pertinent question, however, concerns the impact that liberalisation has had on margins, and for this the evidence is much weaker. There is no good data to support the idea that either liberalisation or privatisation have had a noticeably depressive impact on system margins.

The second question addressed in this chapter concerned the effect of renewables support mechanisms on system margins. The results can be summarised as follows:

1. An increase in the proportion of renewable generation resulted in an increase in not only the installed capacity but also the derated margin, suggesting that there is a net positive benefit in terms of the grid's Loss of Load Probability.
2. The derated margins of countries that have renewable support mechanisms are noticeably different from those that do not.
3. For countries with TGCs, tendering processes or tax incentives, the margin is lower, whereas for countries that have FITs, their margins tend to be higher.
4. Beyond this, there is some tentative evidence that the introduction of a feed-in tariff increases the overall derated margin of that country's electricity system.

These findings suggest that, thus far, the contribution of renewable generation to the system margin has been positive. This will, however, depend on the calculation of renewables' capacity credit, which may be smaller than has been assumed in this research. The data available for specific renewables mechanisms across the OECD countries are limited at this stage, but it appears that any benefit to margin that may be drawn from renewables depends on the means

by which the expansion of the renewable sector was achieved. As has been discussed, it appears that Feed-in Tariffs have been most able to maintain or improve margins whilst expanding the level of renewable generation, whereas schemes such as the Renewables Obligation have been less successful on this measure. The relevance of this finding to UK energy policy will be discussed in Part III.

The next chapter discusses the impact that privatisation, liberalisation and regulation have had on the diversity of the generating technologies that comprise an electricity system.

6

System Diversity

6.1 Defining Diversity

This chapter attempts to analyse how the diversities of different electricity systems have changed as a result of privatisation and liberalisation. One issue that is not always made explicit when discussing diversity, however, is precisely how the term is being defined. Diversity can be subdivided into properties of variety, balance and disparity (Jansen *et al.*, 2004) referring, respectively, to the number of different elements in a system, their relative contribution and a measure of how different they are from each other. Variety and balance have been widely adopted as measures of diversity, and indices, such as the Shannon-Weiner index (Stirling, 1998), have been devised to compare the diversity of different systems.

A resilient system is one that can cope well with a wide variety of unforeseen adverse scenarios. As has been discussed in previous sections, an electricity system, and in particular a privatised electricity system, is susceptible to adverse events that fall under the categories of 'uncertainty' and 'ignorance' (Grubb *et al.*, 2006). Diversity provides a hedge against a wide range of adverse scenarios, both from within the system ('reliability-type' failures) and from outside the system ('exposure-type' events).

As has already been discussed, there is a risk when making energy security decisions, of falling into the ludic fallacy (Taleb, 2007). A system cannot ever be fully understood; there will always be adverse events that will not be anticipated. This is true for all systems, but the ludic fallacy can be particularly pernicious in "high-reliability" designs. As modelling techniques become more sophisticated, the confidence of decision-makers and system designers grows. The quantified risks are managed, but the exposure to unforeseen events can be inadvertently increased. Viewing system security instead in terms of "diversity" can address many of these unforeseen risks.

A system with a large number of disparate technologies makes a system resilient for a number of reasons. First, if the generation mix runs on a number of different fuels, an adverse event cutting off the supply of one of these fuels is unlikely to affect all generators. Second, any adverse-event that is technology-specific (such as droughts forcing certain generators to shut down as a result of a lack of coolant) is minimised if the affected technology represents only a small proportion of the overall technology mix.

A lack of diversity, whether in terms of fuel or technological design, can lead to energy supply risks in a number of different ways. Tokyo, for example, experienced an energy security risk as a result of a lack of resilience in their generating mix.

> The supply of electricity in Tokyo and other cities in the Kanto region is dominated by the Tokyo Electric Power Company (TEPCO). Nuclear safety concerns in the winter of 2002 led to the closing of 17 TEPCO-owned nuclear power stations, representing 29% (17GW) of Japans generating capacity. A fault had been discovered in only one of these generators, but these 16 other generators had been similarly designed so it was believed that they all could be similarly at risk and were consequently shut down. The crisis did not threaten the whole of Japan, but the potential for power transfers into the affected region was limited as the TEPCO-supplied network operates at 50Hz, while most of the rest of Japan operates at 60Hz.

To return to some terminology introduced in section 3, the initial adverse event is classified here as a '*reliability*-type' failure, since it originated from within the system. The failure itself, however, would not have presented a problem to the system as a whole because the system margin would have been sufficient. The problem came as a result of a lack of diversity in generator design. If the identification of a fault in one generator means that a number of similar generators have to be shut down, this could result in a high forced outages. The problem is not unique to Japan; a similar case occurred in the UK, although not on the scale seen in Tokyo. In 2007 a problem was found with the boiler of one of the Hartlepool nuclear reactors. Its twin reactor was shut down to check for a similar design problem, as was a unit in Heysham.

The need for diversity in dealing with *exposure*-type events is more commonly seen. In particular, shortages of a particular fuel are commonly seen. For this reason, a discussion of 'diversity' in the context of energy security is often reduced to one of 'fuel diversity'. When gas supplies are physically constrained, a country with only a small proportion of gas generators is more likely to be able to continue normal operation using its existing generating capacity that a country that is dominated by gas-fired generators.

6.2 Diversity in the UK Policy Literature

Of all the attributes that have been associated with a system's resilience, *diversity* is perhaps the most prominent in the energy policy literature. For example, from the 2003 Energy White Paper, 2006 Energy Review, 2007 Energy White Paper and 2008 Nuclear White Paper, respectively make reference to the concept:

> "*diversity is the best way of protecting ourselves* against interruptions of supply, sudden price rises, terrorism or other threats to reliability of supply. As the UK becomes a net importer of energy we will need many sources, many suppliers and many routes" (DTI, 2003)

> "For the UK, the Government believes that the best way to maintain energy reliability is through *energy diversity* in our sources of energy, our suppliers, and our supply routes. Competitive markets can help us achieve diversity, as companies themselves seek diversity in order to manage risks". (DTI, 2006a)

> "Our aim will be to ensure that companies have a wide range of low carbon options available so we can retain a diverse energy mix, which is good for our security of supply, and will help us to become a low carbon economy ... We have a diverse mix of power stations: coal and gas account for over one third each; nuclear about a fifth; and renewables around 4%. This diversity helps avoid over-dependence on a single fuel type, contributing to security of supply." (DTI, 2007)

> "It is our view that, given these uncertainties, our energy strategy should be based on diversity and flexibility in the energy mix and has accordingly developed policies which keep open the widest possible range of low-carbon generating options." (BERR, 2008a)

Whilst diversity has long been seen as being an important component in delivering supply security to the UK electricity system, the perceived need for *governments* to maintain levels of energy diversity has, as with the wider question of energy security, fluctuated over the years. Prior to 1990, of course, all electricity planning was centrally controlled. It would seem, however, that the government in the period immediately following privatisation saw little need for extensive regulation in order to maintain adequate levels of security in general, and diversity in particular. The 1995 White Paper, "The Prospects for Nuclear Power in the UK" ((DTI, 1995), cited in (Helm, 2002)), states, for example:

> "the government cannot identify any reasons why the electricity market should not of its own accord provide an appropriate level of diversity"

This 1995 quotation is to some extent reflected in the government's later references to diversity, as is illustrated by the quotations above. In particular, the 2006 Energy Review states that the competitive markets can encourage the diversification of the system. The two most recent quotations speak of the role of government in facilitating the markets to ensure that diversity can be maintained. Whilst these more recent publications in no way suggest that the markets are inadequate to deliver diversity, they suggest that the government should have a role in monitoring diversity, and perhaps making policy to ensure that it is adequately maintained.

This raises two questions:

- Will the real market (as opposed to a theoretical idealised market) deliver adequate levels of diversity?
- What regulations, if any, are necessary to ensure that this diversity can be achieved?

We need to establish whether the view expressed in the 1995 White Paper is a good reflection of how a free market in electricity generation functions, or whether, as later reviews suggest, some government involvement could be necessary to provide the market with technological 'options' from which to choose. Furthermore, it should be asked whether the principle of the free market, either in theory or in practice, should be expected to deliver the collectively optimal level of diversity through the collective decisions of individual market actors.

6.2.1 Liberalisation and Diversity

Those countries that are nearly exclusively electrified by a single fuel tend to be those that are state run: nuclear power in France and hydroelectric power in Brazil, Chile, Norway and New Zealand provide examples of this (IEA, 1998). Furthermore, it could be argued that a large number of individuals operating with incomplete information will make different investment decisions at different times, which would result in different generator types being constructed. For example, the future gas price is extremely uncertain; one investor may decide that future gas prices will be low and will conclude that gas-fired generation provides the best expected profit. Another investor, conducting his analysis under different assumptions may decide that the future price of gas is likely to be high, and may choose instead to build coal or nuclear generators.

Of course, in centrally planned systems, governments could make a conscious decision to optimise the diversity of the electricity system (or, rather, to make a trade-off between optimum diversity and technology and fuel costs). It is not, therefore, necessary that central planning must lead low levels of fuel diversity.

The other approach that needs to be considered in this context is 'portfolio theory' (Awerbuch and Berger, 2003; Awerbuch, 2006). Private investors do not simply look outward, predicting future gas and electricity prices to make investment decisions. Rather, they base their decision in part on their existing generating portfolio. From a wider system security perspective, we want diverse generating technologies in order to protect against fuel supply disruptions. An energy company wants its own portfolio to be diverse in order to provide a *financial* hedge against fuel

price variations. Physical supply availability and fuel costs are not independent of each other, and the system as whole benefits from diversity in the form of smoothed electricity prices, even in the absence of physical supply constraints.

There is, therefore, good reason to think that the hedging behaviour of individual electricity generation companies will translate into diversity in the electricity system as a whole. We also need to think about how diversity optimisation *scales* when moving from the investor level to the system level. Diversity involves choosing technologies that are not least-cost – reducing risk at the expense of expected profits. Given this fact, it is clear that there is a limit beyond which diversity is costing more than it is worth in terms of providing resilience. Individual investors will presumably make investment decisions in a relatively rational way, attempting to place their portfolio on the efficient frontier of risk and expected profit (Awerbuch and Berger, 2003). The wider system's position in relation to this frontier, however, depends on how diversity scales up over all the different generating companies. It is possible that the optimal level of investor portfolio diversity, when summed over all investors, results in sub-optimal diversity for the system as a whole. Conversely, it may be that summing over all investors provides excessive diversity, meaning that consumers are paying more for system diversity that they would 'choose'.

In his paper, *Energy policy: security of supply, sustainability and competition*, Dieter Helm 2002 notes that whereas typical energy security measure relate to supply and demand, *diversity* is particularly concerned with risks associated with shocks. This fits with the thesis of this work that diversity is a key component of a system's resilience. Helm 2002 argues "there is no reason to believe that competition will necessarily *inhibit* securing diversity. In many cases, it might help by allowing markets to experiment with new technologies, and by facilitating entry". This reiterates the 2006 Energy Review, which argues that as companies seek to diversify individually, the diversity of the whole system is increased (DTI, 2006a). Helm nonetheless rejects the conclusion that competition will be *sufficient* to deliver security, particularly, he argues, when other political constraints are placed on the electricity system.

It is worth noting that fuel diversity is not the only form of diversity that needs to be considered for exposure-type events (adverse events that originate outside the electricity system). Australia, for example, has at times had its supplies threatened because regional droughts had caused the availability of water in the rivers and lakes to decline. This meant that a number of generators could not operate, since they required the water to be used as coolant. The two generator types that were affected were coal-fired power stations and hydro-electric plant. A crude analysis of diversity may conclude that a country's generator diversity is adequate, whereas they may be

similarly susceptible to a single source of insecurity. Fuel is therefore just one of a number of 'inputs' into an electricity system; a complete diversity analysis should attempt to include as many of these inputs as possible.

The most common use of the term "diversity" in the context of electricity systems, is "generator diversity", or perhaps more broadly, "technological diversity". These terms reflect the need for the generating capacity itself to be sufficiently diversified in terms of its design and its fuel in order to reduce the risk of common-mode failures to a reasonable level.

The following analysis is intended to answer two questions:

1. How has market liberalisation affected the diversity of the electricity mix?
2. How will efforts to expand the renewables sector affect diversity?

6.3 Diversity Indicators

As discussed in chapter 2.2, there are many potential indicators for the diversity of the generating stock. The most appropriate indicator would, in theory, be one that incorporated the notion of disparity, such as one discussed by Skea (2010), so that not only are the number and proportions of generator types included, but also the comparative "differentness" of them is considered. Whilst the importance of including the disparity of technologies in future analyses is acknowledged, as the research stands there are a number of ways of defining disparity, and there is certainly no consensus on numerical value that should be placed between, say, wind and solar, or gas and coal technologies.

Until such consensus is reached, the approach taken here focuses on a measure of diversity that incorporates only "variety" (the number of generator types) and "balance" their respective proportions, the Shannon-Wiener Index (SWI):

$$\mathrm{SWI} = -\sum_{i=1}^{n} p_i \ln p_i$$

where n is the number of different generator types and p_i is the proportion of the i^{th} generator on the system.

As in the previous chapter, the relevant explanatory variables are:

1. Liberalisation indicators: These indicators describe different aspects of electricity liberalisation and privatisation

   - ***overall_lib***:What is the overall level of liberalisation (this is a function of the following six indicators)
   - ***tpa***:How are the terms and conditions of third party access (TPA) to the electricity transmission grid determined?
   - ***liberalisedpool***:Is there a liberalised wholesale market for electricity (a wholesale pool)? ***liberalised*** is a binary variable generated from ***liberalisedpool***.
   - ***supplychoice***:What is the minimum consumption threshold that consumers must exceed in order to be able to choose their electricity supplier?
   - ***ownercode***:What is the ownership structure of the largest companies in the generation, transmission, distribution, and supply segments of the electricity industry? ***privatised*** is a binary variable generated from ***ownercode***.
   - ***transgensep***:What is the degree of vertical separation between the transmission and generation segments of the electricity industry? ***transgen_unbundling*** is a binary variable generated from ***transgensep***.
   - ***vertsepoverall***:What is the overall degree of vertical separation in the electricity industry? ***overall_unbundling*** is a binary variable generated from ***vertsepoverall***.

2. Low-carbon policies: These explanatory variables indicate the type of policies put in place by governments to encourage the increased contribution of new renewables to the electricity mix

   - ***renew_support_binary***:Is there any form of renewables policy in place?
   - ***newrenewable_proportion***:What proportion of installed capacity is made up of new renewable technologies?
   - ***fit***, ***tgc***, ***tender***, ***tax***: Is there a Feed-In Tariff, Tradeable Green Certificate, Tendering or Tax/Incentive scheme, respectively, in place for renewable generation technologies?

6.3.1 Statistical Method

The statistical approach taken here is very similar to that used for the previous chapter on generator margins. The only difference in terms of analysis is that rather than using the international data to generate panel data of margins, the same data are converted into a number of different indicators of diversity. The steps taken in this analysis are summarised as follows:

1. Import the panel data into Stata (30 electricity systems over 90 time points)
2. Import dummy variables of privatisation and liberalisation
3. Apply mixed effects model using **xtmixed** function
4. Extract p-values for privatisation and liberalisation

The above procedure makes a number of necessary assumptions about the structure of the diversity data. First, the data are assumed to be autocorrelated with order 1 (AR1). This means that for each country, the distribution of possible levels of diversity is a function primarily of the previous year's diversity level. This is consistent with the way that the generation mix changes – namely, through the closure of old plant and the construction of new plant. The current mix is therefore a combination of the previous year's mix and some change in that mix.

The second important assumption comes from the use of the mixed effects model (xtmixed). This model assumes that the data have a fixed and a random component. The assumption of a random component means that the effect of the explanatory variables (in this case, privatisation and liberalisation) is distributed normally over the different electricity systems. This assumption constrains us since it prevents us from asking about the effect of, say, privatisation on a particular country; instead we can only say how privatisation affects countries *such as these* sampled for this analysis. The advantage of making this assumption is that it greatly increases the power of the analysis, making it more likely to see an effect where such an effect is truly occurring. This is particularly important where the amount of data available is relatively small, as is the case here.

6.4 Changes to generator diversity over time

The OECD countries have almost all undergone a period of increasing diversity, as shown in Figure 6.1. This means that most countries have either introduced more types of generation onto their systems, or that the market share between these generation options has become more balanced.

The UK's own diversity has increased considerably since 1980, as shown in Figure 6.2. This rate of increase has been fairly constant except for a period immediately after privatisation, when the rate of diversity increase went up. As Figure 6.3 shows, this is almost entirely attributable to the introduction of natural gas into the generation fuel mix at the beginning of the 1990s.

By way of contrast, both Finland and Sweden are dominated by hydroelectric power and nuclear generation – a situation that has changed little since the early 1980s (Figures 6.4 and 6.5). For this reason, the SWI in these two countries has remained largely static and has, in fact, declined by a small amount.

The question of interest for the remainder of this chapter is whether the change in diversity can be attributed to either the liberalisation or the subsequent regulation of electricity systems.

6.5 Effect of liberalisation and privatisation on diversity

This section asks whether different liberalisation measures are causally associated with a change in the level of generator diversity.

6.5.1 Effect of overall liberalisation

As Figure 6.6 shows, there is a correlation between increasing liberalisation and increasing diversity. More liberalised systems tend to have a higher level of diversity. This representation of the data simply plots the level of diversity against the overall level of liberalisation for all country-years, and does not reveal whether this trend occurs as a result of differences between countries or whether those differences arise within countries over time.

The question of interest is whether an increase in overall liberalisation is associated with a *change*

in the level of diversity. The panel data analysis described above was used to test this question, looking for a relationship between a change in overall liberalisation and a change in diversity from between zero and 5 years into the future.

Figure 6.7 show the results of this analysis. Across all lags the impact of an increase in the level of overall liberalisation is positive although, with the exception of the lag at 3 years, these effects do not appear to be significant. The 3-year lag, however, does not appear to be an outlier. Rather, it appears to be the apex of an effect that increases steadily from the initial policy change and declines steadily afterwards.

This suggests that not only do countries with higher levels of overall liberalisation tend to have higher levels of diversity, but that there is evidence of a causal relationship. If true, this would mean that an increase in overall liberalisation *caused* an increase in the diversity of the generation mix.

It is possible that the association is not causal. The lagged effect eliminates the possibility of reverse causality (in which an increase in system diversity would increase the probability that a government chose to increase the level of liberalisation). There remains, however, the possibility that overall liberalisation and the increase in diversity shared a common cause. For example, an increase in GDP could encourage investment in new forms of generation, whilst also providing government with the confidence to enact a change in policy.

Indeed, as Figure 6.8 shows, there appears to be some correlation between GDP and SWI.

Further analysis shows that a change in GDP is indeed associated with a change in diversity (Figure 6.9), so there is a possibility that once GDP has been taken into account, the apparent effect of overall liberalisation on SWI will disappear.

Once GDP is controlled for (Figure 6.10), however, the effect of overall liberalisation on SWI remains. There may still be other confounding variables that have not been identified, but it can be said that, irrespective of changes in the productivity of the wider economy, there is an association between the level of overall liberalisation and the diversity of electricity systems.

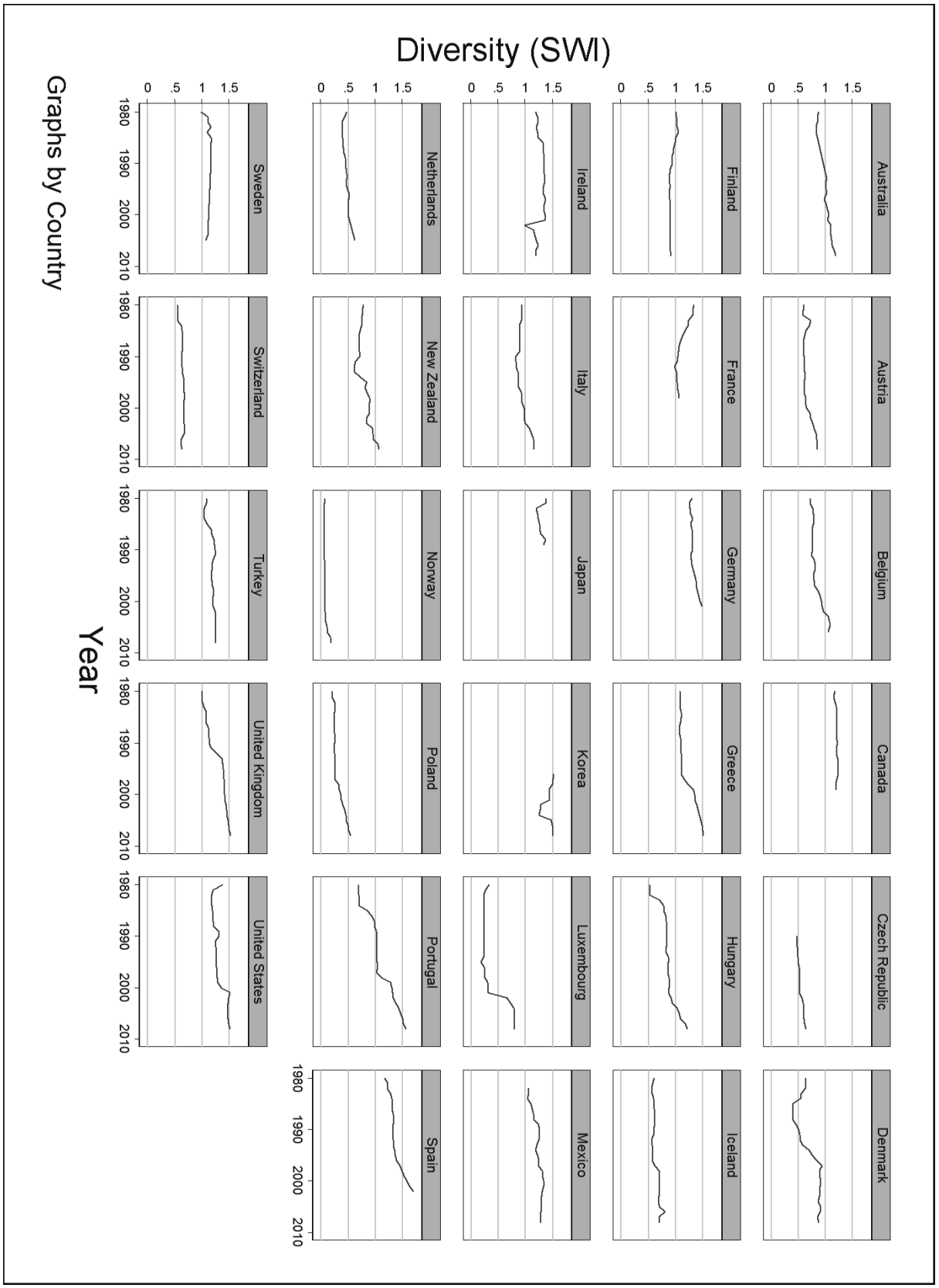


Figure 6.1: Shannon-Wiener Index (SWI) for all OECD countries

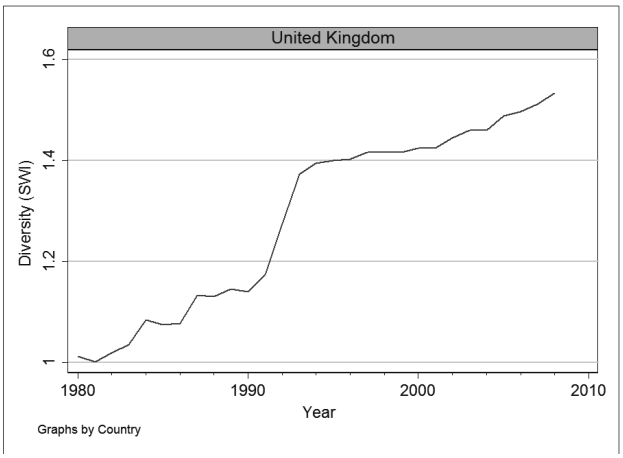


Figure 6.2: SWI for the UK

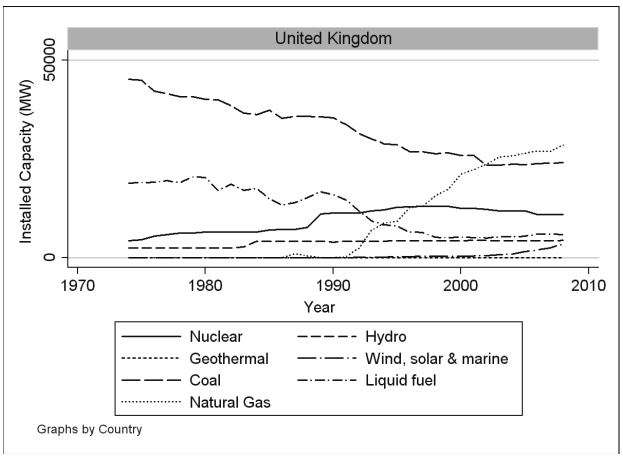


Figure 6.3: Generation mix of the UK

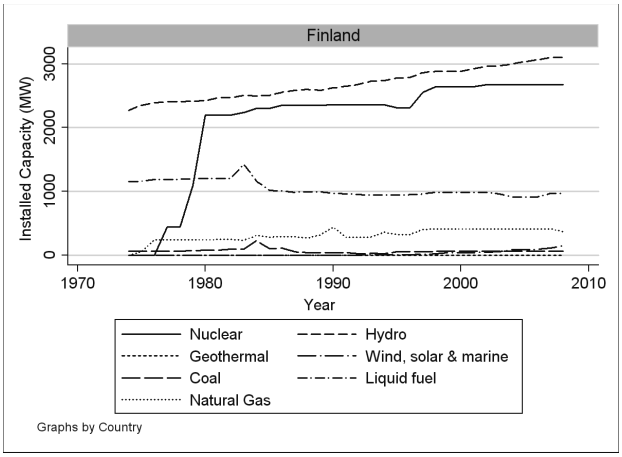


Figure 6.4: Generation mix of Finland

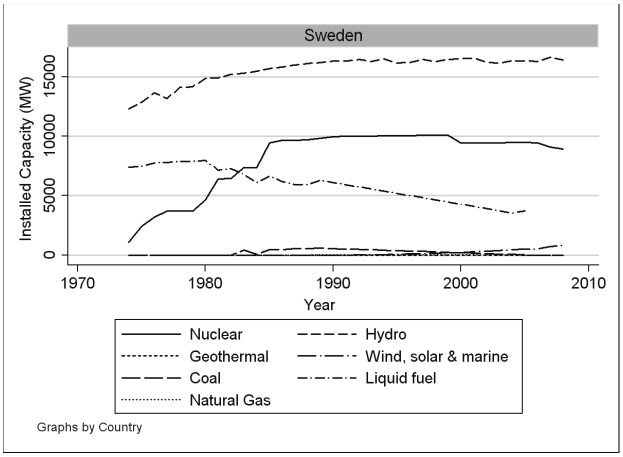


Figure 6.5: Generation mix of Sweden

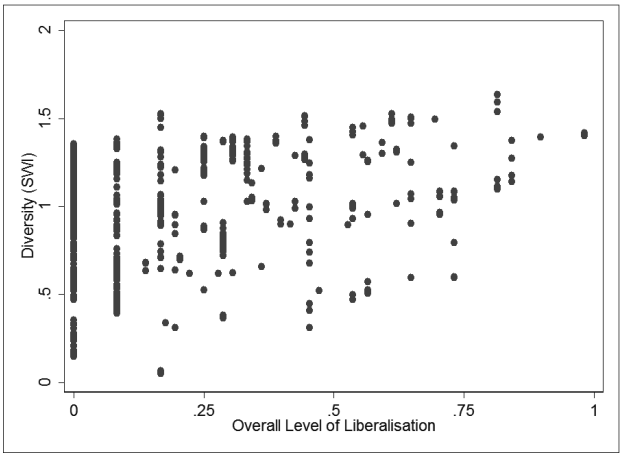


Figure 6.6: SWI (all county-years) vs overall degree of liberalisation

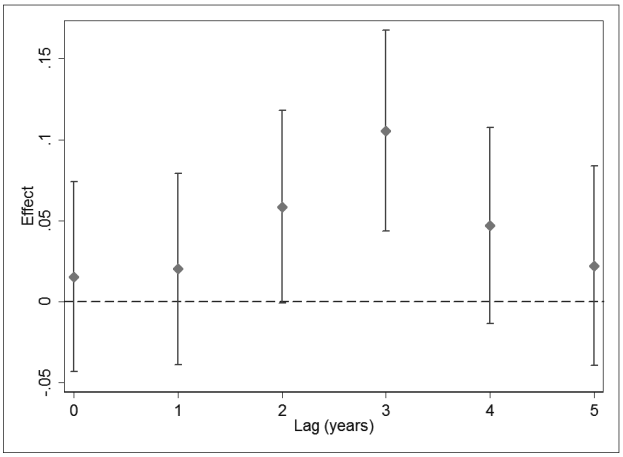


Figure 6.7: Lagged effect of overall liberalisation on SWI

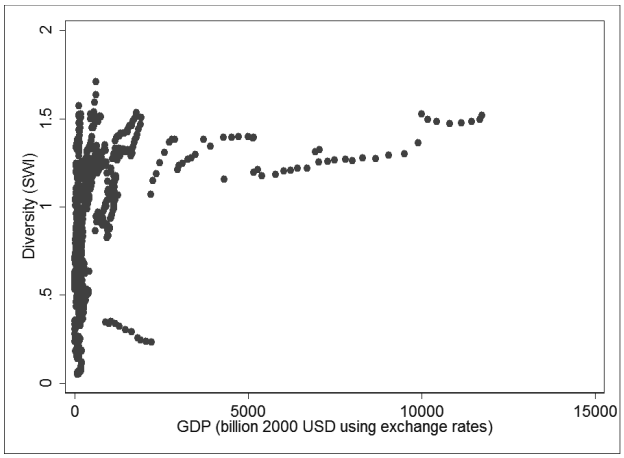


Figure 6.8: SWI (all county-years) vs GDP

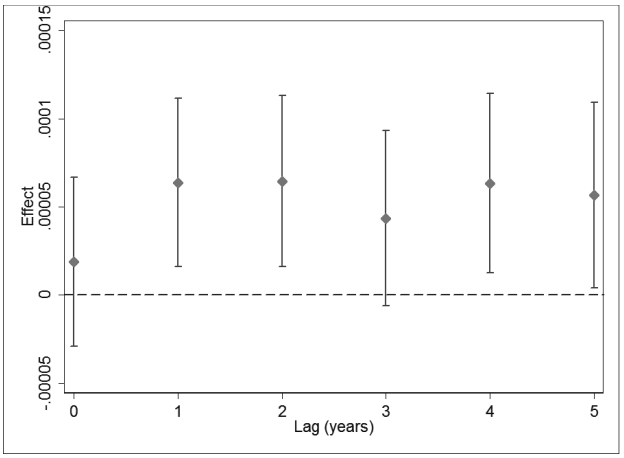


Figure 6.9: Lagged effect of GDP on SWI

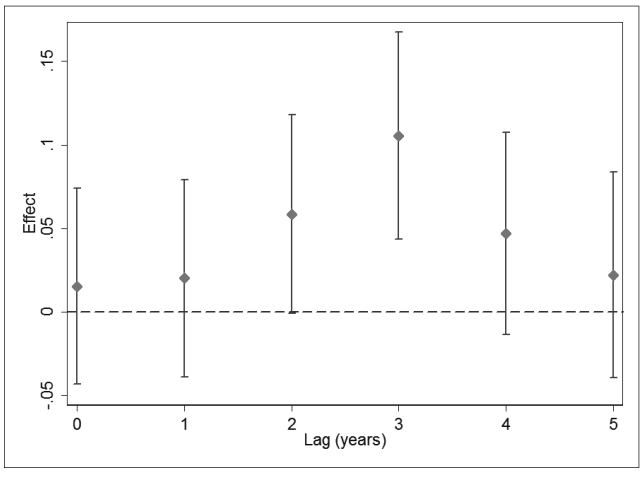


Figure 6.10: Lagged effect of overall liberalisation on SWI, controlling for GDP

Assuming that the relationship between overall liberalisation and diversity is a causal one, there remains the question of what aspects of liberalisation are responsible. The following sections investigate this question.

6.5.2 Effect of the creation of a liberalised pool on diversity

The measure of overall liberalisation (overall_lib) is a composite of a number of different liberalisation indicators defined by the OECD. One of these is a binary indicator that measures whether there is a liberalised pool in operation. As with all the binary explanatory variables used in this research, this has been coded to take a value of 1 if the liberalised pool exists and 0 if it does not.

As can be seen from Figure 6.11, the countries with a liberalised pool have, on average, slightly higher generation diversity than those that do not, but this between-group difference is considerably smaller than the within-group difference.

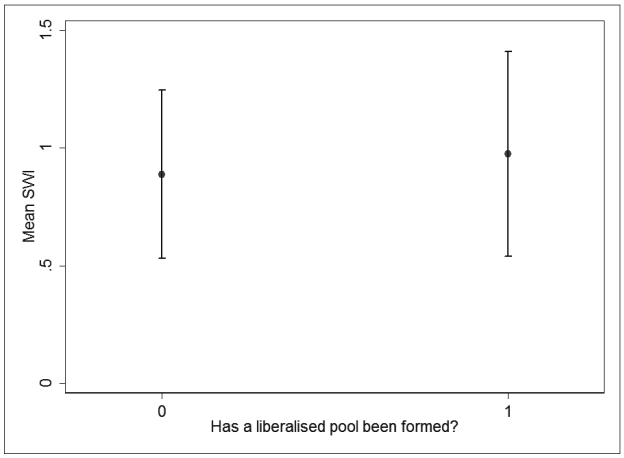


Figure 6.11: Overall mean SWI with and without a liberalised pool

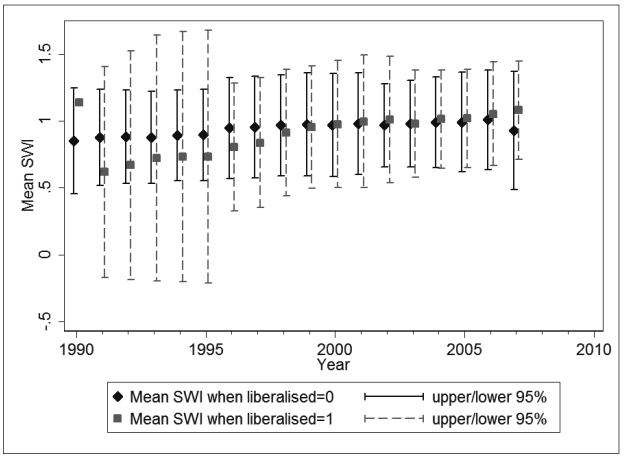


Figure 6.12: Mean SWI by year, with and without a liberalised pool

On a year-by-year basis, as shown in Figure 6.12, the overall trend for both liberalised and non-liberalised systems is towards increasing diversity. Until the year 2000, countries with a liberalised pool had, on average, lower diversity than those that had not liberalised. The rate of diversity increase is higher in the countries with a liberalised pool an diversity was higher in these countries in the years after 2000.

Again, the causal question is whether creating a liberalised pool caused a change in the level of

the SWI. Figure 6.13 shows the result of this analysis.

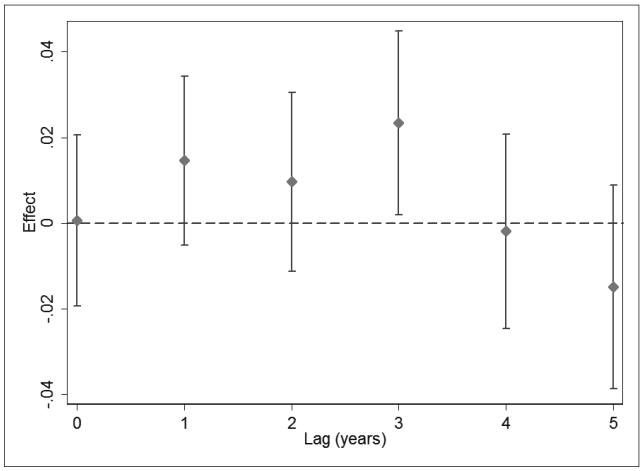


Figure 6.13: Effect of the creation of a liberalised pool on SWI

As with **overall_lib**, the effect of introducing a liberalised pool appears to be to increase the system's diversity. The effect is less marked: the only statistically significant result is again at a lag of 3 years, but the effect on SWI is only an increase of 0.23 (p=0.03). The effect at other lags is not consistently positive, providing less support for the contention that this effect at a lag of 3 years reflects a true association.

If the creation of a liberalised pool does contribute to the association between overall liberalisation and diversity, the contribution is only a small one. The next section considers the effect of privatisation on diversity.

6.5.3 Effect of the ownership arrangements on generation diversity

The ownership arrangements variables describe the extent to which the largest generation, transmission, distribution and supply companies have been privatised in a given country. The 'ownercode' variable takes a value of 0, 0.25, 0.5, 0.75 or 1 depending on whether a country's main electricity companies are, respectively, 'public', 'mostly public', 'mixed', 'mostly private' or 'private'. Further, a binary variable 'privatised' has been generated from the ownercode and takes a value of 1 if a country's system is privatised or mostly privatised, and takes 0 otherwise.

A plot of the mean SWI against ownercode (Figure 6.14) reveals a positive correlation between the degree of privatisation and the level of diversity. In particular it seems to show that systems that

are either fully (0) or mostly publicly (0.25) owned, or are classed as having 'mixed' ownership (0.5) have lower diversity than those that are fully or mostly privatised.

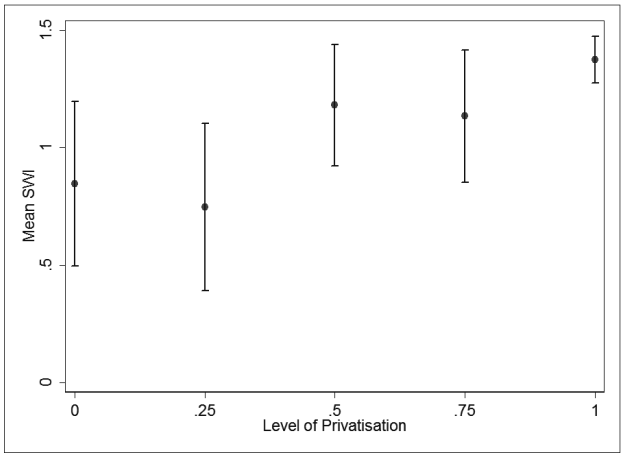


Figure 6.14: SWI (all county-years) against the degree of private ownership

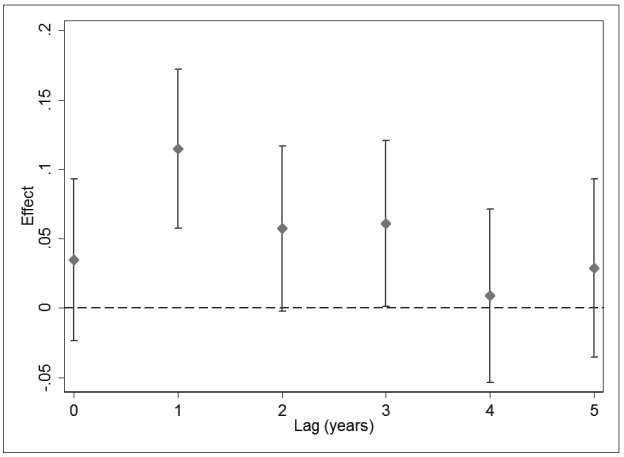


Figure 6.15: Effect of the ownership arrangements on the SWI

As Figure 6.15 shows, the lagged effect after 3 years is significant, but there is also an effect at lags of 1 year and a borderline case at 2 years. The effects at 1-,2- and 3-year lags are 1.2, 0.6 and 0.6, respectively. These are between three and six times larger than the maximum effect exhibited by the creation of a liberalised pool, suggesting that privatisation has a greater effect on the generation mix than the means by which electricity is traded.

As in Chapter 5 a binary variable was created, 'privatised'. This pooled the ownercode variable so that 'privatised' and 'mostly privatised' were considered as one category and 'mixed', 'mostly public' and 'public' were categorised as another.

This variable confirms that that have undergone privatisation have higher mean diversity (Figure 6.16). Breaking this analysis down into separate years reveals the relationship shown in Figure 6.17. In all years the countries with predominantly privately-owned electricity sectors had electricity systems that had a higher level of diversity.

There is a positive effect of privatising a system on its subsequent diversity – an effect that peaks after 3 years after privatisation (Figure 6.18). The maximum effect of privatisation on SWI is 0.6, which is comparable to the effect of overall liberalisation and three times that of the effect of creating a liberalised pool.

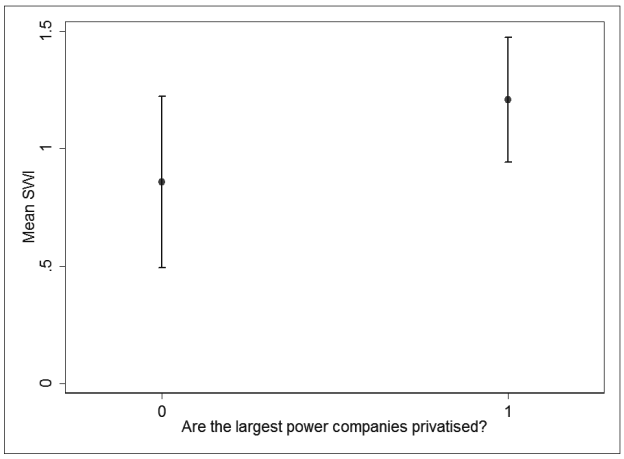


Figure 6.16: Mean SWI whether privatised (1) or not (0)

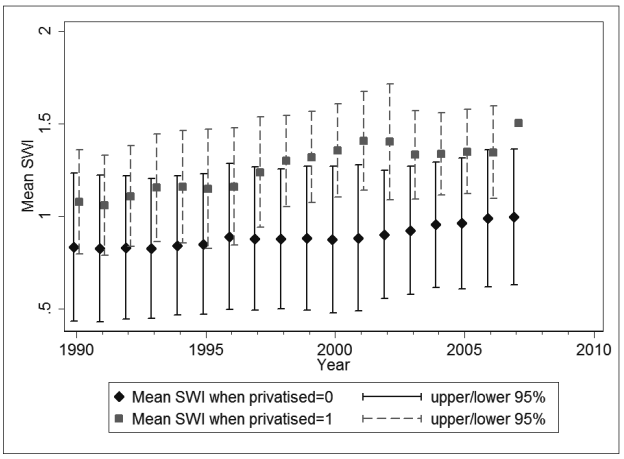


Figure 6.17: Mean SWI by whether privatised and by year

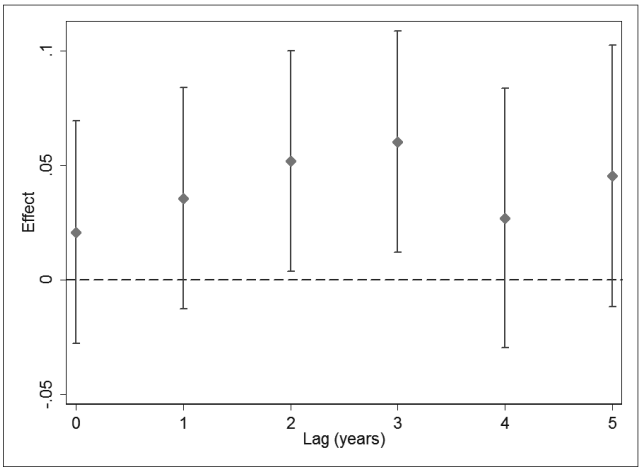


Figure 6.18: Lagged effect of privatisation on SWI

6.5.4 Vertical Separation

Vertical integration is indicated by two variables: the degree of vertical separation between the transmission and generation segments of the electricity industry (**transgensep**, where 0=Integrated, 0.5=Accounting Separation and 1=Separate Companies) and the overall degree of vertical integration (**vertsepoverall**, where 0=Integrated, 0.5=Mixed and 1=Unbundled). As before, two corresponding binary variables were created. These are **transgen_unbundling** and **overall_unbundling**, and take a value of 0 if the system is vertically integrated and 1 otherwise.

There is no significant difference in diversity between countries with different degrees of separation between the transmission and generation sector (Figure 6.19). Nor does the effect of changing

this separation appear to have an effect on the subsequent level of diversity within a country's generation mix (Figure 6.20).

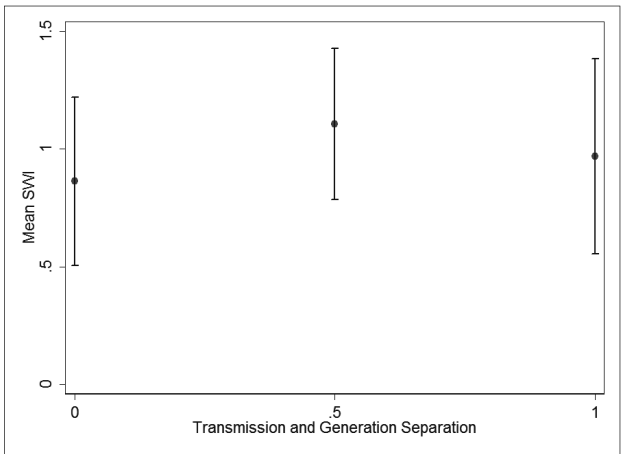


Figure 6.19: SWI (all county-years) against the degree of transmission-generation separation

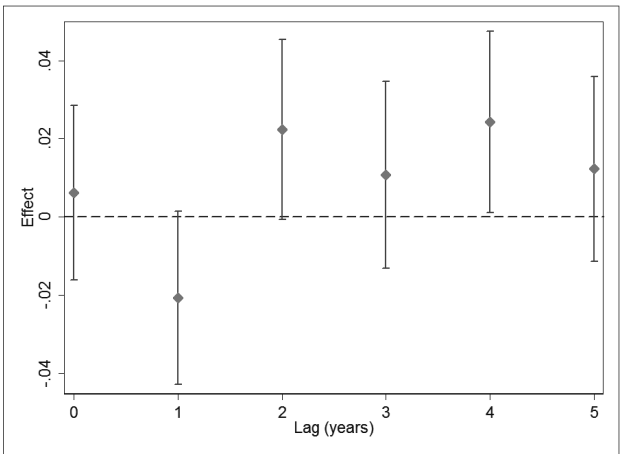


Figure 6.20: Effect of a change to the degree of transmission-generation separation on the SWI

Figure 6.21 shows the difference in SWI between systems with fully integrated transmission and generation sectors and those with some degree of separation. The difference is small in all years, and one group is not consistently higher than the other.

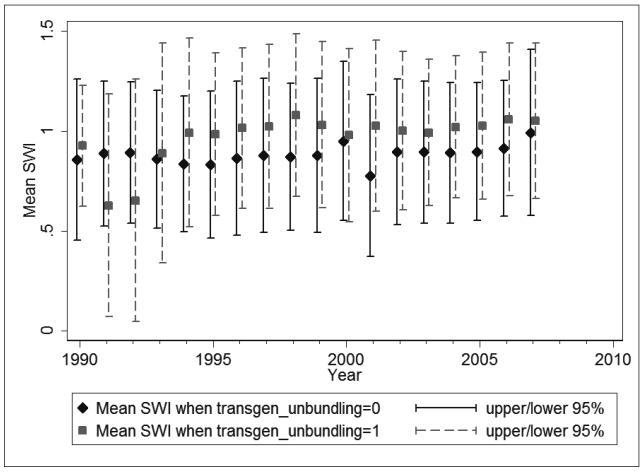


Figure 6.21: SWI by year against whether transmission and generation are integrated (0) or not (1)

Similarly, different levels of overall vertical separation have very similar levels of diversity on average (Figure 6.22), and neither a large nor consistent effect can be seen on SWI of vertical unbundling (Figure 6.23).

The annual view reveals no significant or consistent difference between the diversities of the

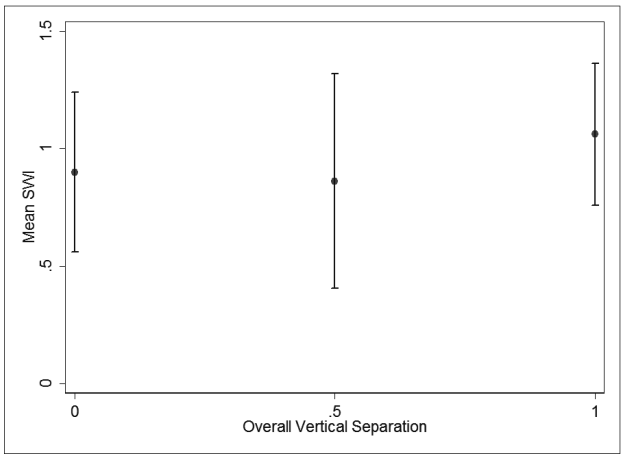


Figure 6.22: SWI (all county-years) against degree of overall vertical integration

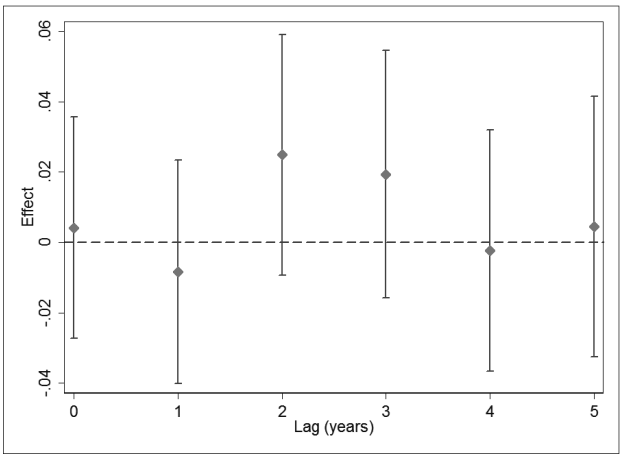


Figure 6.23: Effect of a change to the degree of overall integration on the SWI

integrated and unbundled systems.

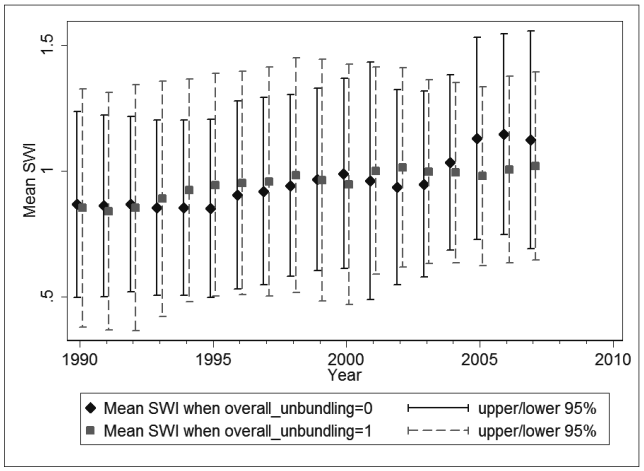


Figure 6.24: SWI against whether the system has undergone vertical unbundling in a given year

In terms of diversity, then, neither the overall vertical separation within the system nor a separation between the generation and transmission sector more specifically seems to have an effect on the subsequent diversity of the generation mix.

The creation of a liberalised pool for trading electricity is associated slightly with an increase in the diversity of the system, but it is the transfer of the generation, transmission, distribution and supply operations from public to private ownership that seems to have the strongest effect.

6.6 Effect of renewable generation and associated policies on system diversity

Using the same methods applied above, this section assesses the relationship between the deployment of renewable generation and the associated renewables policies on the system diversity.

6.6.1 Installed capacity of new renewables

Here, the installed capacity of new renewables (wind, solar and marine renewables) is compared with the overall diversity of the generation mix. As Figure 6.25 shows there is some positive correlation between the level of renewables penetration and the diversity of the system, but this plot is dominated by the years in which little or no renewable generation capacity was installed.

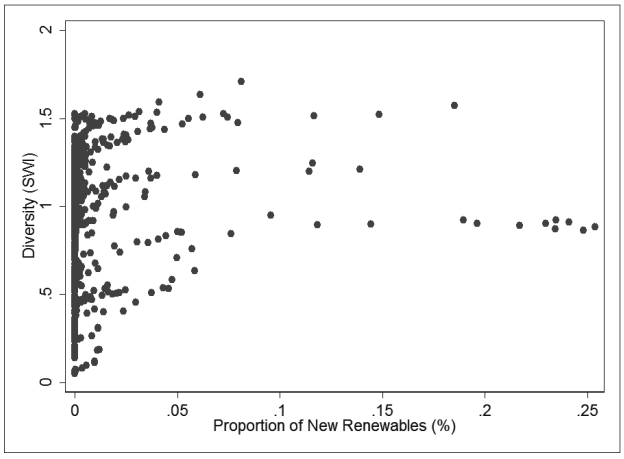


Figure 6.25: SWI (all county-years) against the proportion of new renewables on the system

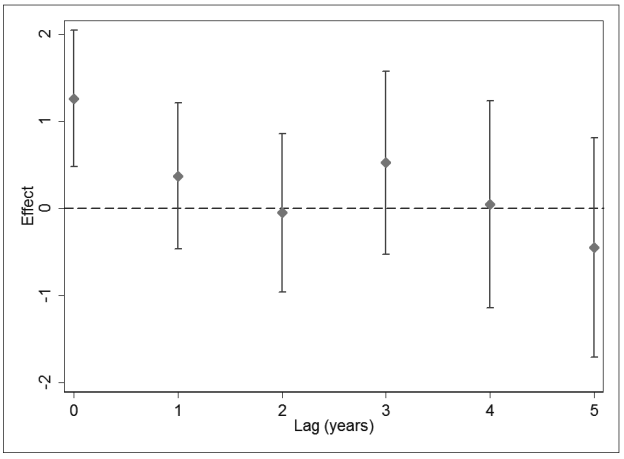


Figure 6.26: Lagged effect of increasing the new renewable proportion on the SWI

Unlike policy changes, which might exhibit an effect for a number of years after their implementation, the relationship between renewables penetration and system diversity is likely to be immediate since the renewables themselves will be contributing to the diversity directly. This is what is observed in Figure 6.26, where it can be seen that the immediate effect of increasing the proportion of renewables on the system is to increase SWI. An increase by 1% of the proportion of renewables is associated with an increase of 0.013 in the level of SWI. This effect is not carried over into the future, meaning that this initial increase in diversity does not last.

6.6.2 Renewable electricity support schemes

The following sections investigate whether the provision of support for these new renewables has an effect on diversity.

6.6.2.1 Any renewable support scheme

The overall difference in diversity and the difference seen on an annual basis (Figures 6.27 and 6.28, respectively) show that diversity is consistently higher in those countries that have in place some sort of support mechanism for renewable generation.

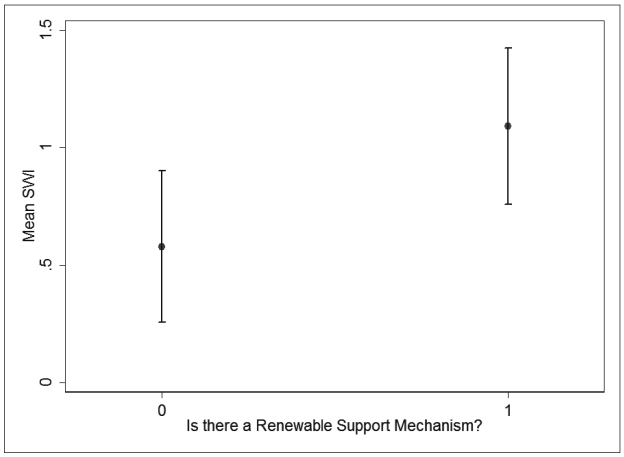


Figure 6.27: Mean SWI by whether some renewable support mechanism is in place (1) or not (0)

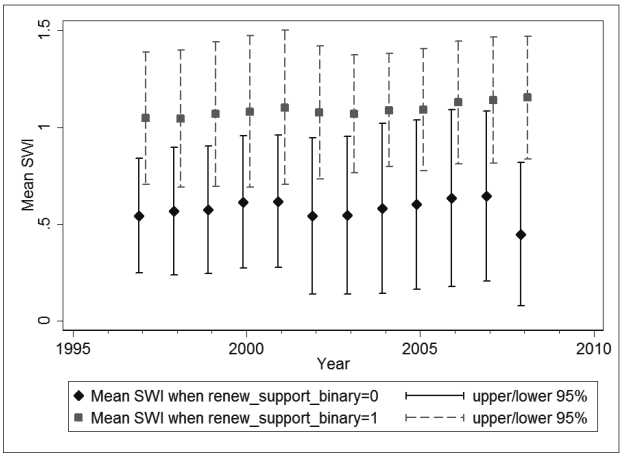


Figure 6.28: Mean SWI by renewable support and by year

The observed effect is shown in Figure 6.29. Whilst the effect is positive for all lags, it is small and the results are not significant. There is little evidence, then, that the implementation of a renewables scheme in general will increase the diversity of the system. Rather, it seems that it is those systems that are diverse that are likely to implement renewable support mechanisms.

It is possible that, whilst renewables policies overall have not significantly increased the system diversity, different types of policy design might show an effect when analysed independently of the others. The following sections show the results of this analysis.

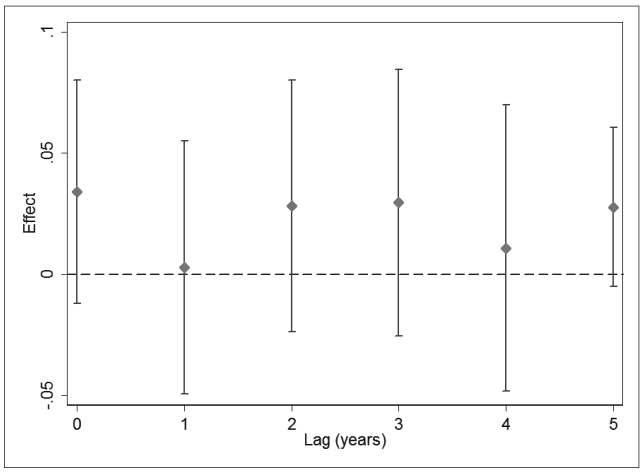


Figure 6.29: Lagged effect of introducing renewables support mechanisms on the SWI

6.6.2.2 Feed-in Tariff

For all the years considered, electricity systems with a Feed-in Tariff (FIT) scheme have higher diversity than those without (Figure 6.30.

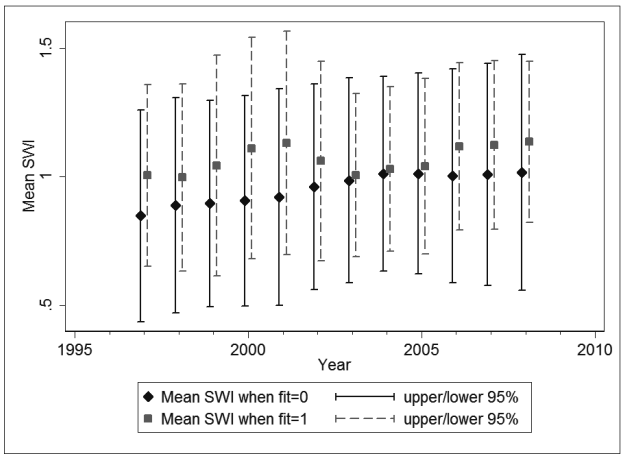


Figure 6.30: Mean SWI by presence of a FIT scheme and by year

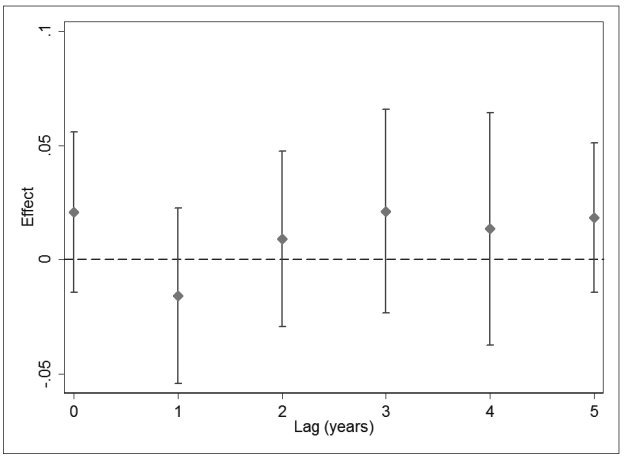


Figure 6.31: Lagged effect of introducing a feed-in tariff on the SWI

The mixed modelling analysis, however, shows no effect of introducing an FIT (Figure 6.31), suggesting that those countries that bring in a FIT scheme tend, on average, already to be more diverse than those that do not.

6.6.2.3 Quota / Tradeable Green Certificate / Renewables Obligation

The first countries to introduce Tradeable Green Certificates (TGC) had less generation diversity than the average, but by 2002 the average SWI in TGC-operating companies was above the average.

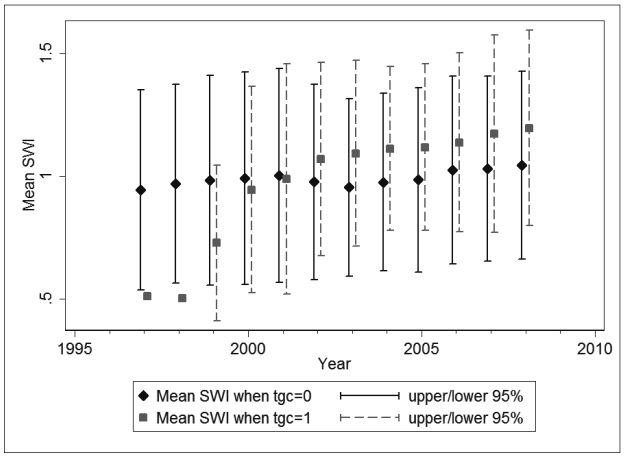


Figure 6.32: Mean SWI by presence of a TGC scheme and by year

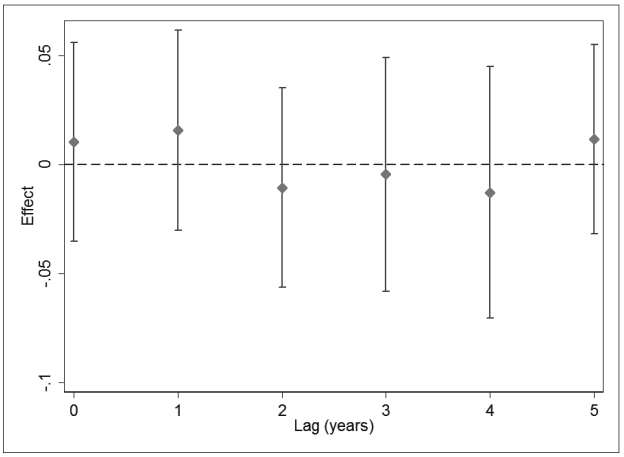


Figure 6.33: Lagged effect of introducing tradeable green certificates (TGC) on the SWI

There is no support, however, for the hypothesis that the introduction of a TGC scheme causes a change to the system diversity, as illustrated by Figure 6.33.

6.6.2.4 Tendering Process

Tendering process have not been widely implemented, so the differences observed between the two groups in Figure 6.34 should not be over-interpreted.

The effect of introducing a tendering process shows no effect on the diversity of the system (Figure 6.35).

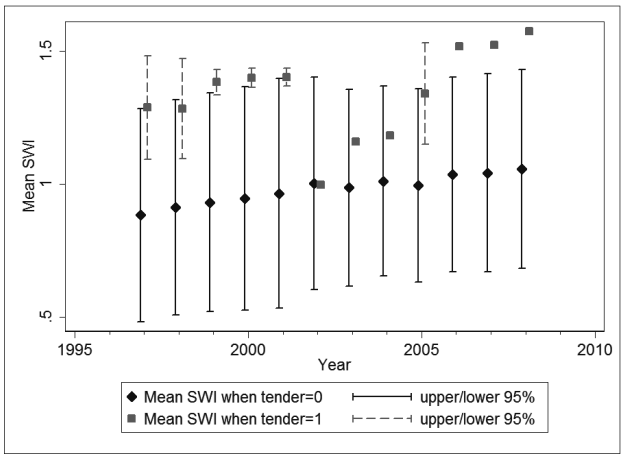


Figure 6.34: Mean SWI by use of a renewables tendering process and by year

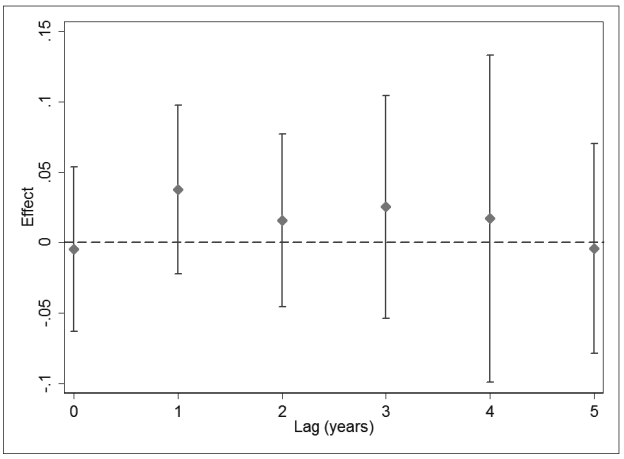


Figure 6.35: Lagged effect of introducing a tendering process on the SWI

6.6.2.5 Renewables Tax Incentives / Investment Grants

The use of tax incentives and investment grants has been more widespread. Those countries that have made use of such mechanisms tend to have more diversity than those without, as shown by Figure 6.36.

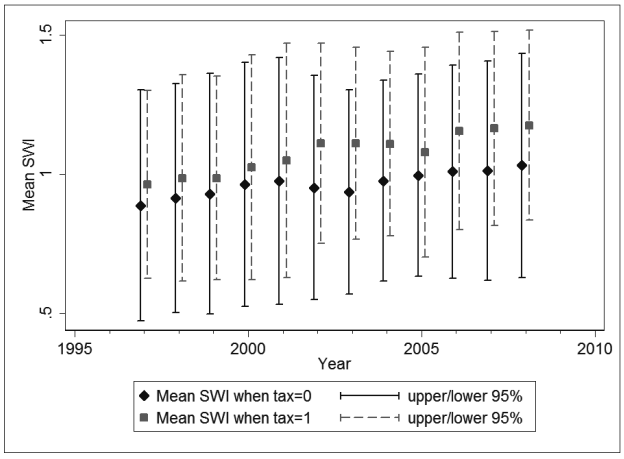


Figure 6.36: Mean SWI by existence of tax incentives for renewables and by year

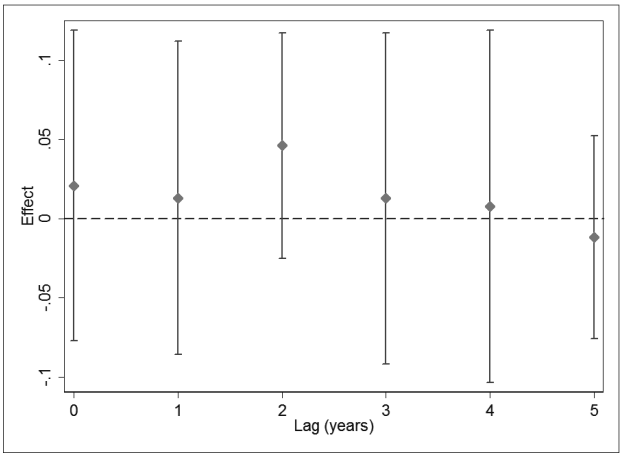


Figure 6.37: Lagged effect of introducing a renewables tax incentive on the SWI

As with the other renewable support mechanisms, however, there is no observable effect of introducing tax breaks or investment grants on the diversity of the system (Figure 6.37).

6.6.3 Conclusions

It would seem from the above analysis that in terms of overall measures of liberalisation and privatisation, the more liberalised systems are more technologically diverse. Furthermore, an increase in overall liberalisation within a given country, on average, increases the diversity. The act of undergoing deregulation a system, therefore, leads to an increase in diversity. Closer analysis, however, revealed, that this appeared to be more a function of privatisation than it was of unbundling. If liberalisation had been the driver of increased diversity, this would have suggested that there would be a competitive pressure to diversify a company's generation portfolio. That the driver appears to have instead been privatisation would reveal something about the underlying mechanism. This point is explored in more depth in Chapter 9.

The next chapter addresses two aspects of resilience indicative of consumers' ability to cope with system disturbances: the intensity of their demand for electricity, and the price of that electricity.

7

Energy Intensity and Prices

The previous two chapters have concerned the resilience of the electricity system itself, via measures of generation margins and generation diversity. The focus of this chapter is on the resilience *of society* to disruptions that might arise from the electricity system. Specifically, it considers the impact of liberalisation and regulation on the intensity of electricity consumption (the electricity consumed per unit GDP and per capita) and the price of that electricity (in real terms), both to industry and to households.

7.1 Energy Intensity

The 'energy intensity' indicators reflect the extent to which economies and the individuals within that economy are dependent on the energy system. In this sense, energy intensity is a measure of society to a disruption in the provision of energy services.

7.1.1 Changes to Energy Intensity over time

Figure 7.2 shows the annual electricity consumption per unit GDP for the OECD countries. Different countries exhibit different trends: some are upward, including Turkey, Greece, Portugal, Spain, Korea and Mexico; some, such as the UK, USA, Germany and the Czech Republic decrease over time. These trends can in part be attributed to structural changes in the economies of these countries. As Figure 7.1 shows, a number of those countries that reduced their energy intensity were also decreasing the proportion of GDP that came from the industrial and construction sectors (OECD, 2010).

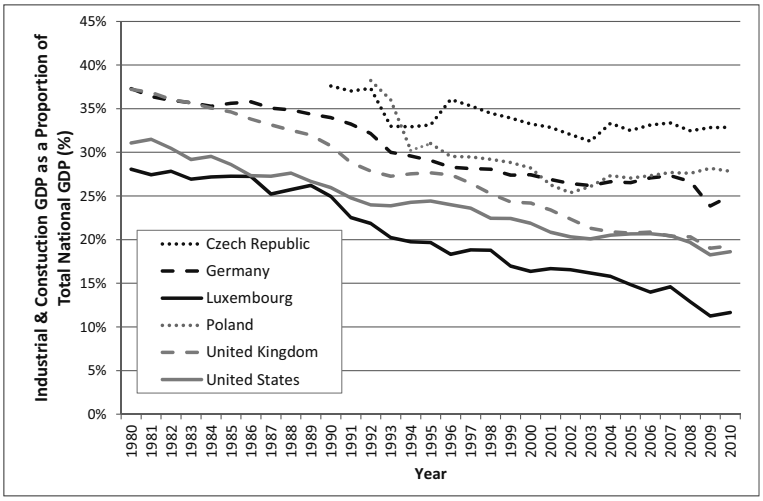


Figure 7.1: Proportion of national GDP attributable to the industrial and construction sectors (OECD, 2010)

Figure 7.3 shows the second energy intensity measure: the electricity consumed on average by each person in a country. Here, the overall trend in the OECD countries is almost universally upward. Despite increases in energy efficiency, these increases in electricity use are driven by both population and per capita income growth in the majority of the OECD countries over this period (Azar *et al.*, 2002).

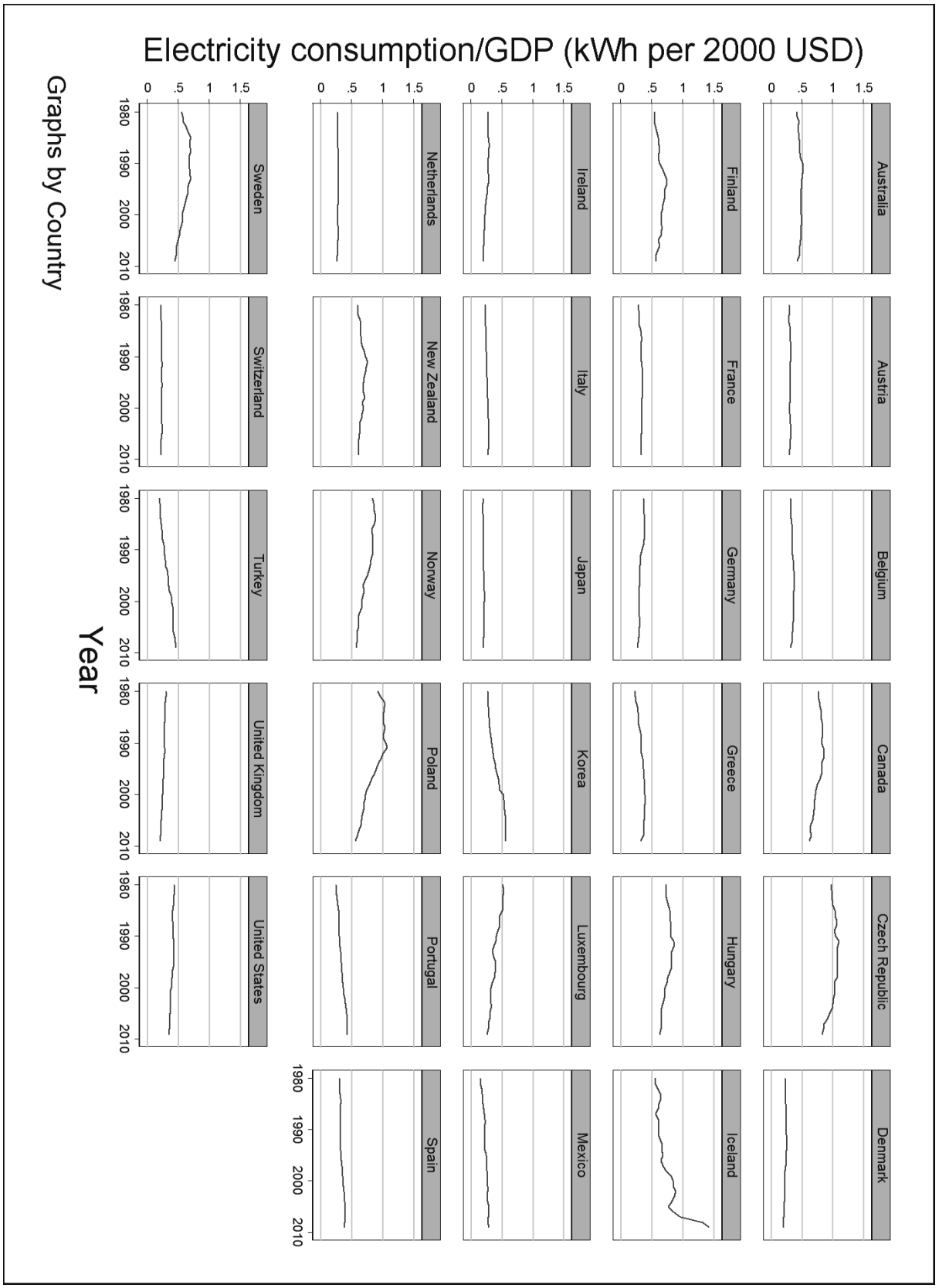


Figure 7.2: kWh/GDP for all OECD countries

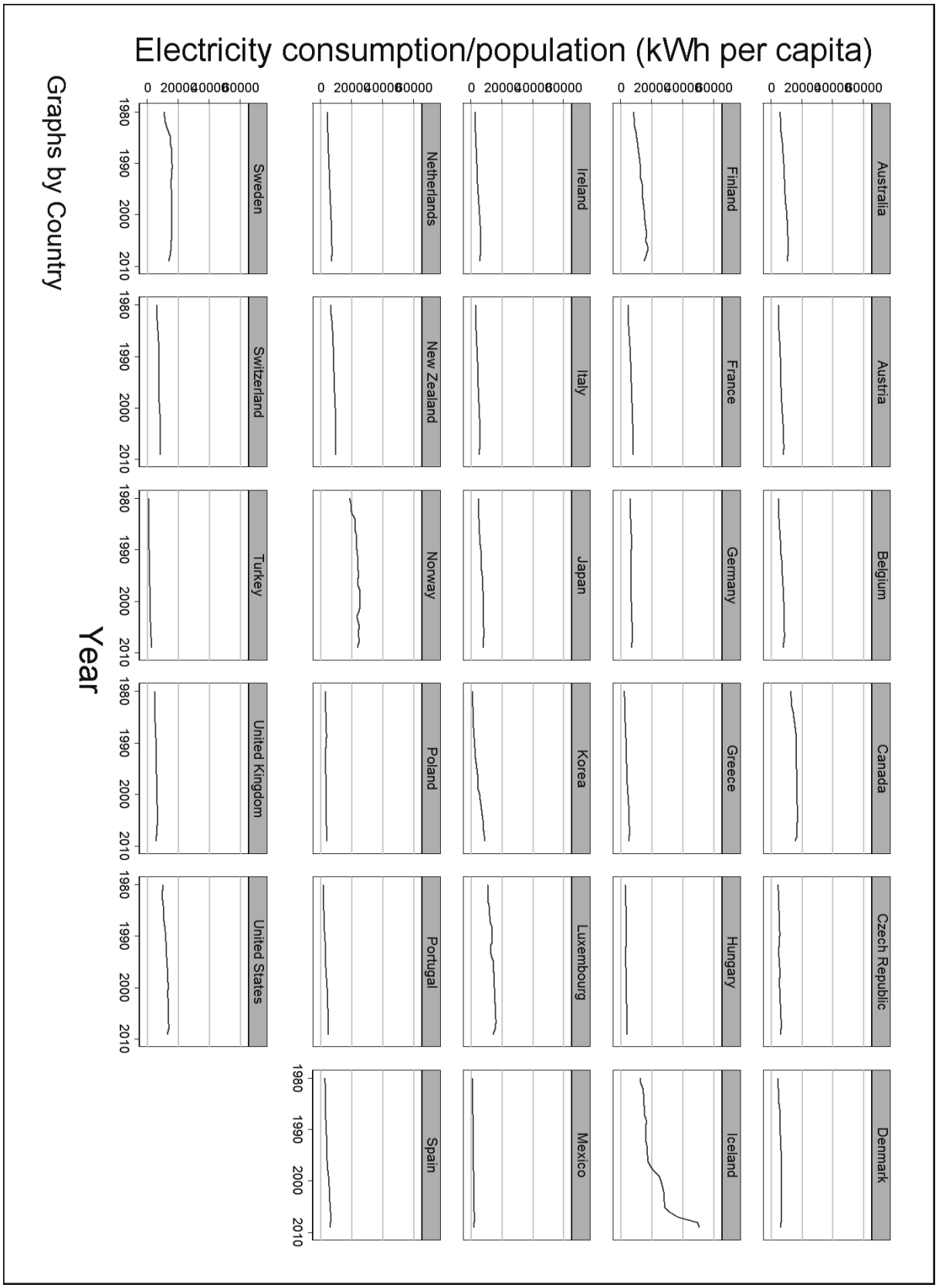


Figure 7.3: kWh per capita for all OECD countries

As with a number of other countries, the UK's economic energy intensity has been decreasing for a number of years (Figure 7.4). Whilst the UK's overall GDP has been increasing over this period, the expansion of the service industry and the contraction of the manufacturing sector has decoupled this growth from the indigenous electricity consumption. In this case the embedded energy associated with consumed products remains the same, but is expended outside of UK national borders.

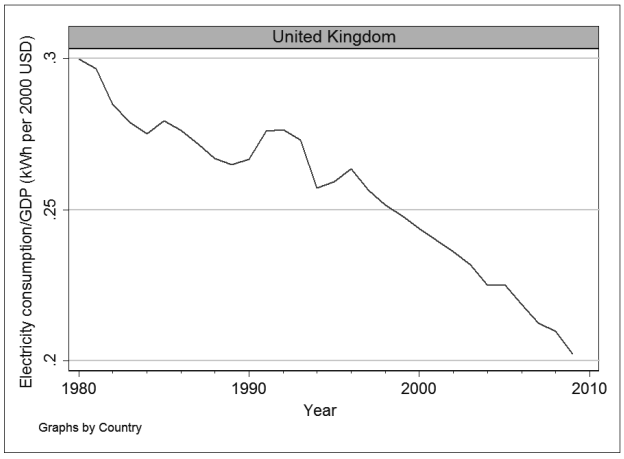


Figure 7.4: kWh/GDP for the UK

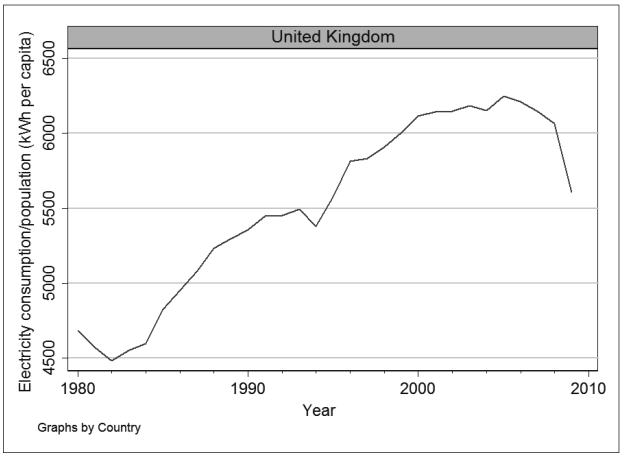


Figure 7.5: kWh per capita for the UK

An alternative explanation for the decoupling of electricity consumption from GDP is that industrial efficiency gains allow the same products to be manufactured using less energy. In either case, the extent to which UK productivity might be affected by a disruption to the UK electricity supply is reflected by the economic energy intensity indicator.

The OECD's per-capita electricity intensity shows an increasing trend in nearly all cases. The UK's trajectory is no exception here, with Figure 7.5 revealing strong growth over this time period, although it peaked in 2005 and showed a considerable drop in 2009.

7.1.2 Effect of liberalisation and privatisation on energy intensity

7.1.2.1 Effect of overall liberalisation

A scatter plot of economic energy intensity against overall liberalisation (Figure 7.6) shows no discernable relationship between the two. This is somewhat confirmed by Figure 7.7, which provides little evidence that a change in the overall level of liberalisation induces a change in the

economic energy intensity.

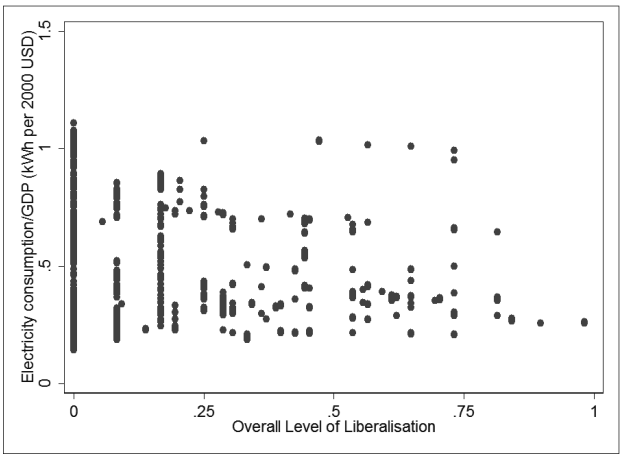


Figure 7.6: kWh/GDP (all county-years) against the degree of overall liberalisation

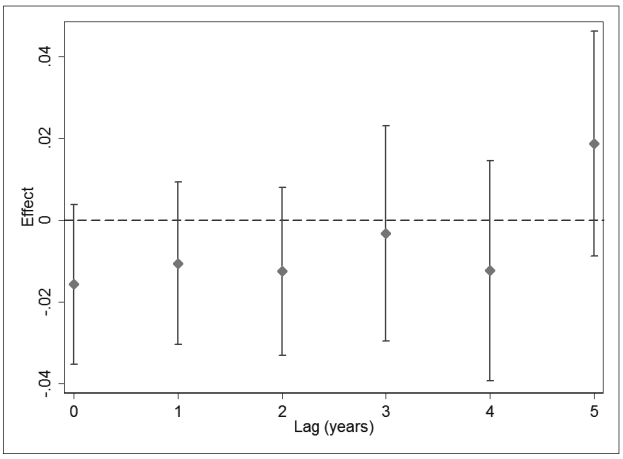


Figure 7.7: Lagged effect of increasing the overall degree of liberalisation on the per-GDP electricity intensity

The per-capita electricity electricity consumption appears to be negatively correlated with overall liberalisation (Figure 7.8), but the relationship is not a strong one. Furthermore, as Figure 7.9, there is no evidence to suggest a causal relationship.

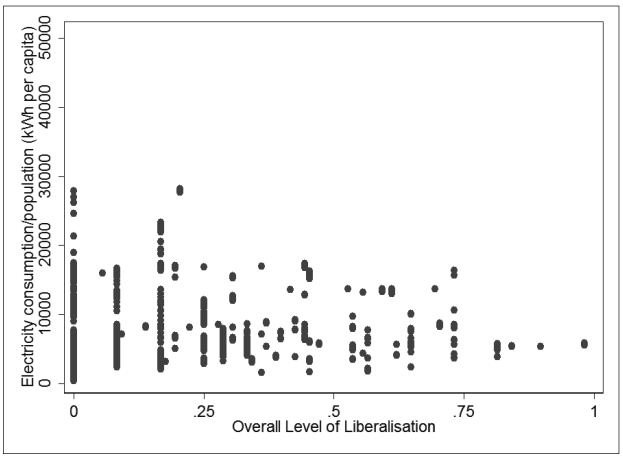


Figure 7.8: kWh per capita (all county-years) against the degree of overall liberalisation

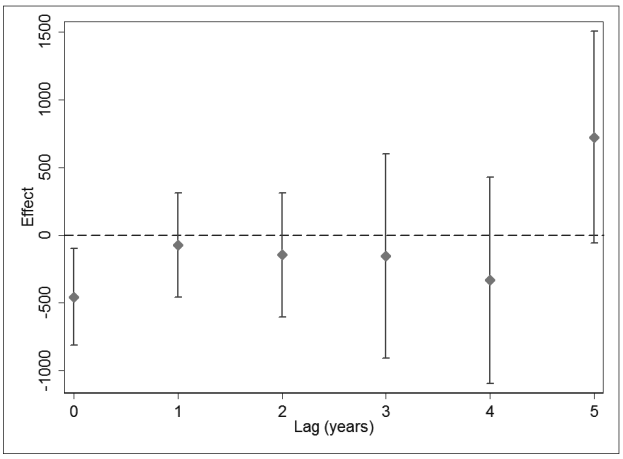


Figure 7.9: Lagged effect of increasing overall liberalisation on per-capita electricity intensity

7.1.2.2 Effect of the creation of a liberalised pool on energy intensity

For most of the years observed, countries with liberalised pools have tended to have higher per-GDP and per-capita electricity consumption levels (Figures 7.10 and 7.11). The mean energy

intensities (for both indicators) of the countries with electricity pools has been declining, whereas for those without pools the trend has either been flat or slightly increasing.

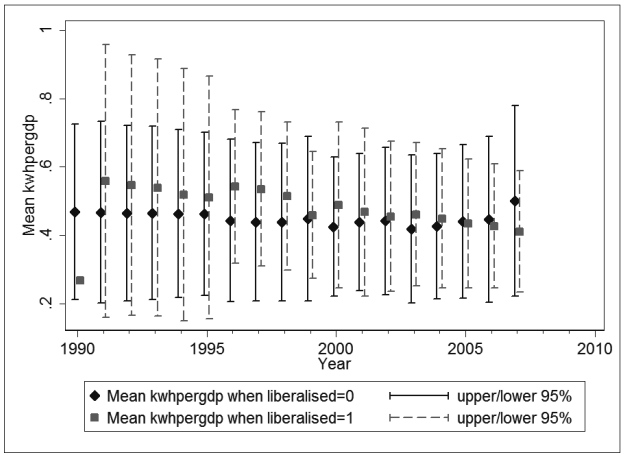


Figure 7.10: Mean kWh/GDP by whether liberalised and by year

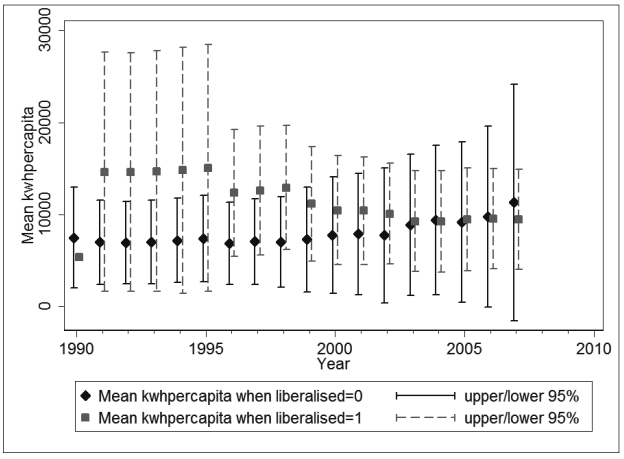


Figure 7.11: Mean kWh per capita by whether liberalised and by year

The figures above suggest that early-liberalisers had more energy-intensive economies. The subsequent decline could either arise as a within-country transformation, such as transition from manufacturing- to service-based economies, or it could be a result of countries with below-average intensities eventually liberalising. Figures 7.12 and 7.13 are somewhat equivocal. No significant effects are seen at the 5% level, but there is some suggestion that 3, 4 and 5 years after introducing a liberalised pool there is an associated decline in the per-GDP and per-capita electricity consumption.

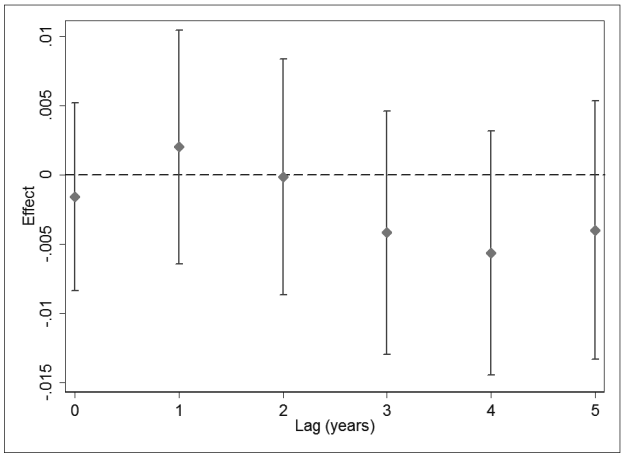


Figure 7.12: Lagged effect of introducing a liberalised pool on kWh/GDP

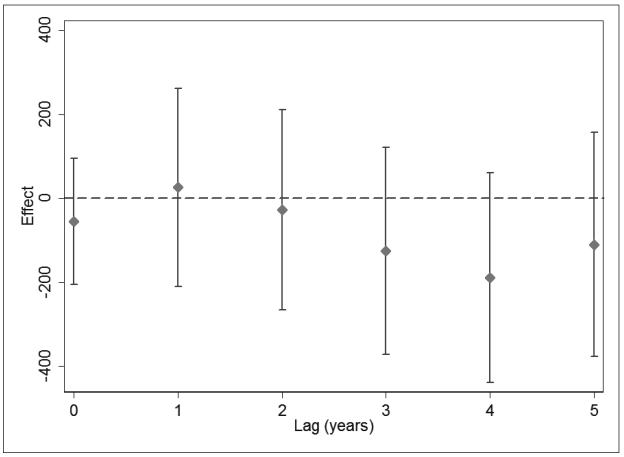


Figure 7.13: Lagged effect of introducing a liberalised pool on kWh per capita

7.1.2.3 Effect of privatisation on energy intensity

As Figure 7.14 shows, there appears to be some overall relationship between increasing levels of private ownership and a decreasing economic energy intensity. No trend, however, is apparent for the per-capita electricity consumption (Figure 7.15).

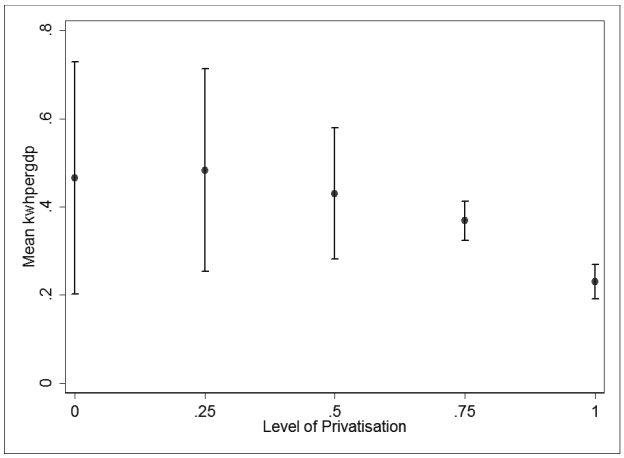


Figure 7.14: kWh/GDP (all county-years) against the degree of private ownership

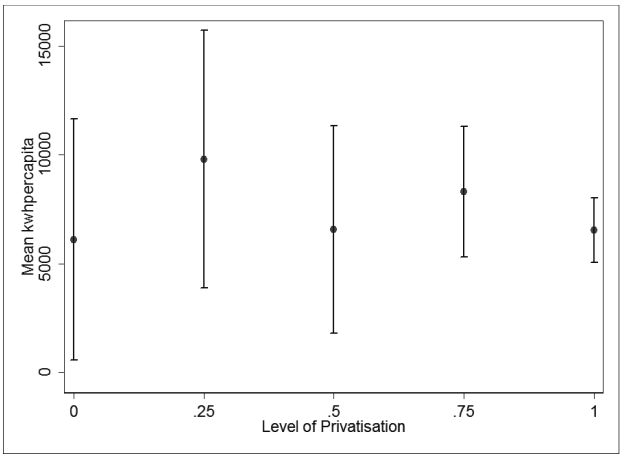


Figure 7.15: kWh per capita (all county-years) against the degree of private ownership

In both cases, however, the lagged effects appear to be negligible (Figures 7.16 & 7.17), meaning that there is no evidence that privatisation affects per-GDP or per-capita electricity consumption.

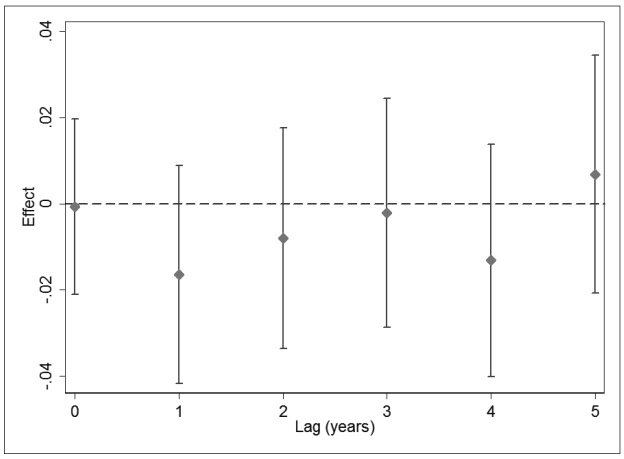


Figure 7.16: Lagged effect of increasing private ownership kWh/GDP

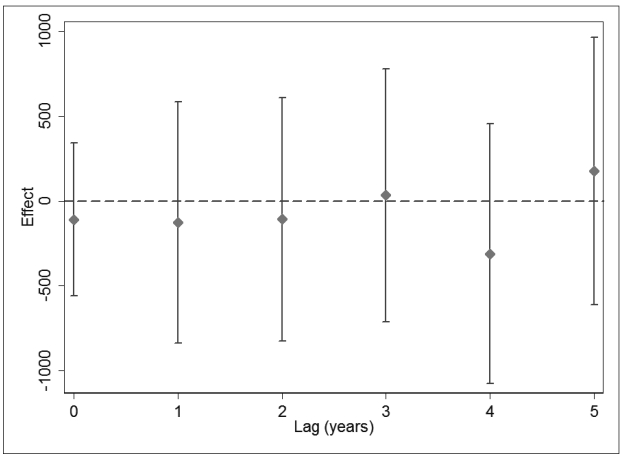


Figure 7.17: Lagged effect of increasing private ownership kWh per capita

The binary "privatised" variable confirms this lack of association, as seen in Figures 7.18 and 7.19, which show no effect of privatisation on either indicator.

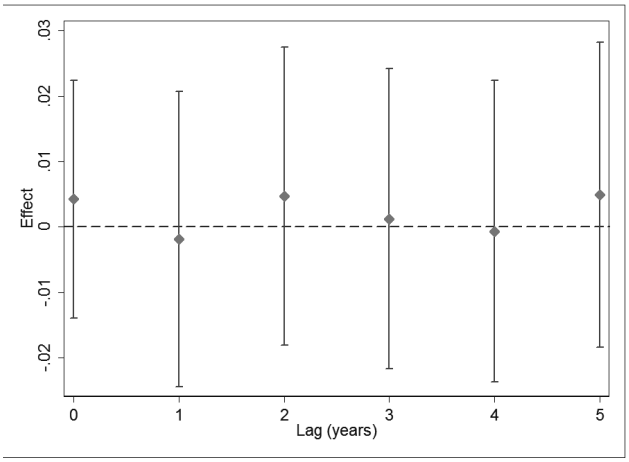


Figure 7.18: Lagged effect of privatising on kWh/GDP

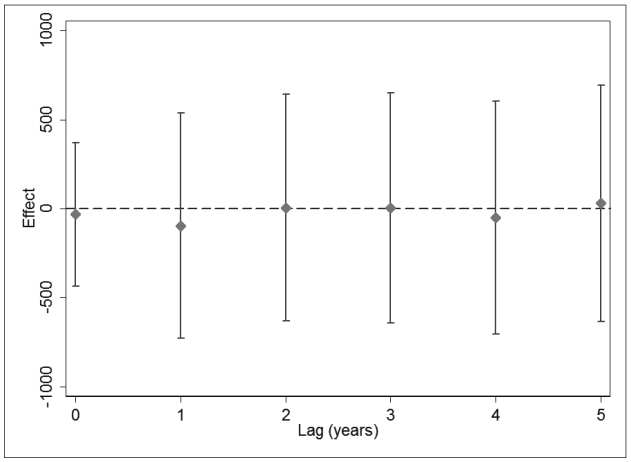


Figure 7.19: Lagged effect of privatising on kWh per capita

The by-year plot for economic intensity (Figure 7.20) shows that across all years privatised systems consume around 40% less electricity for each unit of economic output. There is less of a difference between the two groups on the per-capita indicator (Figure 7.20) showing very similar levels of electricity consumption per head, with both increasing slowly until 1997, after which privatised systems remained at a fairly constant level and non-privatised systems continued to increase their per-capita consumption.

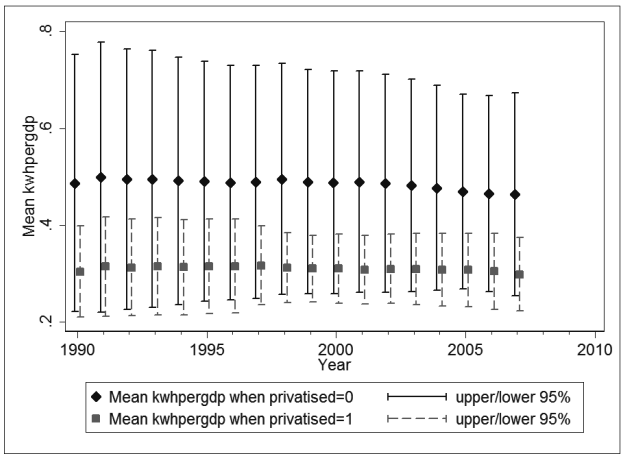


Figure 7.20: Mean kWh/GDP by whether privatised and by year

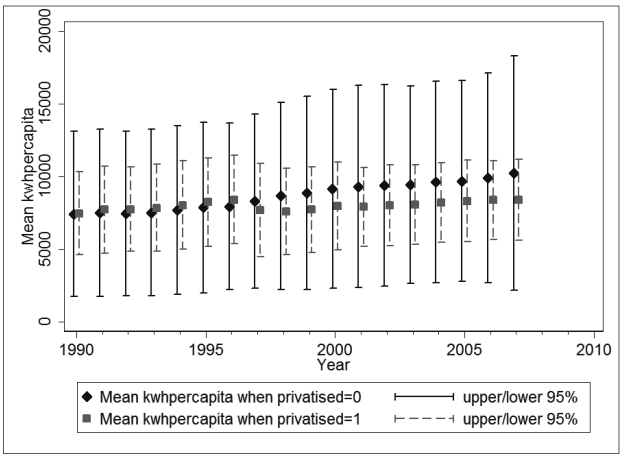


Figure 7.21: Mean kWh per capita by whether privatised and by year

7.1.2.4 Vertical Separation

Vertical separation appears to have little relationship with the economic energy intensity of countries. Figure 7.22 shows that whether generation and transmission are fully integrated, separated by accounting practices or fully separated, there is no difference in terms of the electricity consumed per unit of economic productivity. Figure 7.23 confirms that there is no association between transmission-generation separation and the electricity intensity of the economy.



Figure 7.22: kWh/GDP (all county-years) against the degree of transmission-generation separation

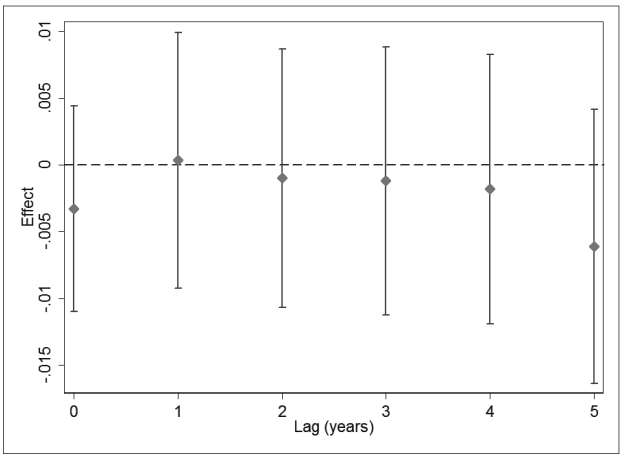


Figure 7.23: Lagged effect of decreasing transmission-generation separation on kWh/GDP

This is also true for the binary **transgen_unbundling** variable. There is a small difference in the kWh per GDP in the early 1990s, but this has gone within a decade (Figure 7.24). Figure 7.25 further shows that there is little evidence of an association here.

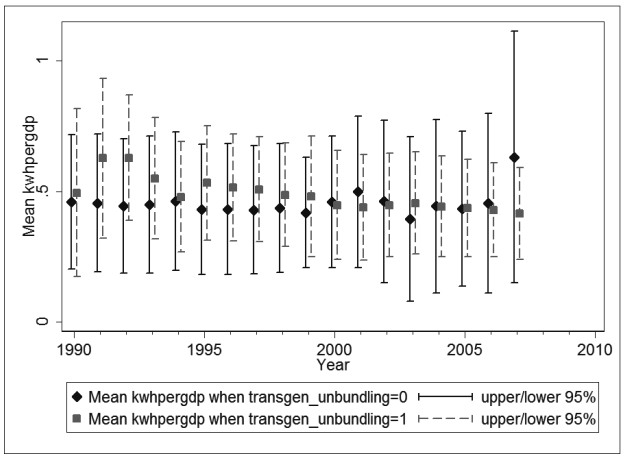


Figure 7.24: Mean kWh/GDP by whether transmission and generation have at least accounting separation and by year

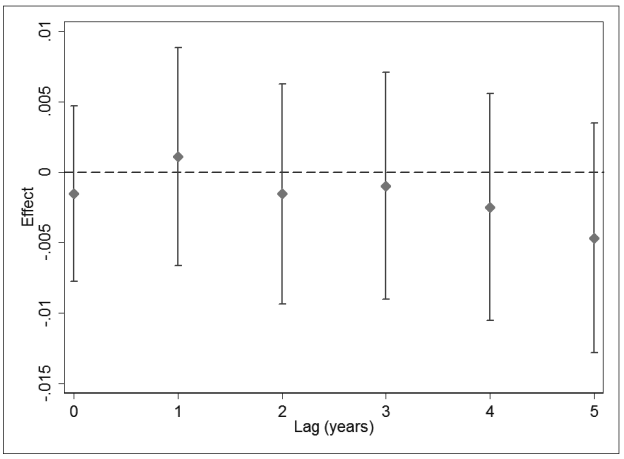


Figure 7.25: Lagged effect of binary trans-gen unbundling on kWh/GDP

The conclusions are very similar when considering overall vertical separation, which includes distribution and supply unbundling. Figures 7.26 and 7.27 do not reveal any association between this measure and the kWh per GDP indicator. Nor does the binary variable **overall_unbundling** show a large difference between integrated and unbundled systems over time (Figure 7.28) or as a result of the fixed effects model (Figure 7.29).

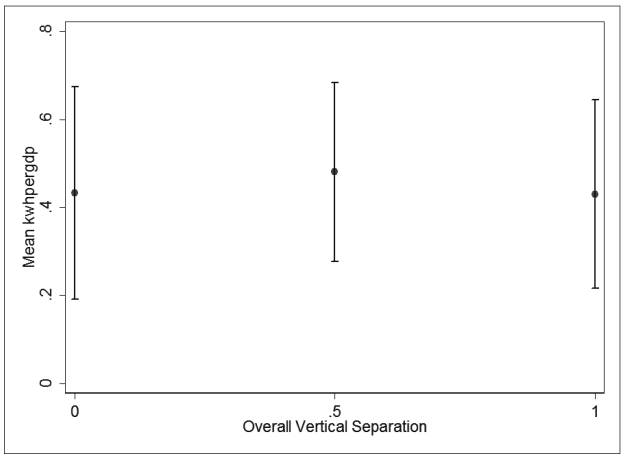


Figure 7.26: kWh/GDP (all county-years) against overall vertical separation

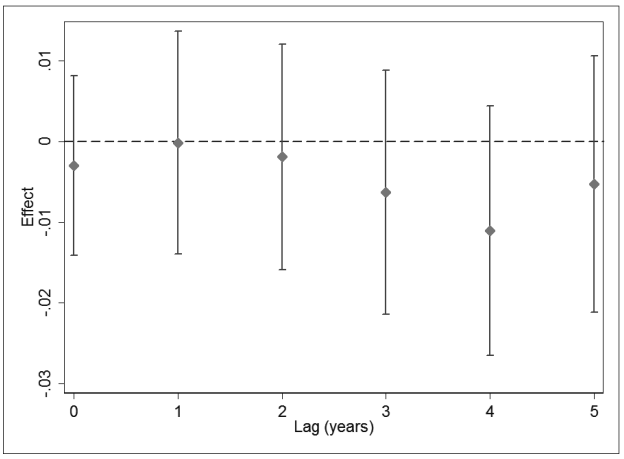


Figure 7.27: Lagged effect of overall vertical separation on kWh/GDP

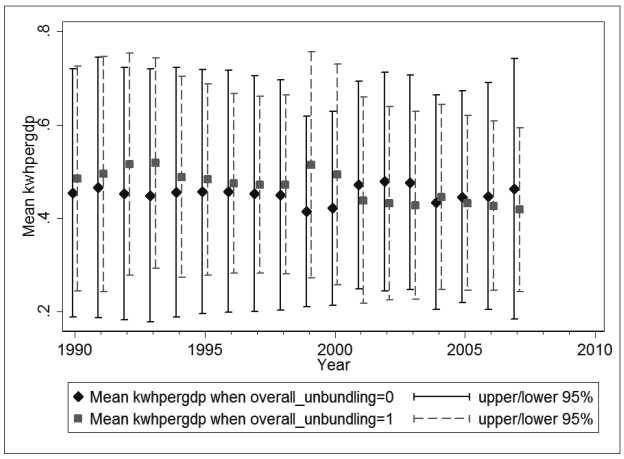


Figure 7.28: Mean kWh/GDP by year grouped into vertically integrated and unbundled or mixed

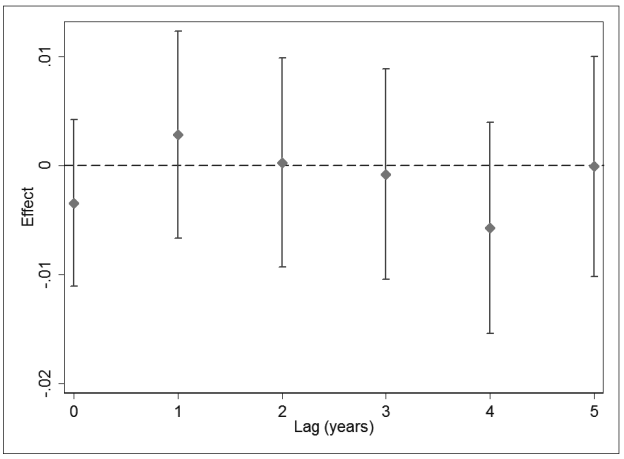


Figure 7.29: Lagged effect of binary overall unbundling on kWh/GDP

As with the electricity-per-GDP indicator, there seems to be little evidence to support a relationship between transmission-generation separation and the per-capita electricity consumption (Figures 7.30 & 7.31).

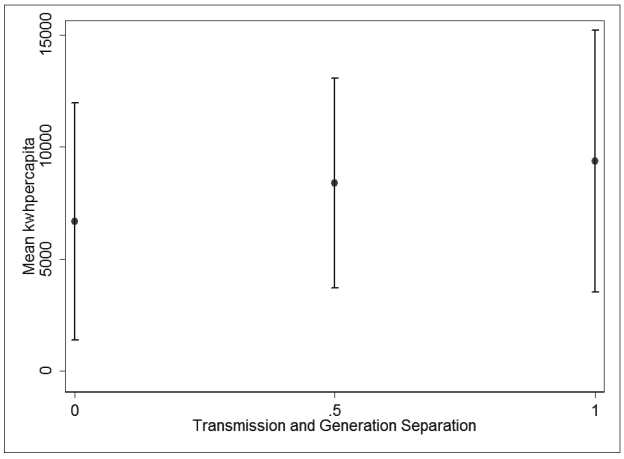


Figure 7.30: kWh per capita (all county-years) against the degree of transmission-generation separation

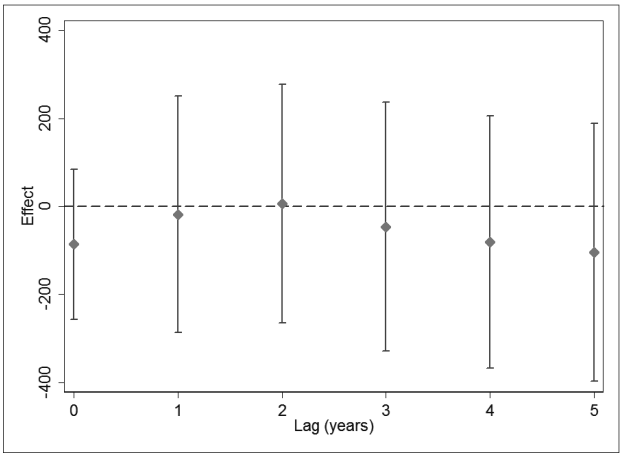


Figure 7.31: Lagged effect of decreasing transmission-generation separation on kWh per capita

Nor does the binary variable **transgen_unbundling** suggest a strong relationship. The kWh-per-capita is initially slightly higher in the unbundled systems, but the rate of increase for those systems that remain integrated is higher (Figure 7.32). Figure 7.33, however, shows no association between unbundling and per-capita consumption.

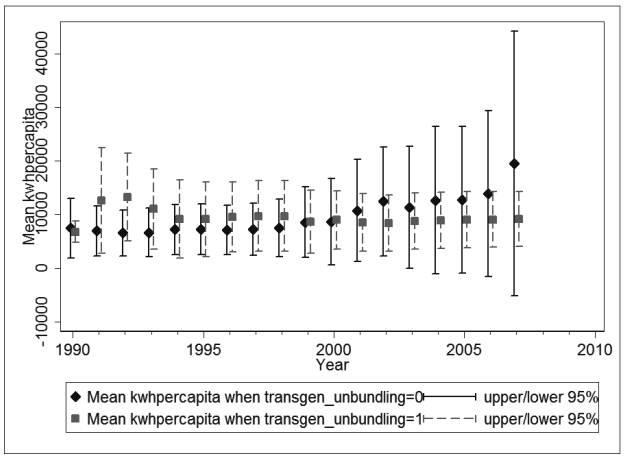


Figure 7.32: Mean kWh per capita by whether transmission and generation have at least accounting separation and by year

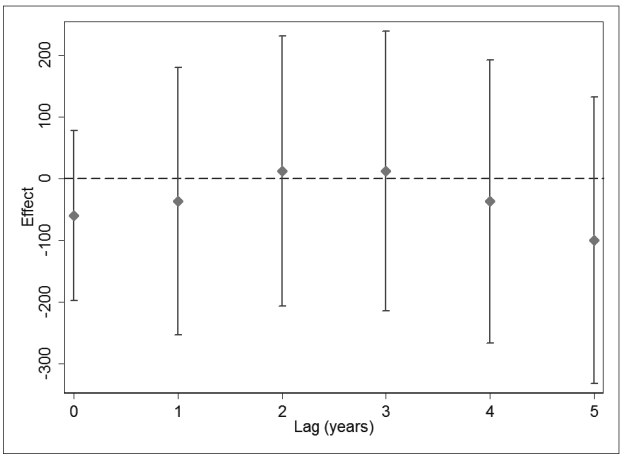


Figure 7.33: Lagged effect of binary trans-gen unbundling on kWh per capita

There is slightly more evidence of an association between overall vertical separation and the per-capita electricity consumption. Figure 7.34 shows that a proportion of the integrated system have above average per-capita consumption levels, and there is weak evidence from Figure 7.35 that there is a negative association.

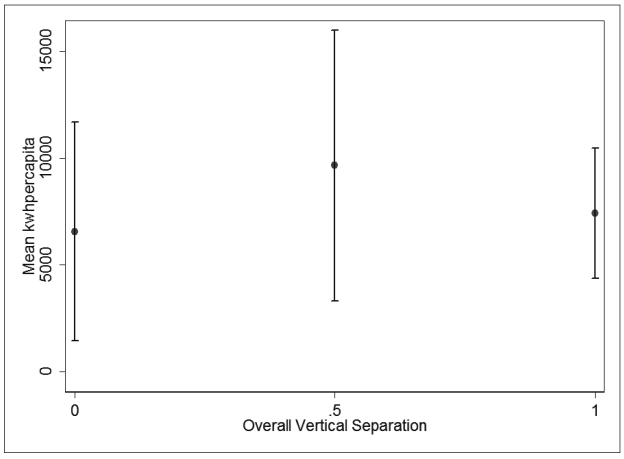


Figure 7.34: kWh per capita (all county-years) against overall vertical separation

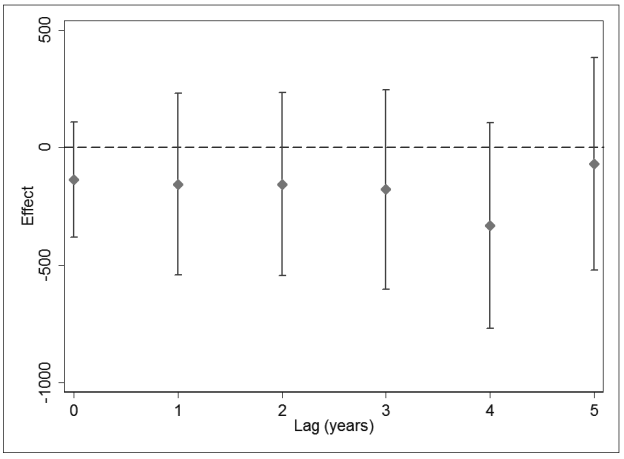


Figure 7.35: Lagged effect of overall vertical separation on kWh per capita

The binary variable **overall_unbundling** again shows an initially higher level of per-capita consumption for unbundled systems, but that this declines over time, whereas for the systems that remain vertically integrated the reverse is true (Figure 7.36). The evidence of association, shown in Figure 7.37, is not strong, providing little evidence for the idea that unbundling the system leads to a change in per-capita electricity consumption.

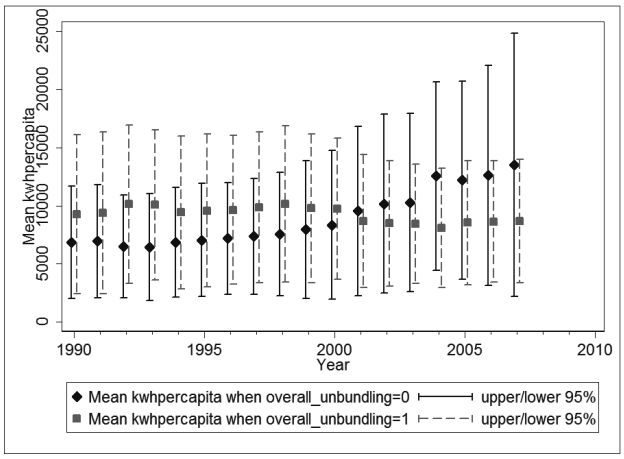


Figure 7.36: Mean kWh per capita by year grouped into vertically integrated and unbundled or mixed

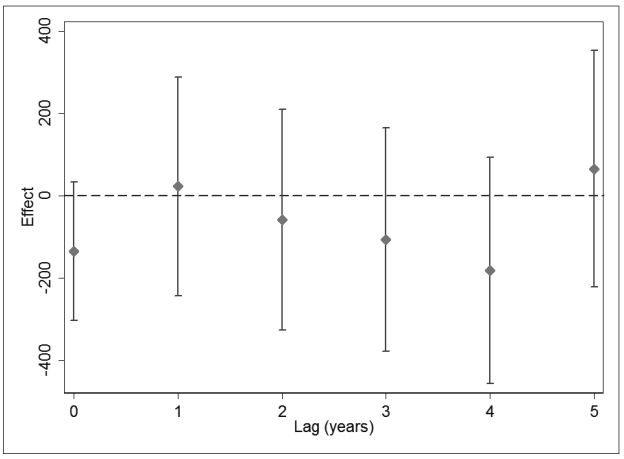


Figure 7.37: Lagged effect of binary overall unbundling on kWh per capita

7.1.3 Effect of renewable generation and associated policies on electrical energy intensity

Using the same methods applied above, this section assesses the relationship between the deployment of renewable generation and the associated renewables policies on the levels of per-GDP and per-capita electricity consumption.

7.1.3.1 Installed capacity of new renewables

Figure 7.38 suggests that there is a negative correlation between the level of renewables penetration and per-GDP electricity consumption. Figure 7.39 provides only weak support for this hypothesis, however.

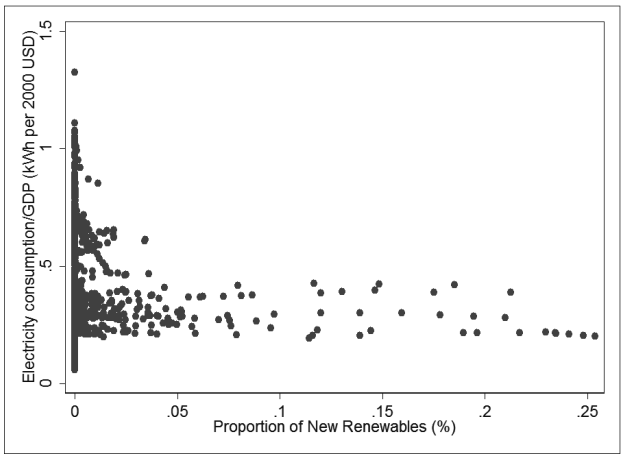


Figure 7.38: kWh/GDP (all county-years) against the proportion of new renewables on the system

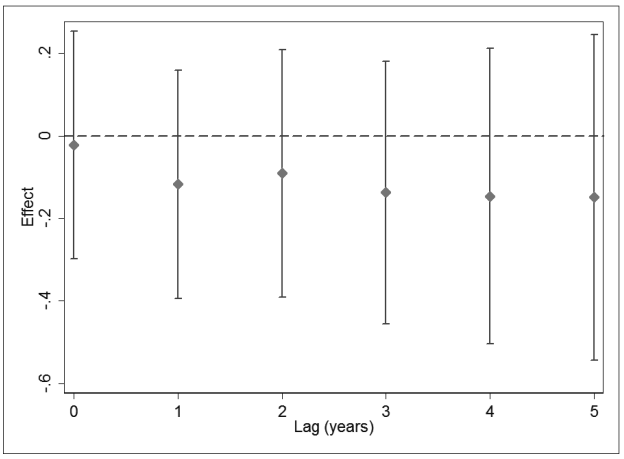


Figure 7.39: Lagged effect of increasing the new renewable proportion on the kWh/GDP

The relationship between renewables penetration and per-capita electricity consumption is more marked. Again, a scatter plot indicates some correlation (Figure 7.40), but it is the mixed effects model that reveals the association (Figure 7.41). This association discounts the differences between countries with low and high levels of penetration, and shows that a within-country increase in the proportion of renewables on the system is associated with an immediate and sustained reduction in the amount of electricity consumed by the average person.

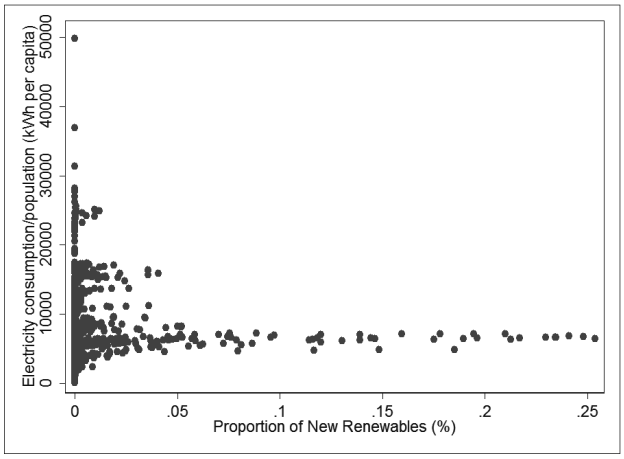


Figure 7.40: kWh per capita (all county-years) against the proportion of new renewables on the system

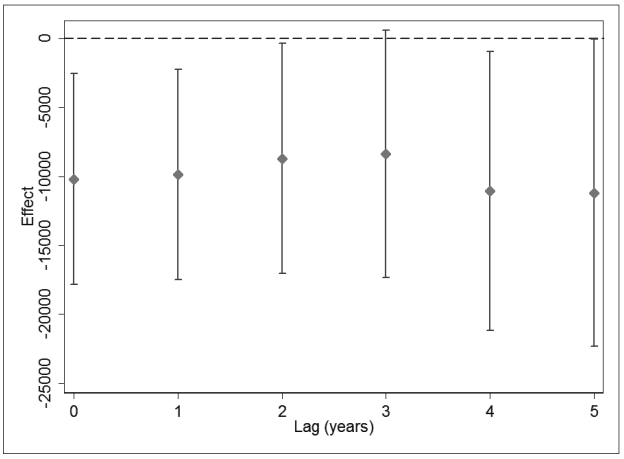


Figure 7.41: Lagged effect of increasing the new renewable proportion on the kwhpercapita

None of the changes in these explanatory variables occurs independently of the others, so it is not possible to conclude that an increase in renewables *causes* a reduction in electricity demand. The two variables may share a proximal cause (perhaps unmeasured). Even if the association is truly

a causal, the causal pathway needs to be clarified. It is likely, for example, that an increase in the proportion of renewables leads to an increase in the electricity price, which in turn constrains demand. This would still represent a causal chain between renewables penetration and demand reduction, but the pathway has implications for policy.

The particular question of the effect of renewables penetration levels and policies are addressed later in Section 7.2.3.

7.1.3.2 Renewable electricity support schemes

The following sections investigate whether the provision of support for these new renewables has an effect on the energy intensity of the economy or individual consumers.

Any renewable support scheme

The overall difference in diversity and the difference seen on an annual basis (Figures 7.42 and 7.43, respectively) both show that countries with a renewable support mechanism in place tend on average to have a lower per-GDP electricity consumption that those without.

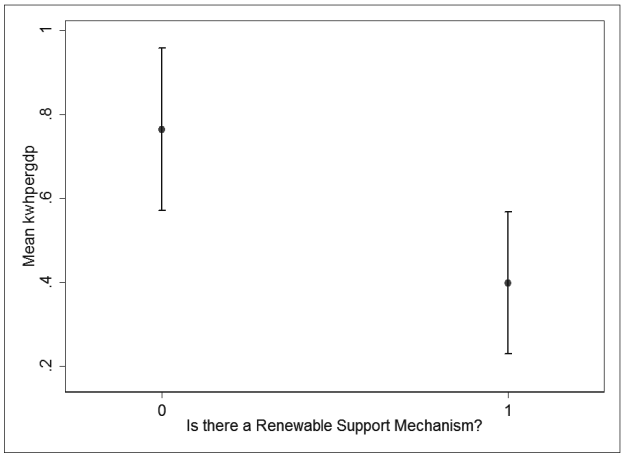


Figure 7.42: Mean kwhpergdp by renewable support

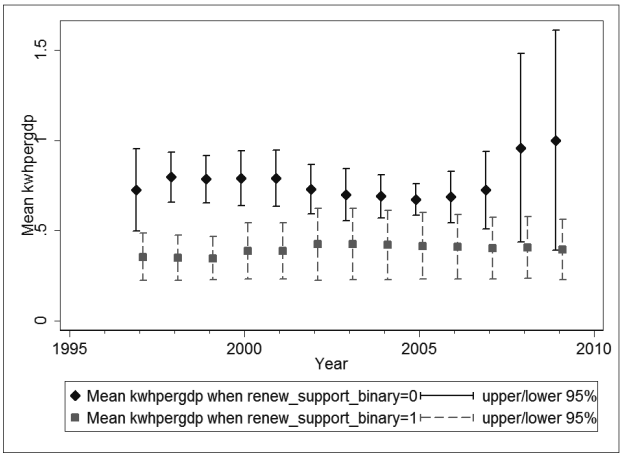


Figure 7.43: Mean kwhpergdp by renewable support and by year

The same can be said of the per-capita electricity consumption. Economies without a renewable support mechanism tend to use electricity more intensively, and this appears to be an increasing trend (Figure 7.45).

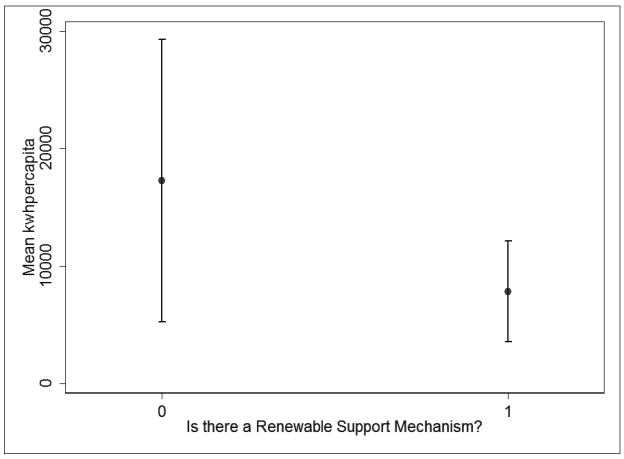


Figure 7.44: Mean kwhpercapita by renewable support

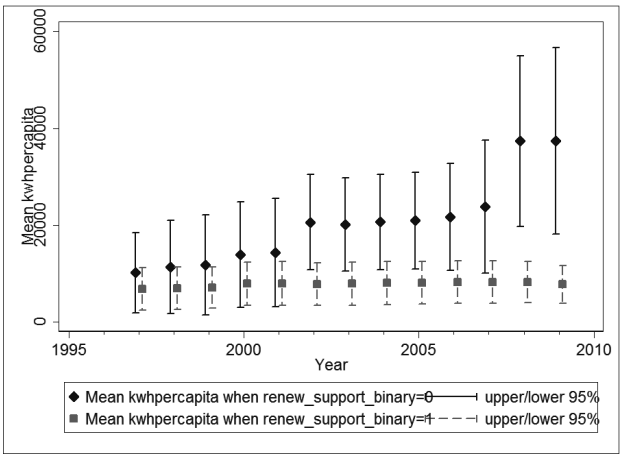


Figure 7.45: Mean kwhpercapita by renewable support and by year

On both the per-GDP and the per-capita measure, the results of the mixed effects analysis are not significant at the 5% level (Figures 7.46 & 7.47). There is some weak evidence, however, that the introduction of a renewables support mechanism has a depressive effect on the per-GDP electricity consumption, and this holds for all observed lags. The effects on per-capita consumption are also negative, but the effect is a very small proportion of the overall variability.

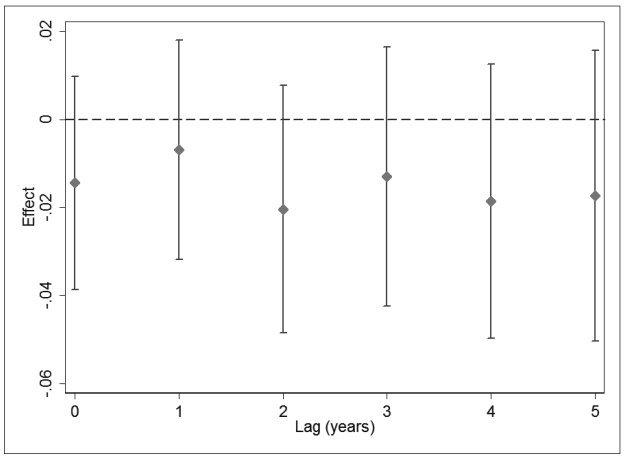


Figure 7.46: Lagged effect of introducing renewables support mechanisms on the kwhpergdp

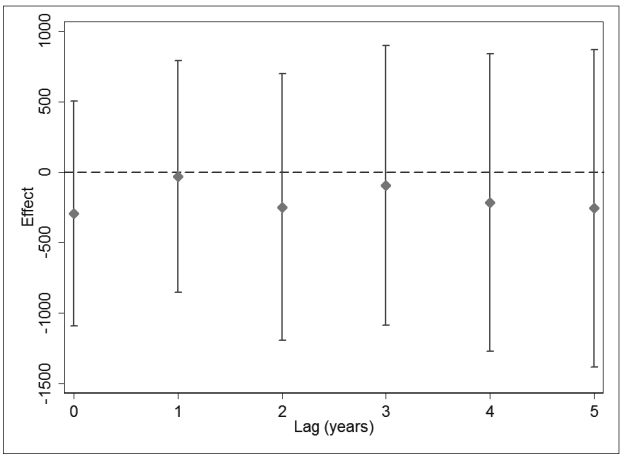


Figure 7.47: Lagged effect of introducing renewables support mechanisms on the kwhpercapita

Feed-in Tariff

The trends observed for renewables policies in general seem to hold with respect to the particular case of Feed-in Tariffs (FITs). Electricity systems with a Feed-in Tariff (FIT) scheme have lower

per-GDP and per-capita electricity consumption than those without (Figures 7.48 & 7.50. In both cases, however, whilst the results of the mixed effects analysis show a negative impact of FITs on electricity intensity (Figures 7.49 & 7.51), these impacts are small and well within the margin of error.

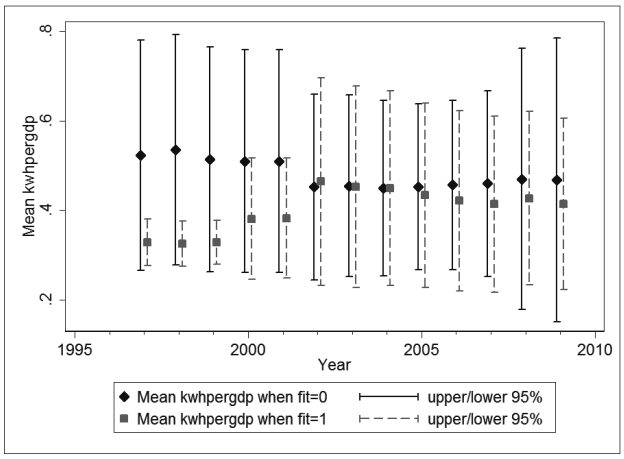


Figure 7.48: Mean kwhpergdp by FIT and by year

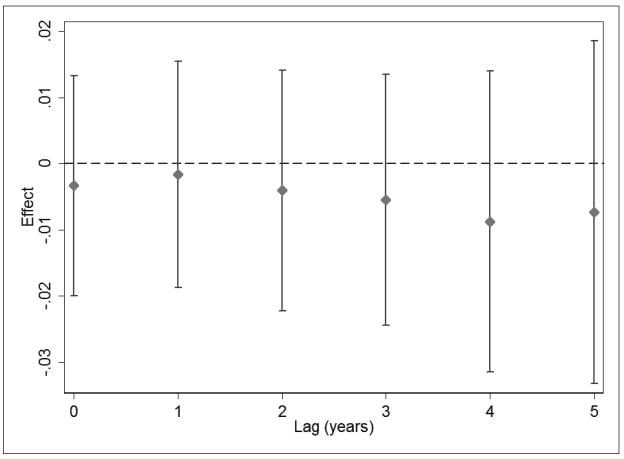


Figure 7.49: Lagged effect of introducing a feed-in tariff on the kwhpergdp

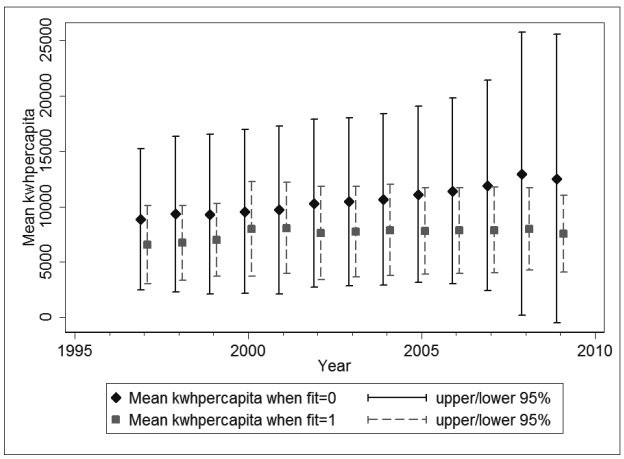


Figure 7.50: Mean kwhpercapita by FIT and by year

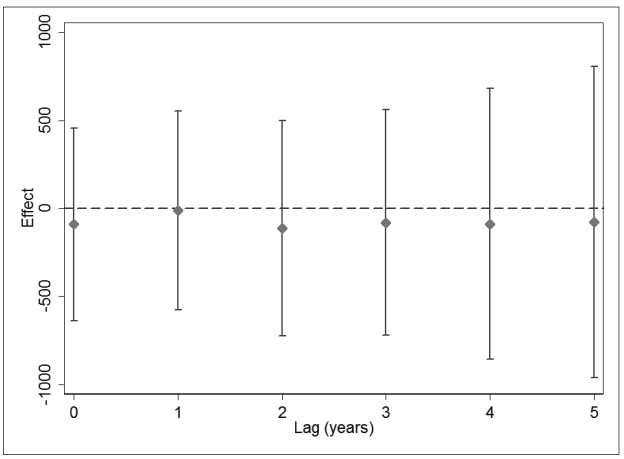


Figure 7.51: Lagged effect of introducing a feed-in tariff on the kwhpercapita

Quota / Tradeable Green Certificate / Renewables Obligation

Countries that have implemented Tradeable Green Certificates (TGCs) have consistently had lower per-GDP electricity consumption than the average (Figure 7.52). There is, however, little evidence to suggest that this is predominantly a causal association, as shown by Figure 7.53.

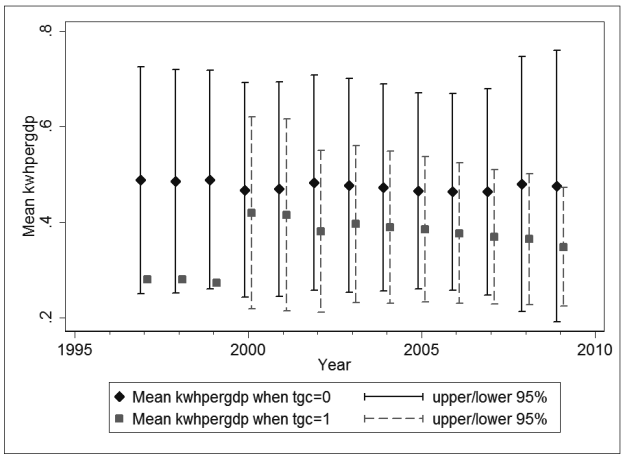


Figure 7.52: Mean kwhpergdp by TGC and by year

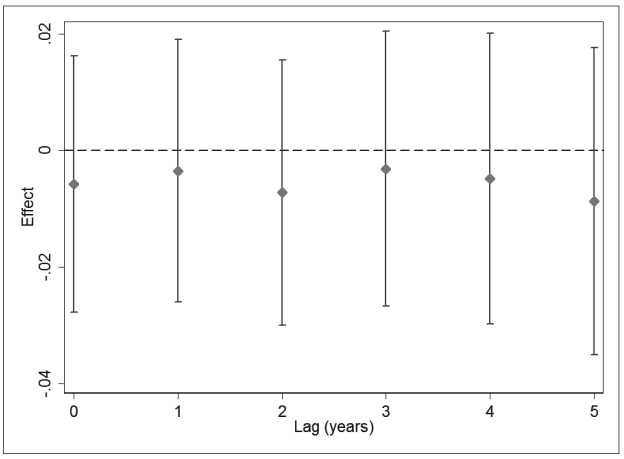


Figure 7.53: Lagged effect of introducing tradeable green certificates (TGC) on the kwhpergdp

The same is true for the per-capita electricity consumption, where countries with TGCs tend to be lower than those without (Figure 7.54) but with no evidence of a causal link (Figure 7.55).

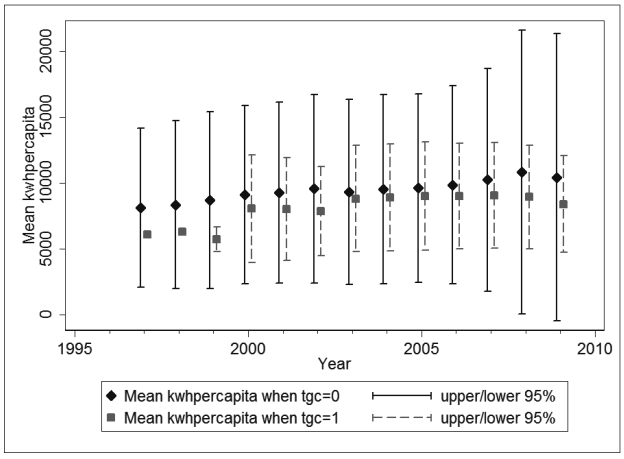


Figure 7.54: Mean kwhpercapita by TGC and by year

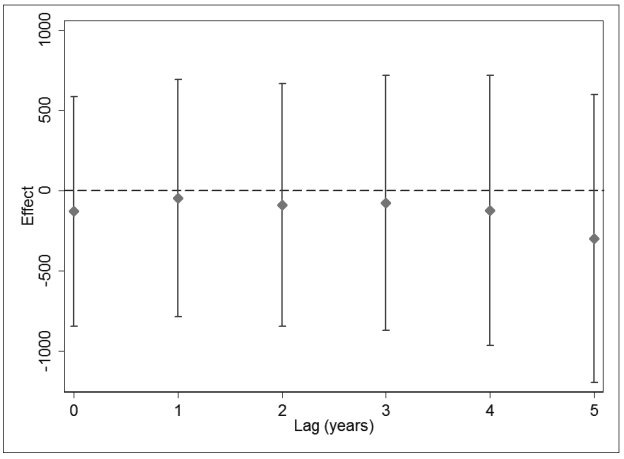


Figure 7.55: Lagged effect of introducing tradeable green certificates (TGC) on the kwhpercapita

Tendering Process

As mentioned in previous chapters, tendering processes have not been widely implemented. Until 2006, the countries with tendering processes tended to have lower per-GDP electricity consumption (Figure 7.56). The per-capita electricity consumption difference between the two groups is smaller (Figure 7.57).

In both cases, there is little evidence that there is a causal relationship in effect. Neither Figures

7.56 nor 7.57 show a consistent association, and at all lags the effect is well within the margins of error.

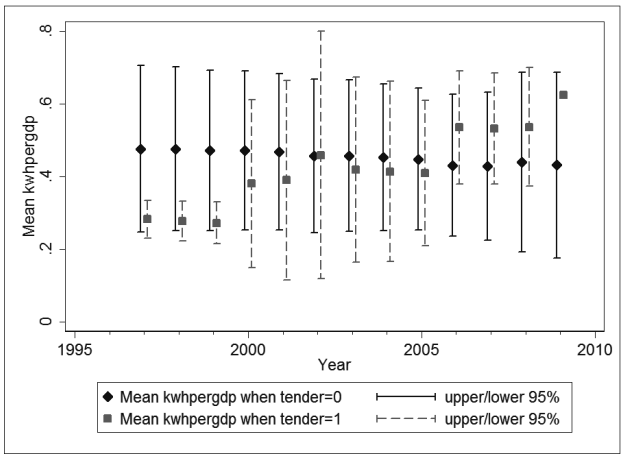


Figure 7.56: Mean kwhpergdp by tendering process and by year

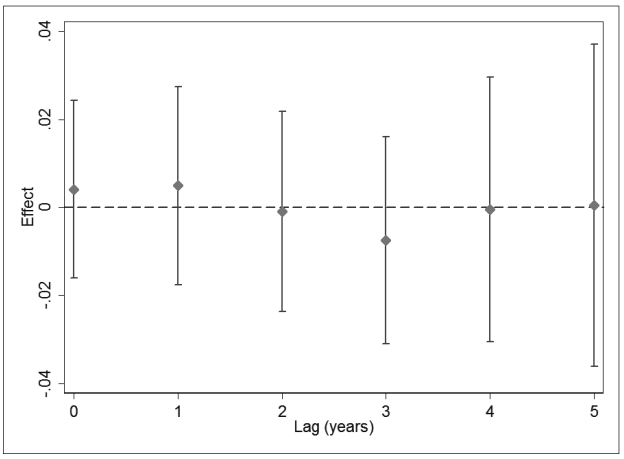


Figure 7.57: Lagged effect of introducing a tendering process on the kwhpergdp

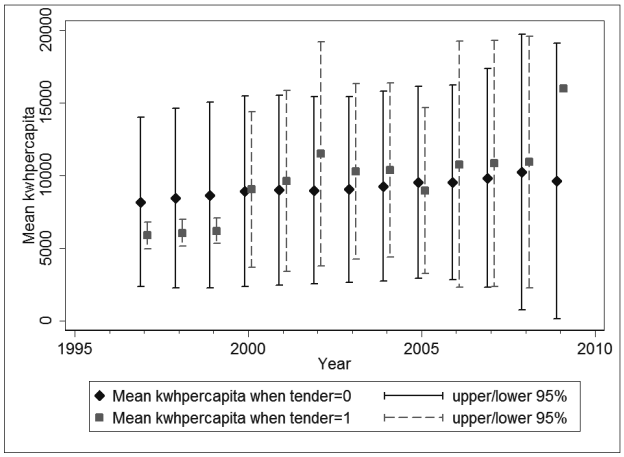


Figure 7.58: Mean kwhpercapita by tendering process and by year

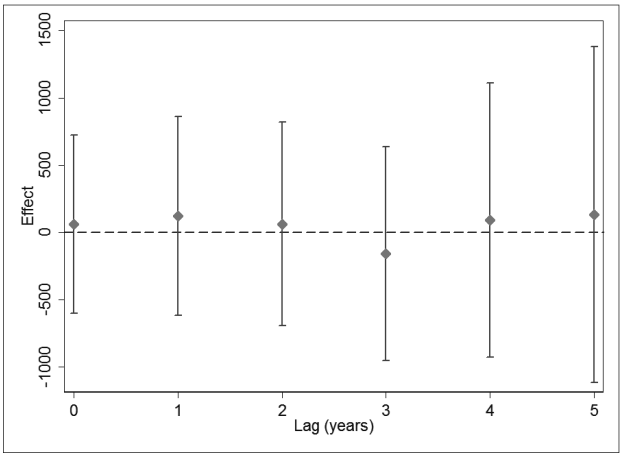


Figure 7.59: Lagged effect of introducing a tendering process on the kwhpercapita

Renewables Tax Incentives / Investment Grants

The use of tax incentives and investment grants has been more widespread. Those countries that have made use of such mechanisms have, on average, slightly lower per-GDP and per-capita levels of electricity consumption (Figures 7.60 & 7.62). The difference is very small, however, and as Figures 7.61 and 7.63 show, there is no evidence that introducing taxes or incentives in favour of renewables has any causal relationship with the energy intensity measures.

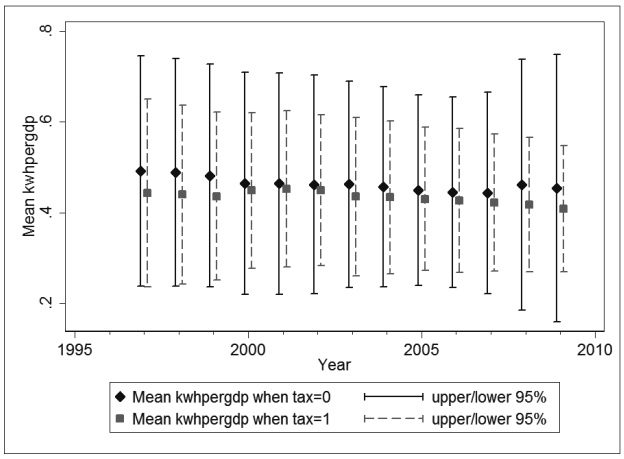


Figure 7.60: Mean kwhpergdp by tax incentive and by year

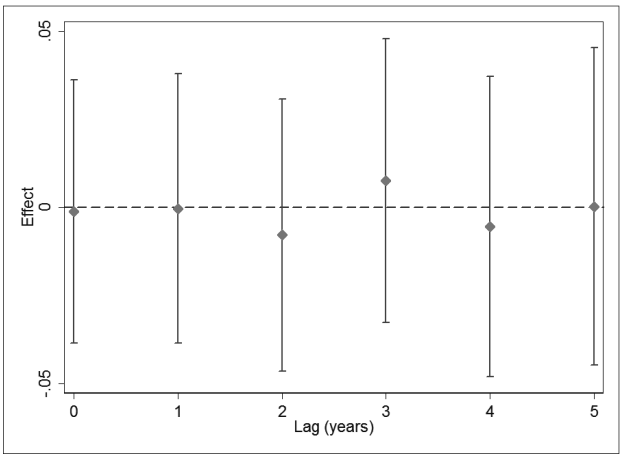


Figure 7.61: Lagged effect of introducing a renewables tax incentive on the kwhpergdp

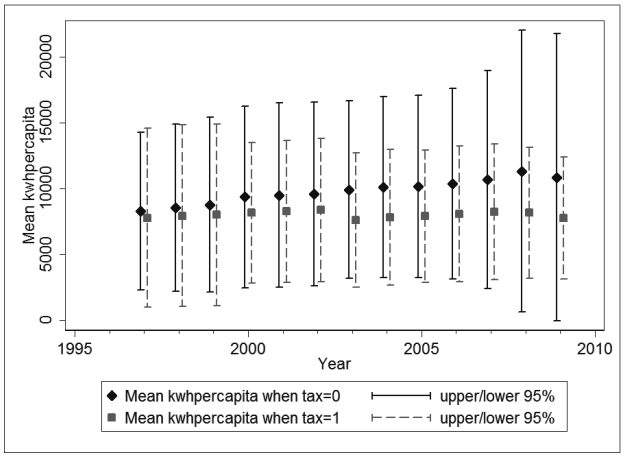


Figure 7.62: Mean kwhpercapita by tax incentive and by year

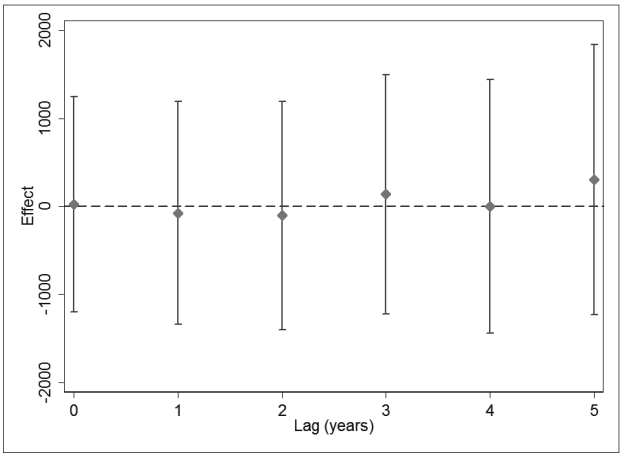


Figure 7.63: Lagged effect of introducing a renewables tax incentive on the kwhpercapita

7.2 Electricity Prices

The price of electricity relates to the resilience of society to changes in electricity availability. Physical unavailability in countries such as the UK, which have well-developed energy systems, occurs fairly infrequently. Furthermore, when it does occur it tends to be a localised event arising from a failure in the distribution network.

Of more concern to most consumers is the price of electricity. For some, there will be a price point beyond which basic energy services such as heating and lighting become unaffordable. Access to electricity, more broadly then, should account for both the physical availability and

the affordability of a resource.

Indirectly, electricity prices are also likely to be one of the causal pathways between other explanatory variables and the resilience indicators. For example, in Section 7.1.3 it was found that increasing renewables penetration was associated with a reduction in demand. One explanation for this is that increasing the proportion of renewable forms of generation pushes up electricity prices, which in turn pushes down demand.

7.2.1 Changes to electricity prices over time

Figures 7.64 and 7.65 shows the industrial and household electricity prices for the OECD countries, respectively.

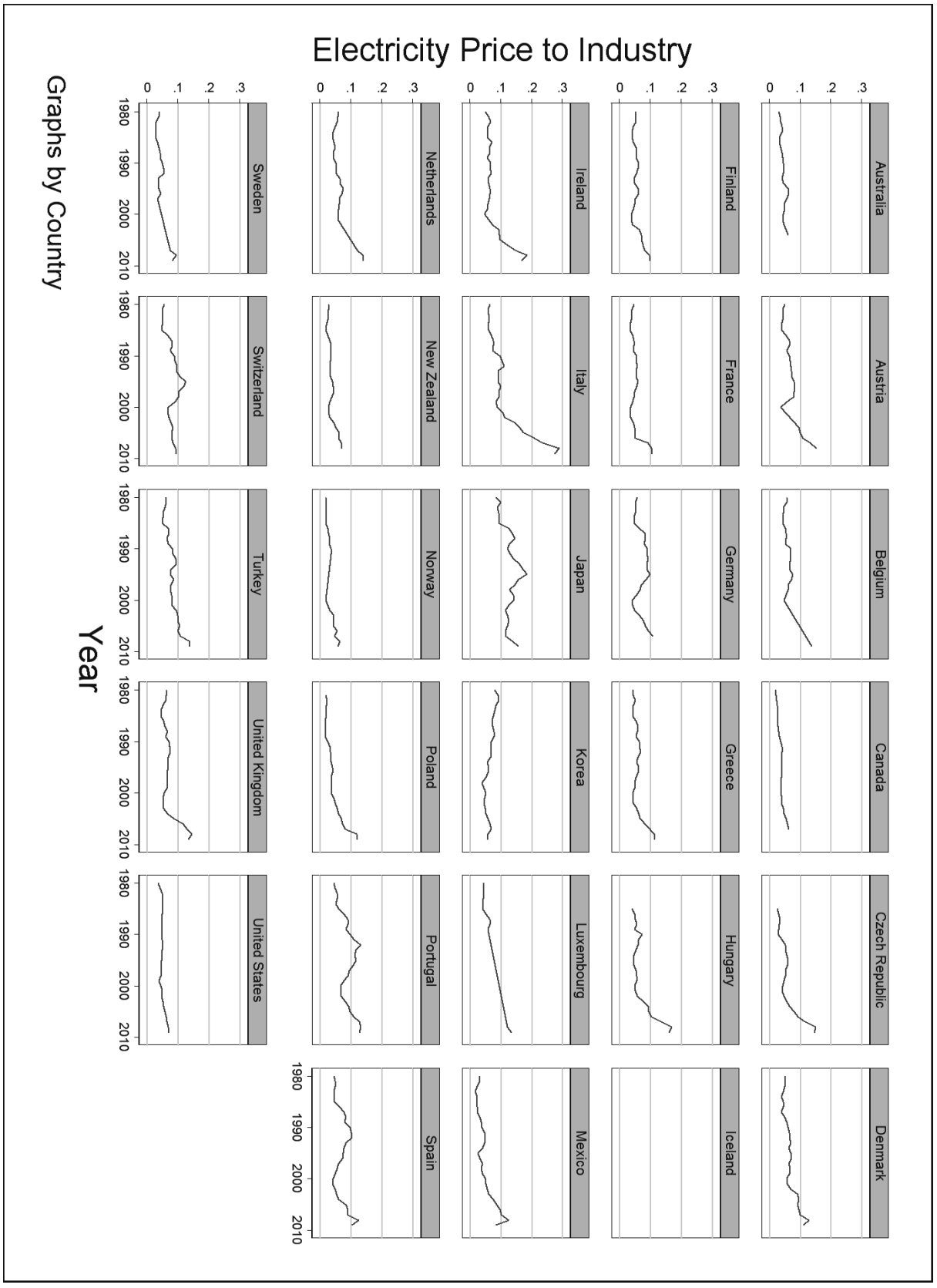


Figure 7.64: Industrial electricity price for all OECD countries

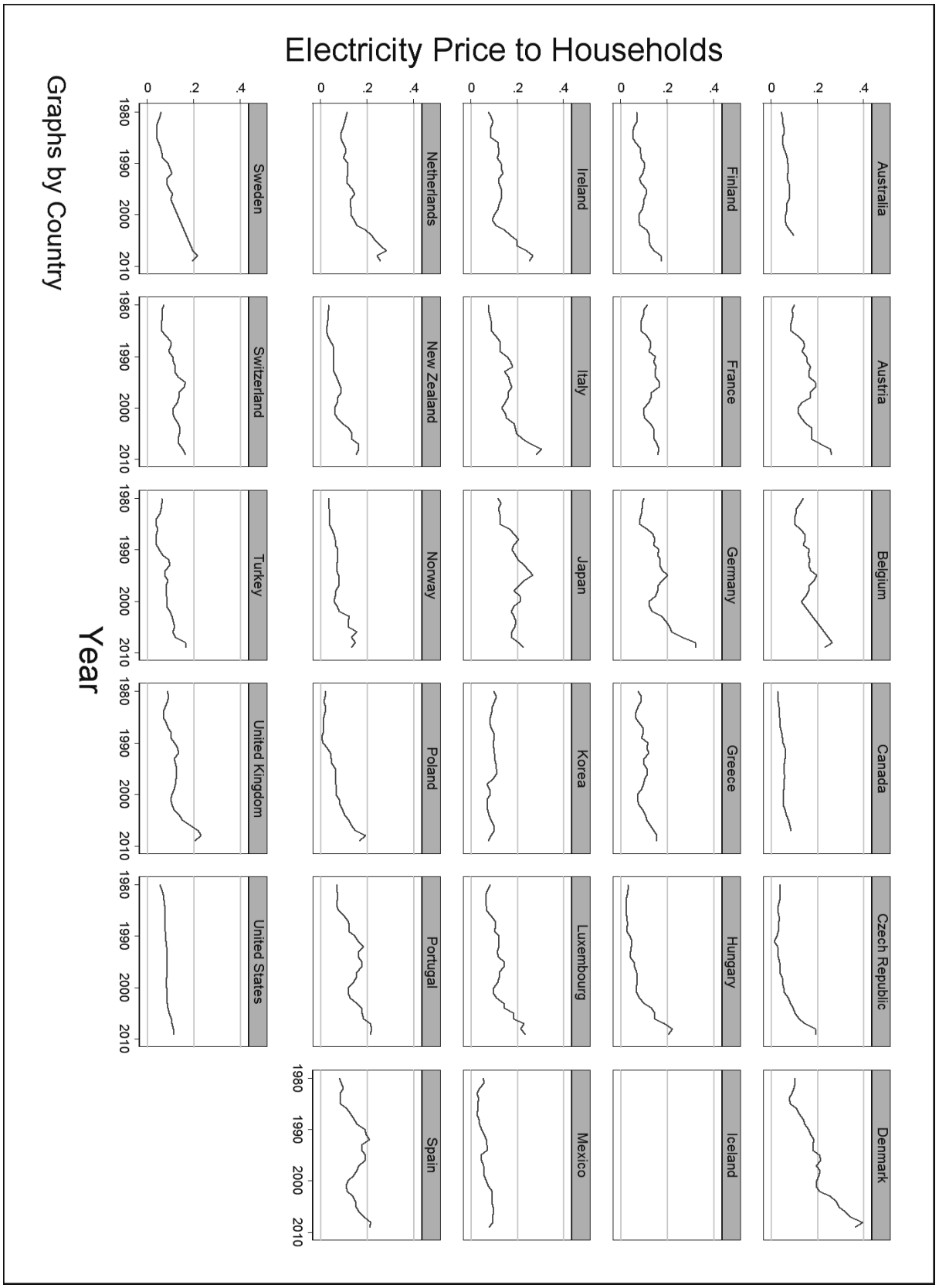


Figure 7.65: Household electricity price for all OECD countries

In nearly all countries the price of electricity for industry and households have been steadily increasing over the past two decades. The rate of increase has also gone up since the turn of the century in the vast majority of the OECD countries, including the UK (Figures 7.66 & 7.67).

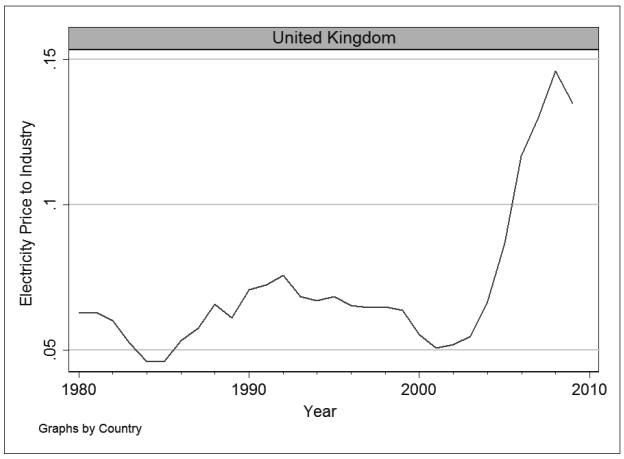


Figure 7.66: Industrial electricity price for the UK

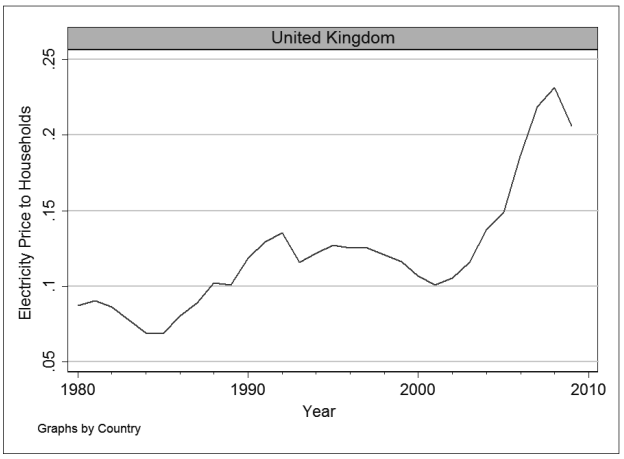


Figure 7.67: Household electricity price for the UK

7.2.2 Effect of liberalisation and privatisation on electricity prices

7.2.2.1 Effect of overall liberalisation

A scatter plot of industrial electricity prices against overall liberalisation (Figure 7.68 seems to suggest a slight positive correlation between the two. Figure 7.69 provides some weak evidence that there is a positive association here, meaning that an increase in overall liberalisation within a country pushes up industrial electricity prices within a year.

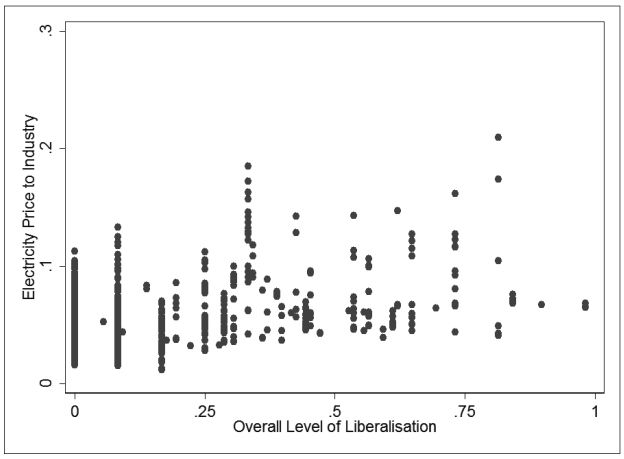


Figure 7.68: Industrial electricity price (all county-years) against overall_lib

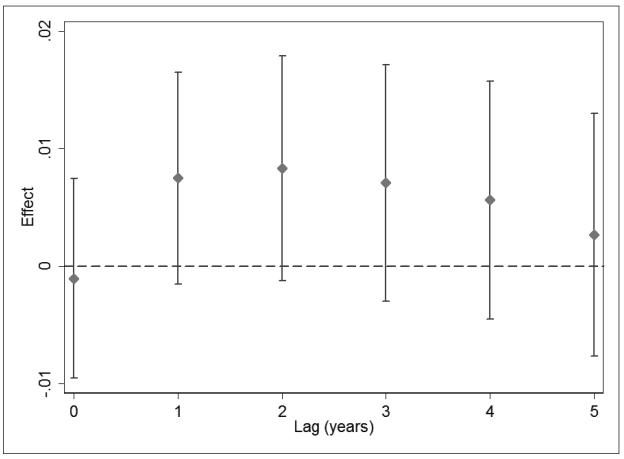


Figure 7.69: Lagged effect of overall_lib on the industrial electricity price

A similar conclusion can be drawn about the household electricity price, which shows a positive correlation in Figure 7.70 and evidence of an association in Figure 7.71. At a lag of 3 years there is a drop in effect, which appear to be in contrast with the general trend, so may be an outlier.

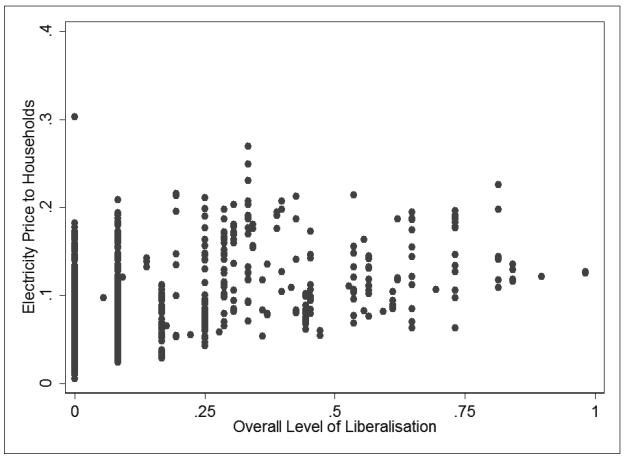


Figure 7.70: Household electricity price (all county-years) against overall_lib

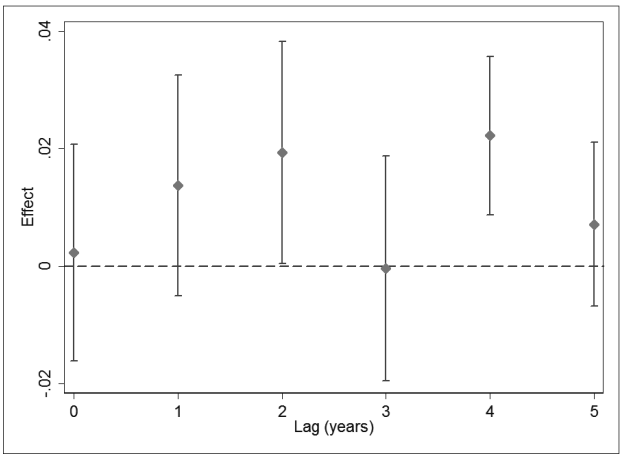


Figure 7.71: Lagged effect of overall_lib on the household electricity price

For both households and industry, the impact of increasing overall liberalisation seems to have the effect of increasing the price of electricity. This somewhat surprising conclusion runs counter to one of the precepts of the privatisation and liberalisation program: that a combination of private ownership and competitive markets will increase the efficiency of electricity generation, resulting in lower prices to customers.

The following sections investigate the components of the **overall_lib** indicator to further under-

stand this behaviour.

7.2.2.2 Effect of the creation of a liberalised pool on electricity prices

Figure 7.72 describes the industrial electricity prices in countries with and without a liberalised electricity trading pool. From 1990 to 1996 the two groups are very similar. From 1996 to 2003 the price of electricity to industry was cheaper on average in 'liberalised' systems, fitting with the theory that competition leads to price reductions. From 2004 onwards, however, the relationship had switched, and the 'liberalised' systems had on average more expensive electricity.

This behaviour is also reflected in the household electricity prices. Liberalised systems had cheaper prices in the early years of liberalisation, but by 1997 this difference had gone, and from 2001 onwards liberalised systems's household electricity had become more expensive. This difference increased further as time progressed.

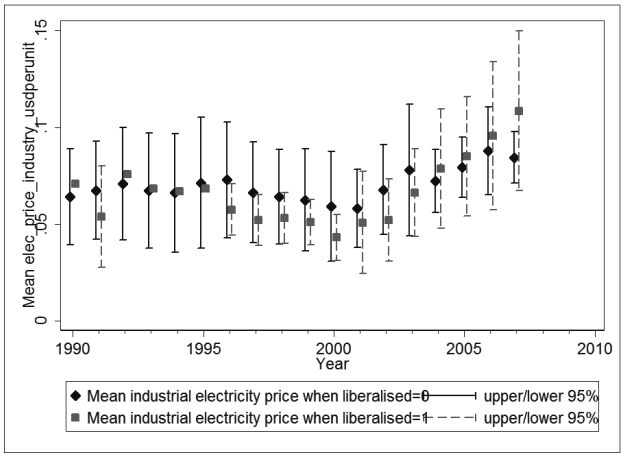


Figure 7.72: Mean industrial electricity price by liberalised and by year

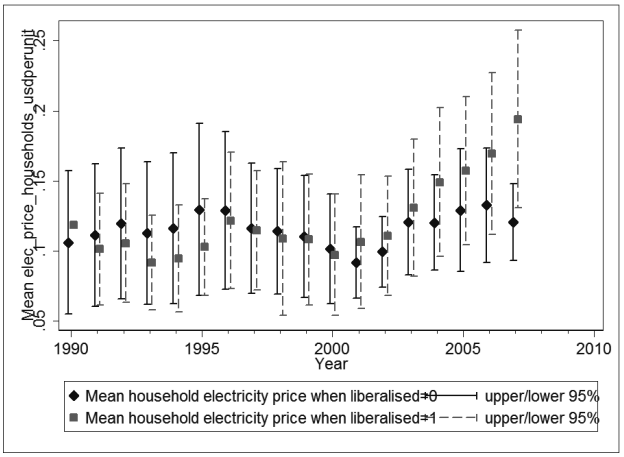


Figure 7.73: Mean household electricity price by whether liberalised and by year

However, the lagged effects shown by the mixed modelling analysis (Figure 7.74 & 7.75) do not show good evidence of an association, and certainly not as strong as was seen for the **overall_lib** indicator. This would suggest that whilst the presence of a liberalised pool might be a good predictor of a country having above-average electricity prices, this does not mean that a given country's electricity price would be expected to rise as a result of introducing its own trading pool.

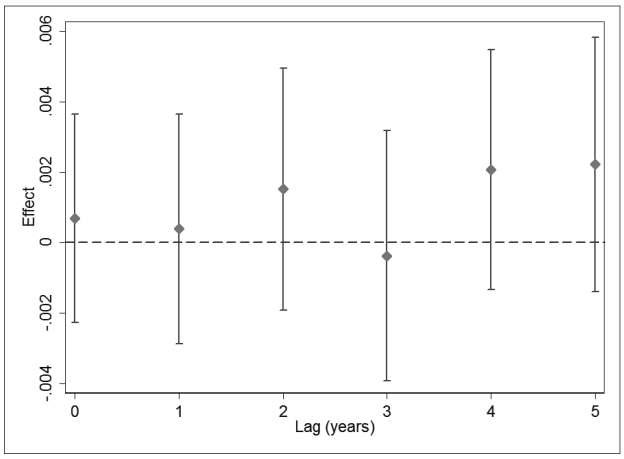


Figure 7.74: Lagged effect of introducing a liberalised pool industrial electricity prices

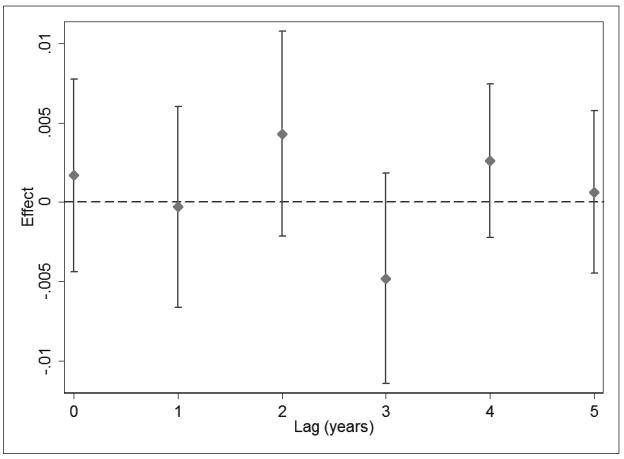


Figure 7.75: Lagged effect of introducing a liberalised pool on household electricity prices

7.2.2.3 Effect of privatisation on electricity prices

Figures 7.76 and 7.77 show a scatter plot of electricity prices against the degree of privatisation. On this snapshot view, which plots a value for each country-year, neither industrial nor household electricity prices seem to be related to the degree of privatisation.

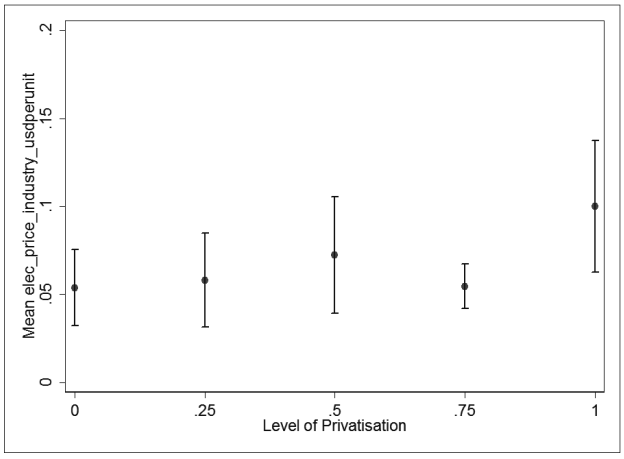


Figure 7.76: Industrial electricity price (all county-years) against the degree of private ownership

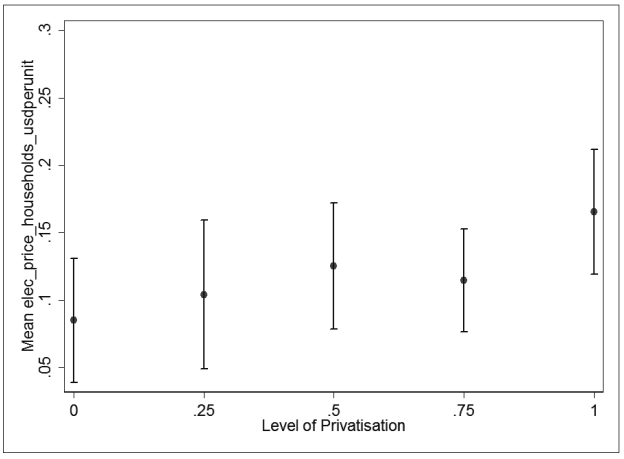


Figure 7.77: Household electricity price (all county-years) against the degree of private ownership

The mixed modelling analysis broadly supports this conclusion (Figures 7.78 & 7.79), showing no effect of privatisation on household electricity prices, and only a tentative positive association between privatisation and industrial electricity prices between 1 and 3 years after a change in the ownership structure.

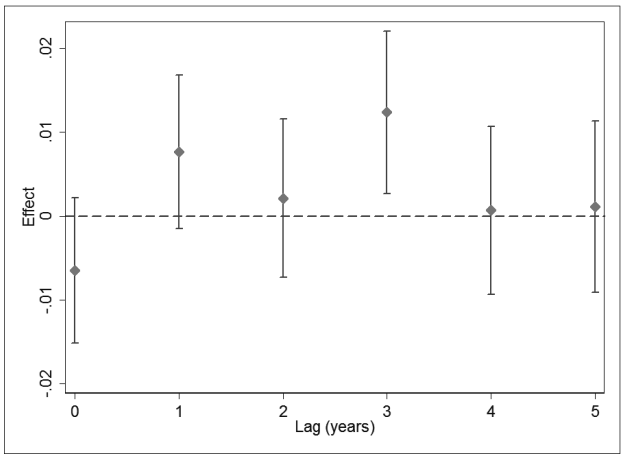


Figure 7.78: Lagged effect of increasing private ownership on industrial electricity prices

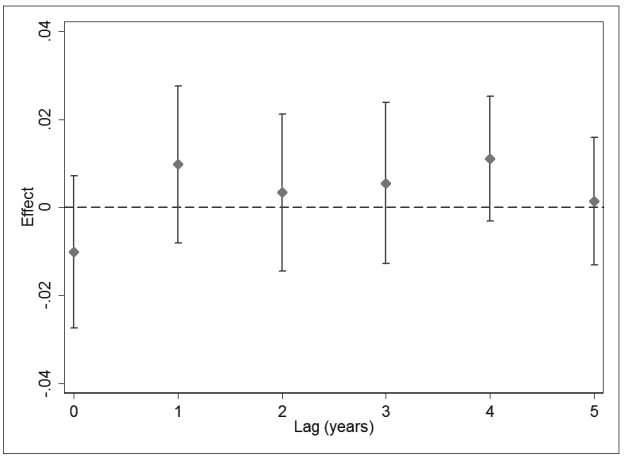


Figure 7.79: Lagged effect of increasing private ownership on household electricity prices

Using the binary **privatised** indicator, the by-year differences in electricity prices between privatised and nationalised systems can be seen (Figures 7.80 & 7.81). For both industrial and household electricity prices, the early-privatising countries had, on average, higher electricity prices. For nearly all years observed, however, the two groups' prices have been converging, meaning that the average electricity price has been increasing more rapidly in the nationalised group than the privatised group.

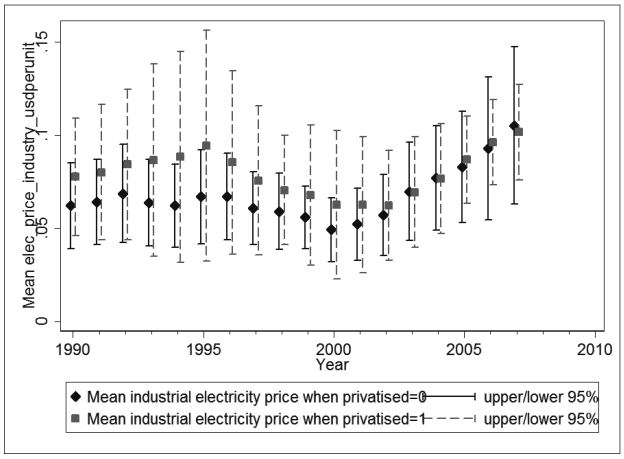


Figure 7.80: Mean industrial electricity price by whether privatised and by year

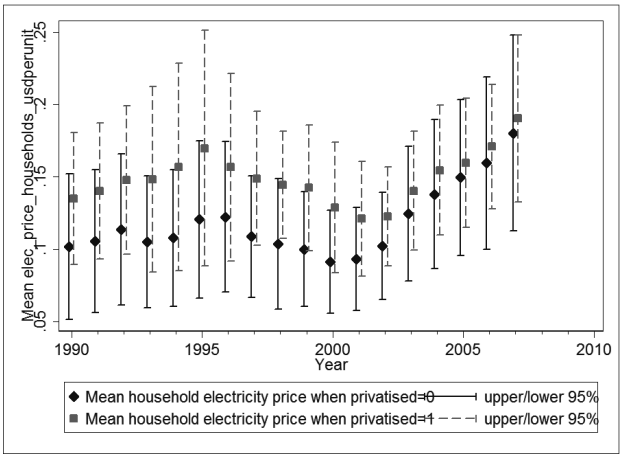


Figure 7.81: Mean household electricity price by whether privatised and by year

Figures 7.82 and 7.83 show the effect of the **privatised** variable. The effect is slightly negative, but is very small and is well within the confidence intervals. The conclusion here, then, is that the convergence seen in Figures 7.80 and 7.81 arise because the late-privatising countries have

lower prices than the early-privatising countries, thereby deflating the average of the 'privatised' set and inflating the average of those countries that remain predominantly nationalised. There is little evidence, then, that privatising the system increases electricity prices within that system.

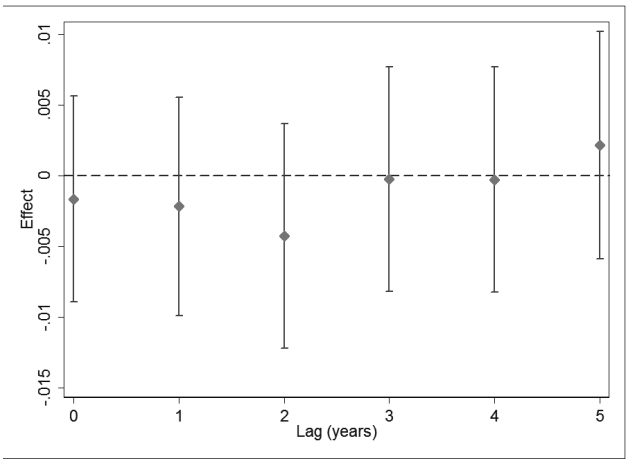


Figure 7.82: Lagged effect of **privatised** on industrial electricity prices

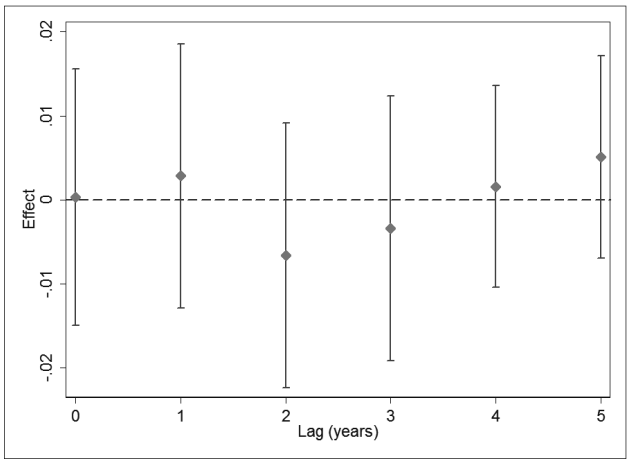


Figure 7.83: Lagged effect of **privatised** on household electricity prices

7.2.2.4 Vertical Integration

This section concerns the relationship between vertical integration in the electricity sector and the price of electricity. The first indicator describes the degree of separation specifically between the transmission and the generation parts of the industry. Figures 7.84 and 7.86 show this relationship over all country-years, and the effect of increasing this level of separation is described in Figures 7.85 and 7.87, respectively. The price of electricity seems to be largely unaffected by separating these two sectors of the industry.

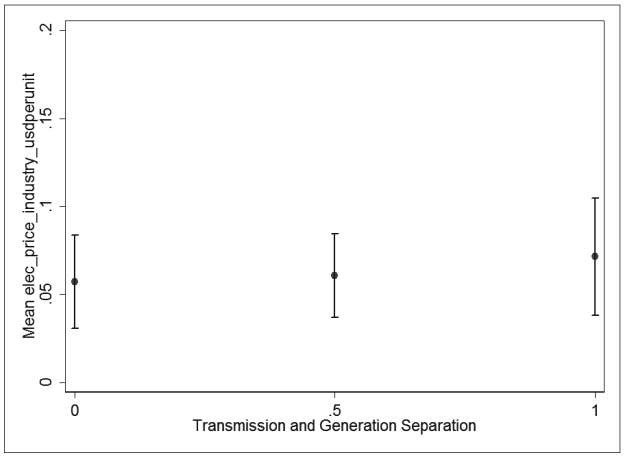


Figure 7.84: Industrial electricity price (all county-years) against the degree of transmission-generation separation

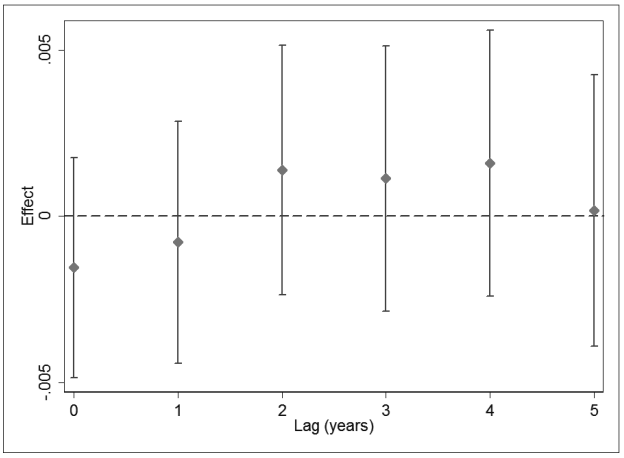


Figure 7.85: Lagged effect of decreasing transmission-generation separation on industrial electricity prices

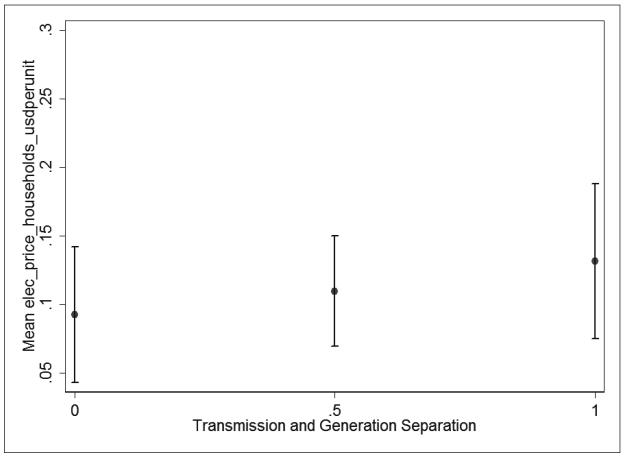


Figure 7.86: Household electricity price (all county-years) against the degree of transmission-generation separation

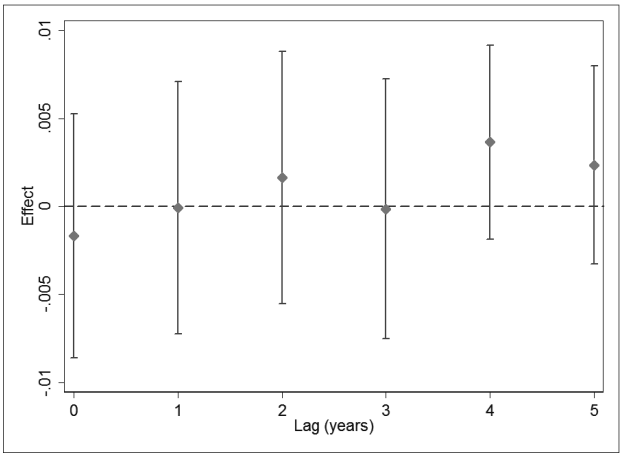


Figure 7.87: Lagged effect of decreasing transmission-generation separation on household electricity prices

The binary variable **transgen_unbundling** combines systems that have completely unbundled with those that have accounting separation, comparing them with systems that are fully integrated in this respect. Figures 7.88 and 7.90 shows the prices in these groups over time. There is little difference between the two groups, and this finding is confirmed by Figures 7.89 and 7.91, which show no association between separating transmission from generation and the price of electricity to consumers.

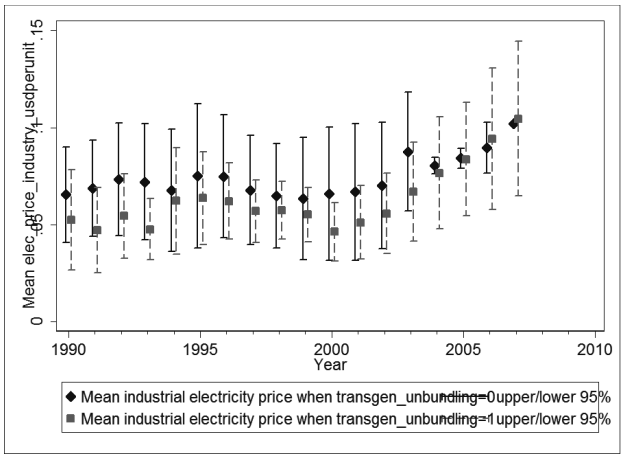


Figure 7.88: Mean industrial electricity price by whether transmission and generation have at least accounting separation and by year

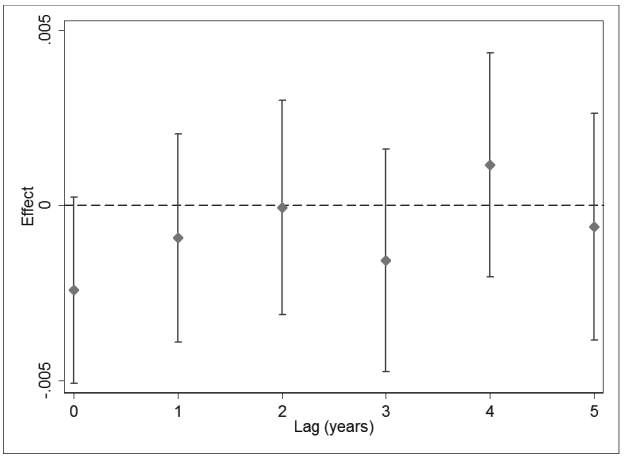


Figure 7.89: Lagged effect of binary trans-gen unbundling on industrial electricity prices

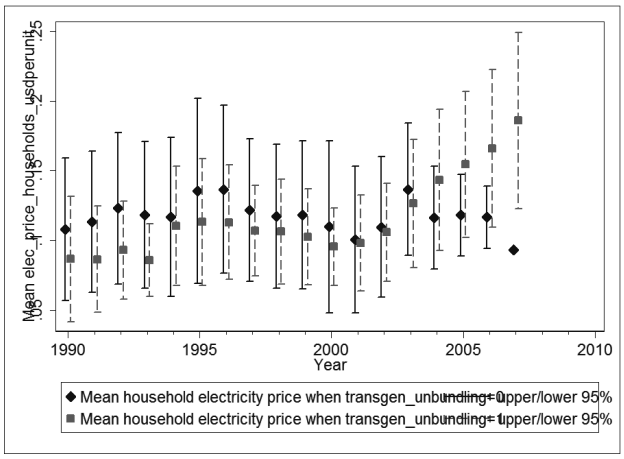


Figure 7.90: Mean household electricity price by whether transmission and generation have at least accounting separation and by year

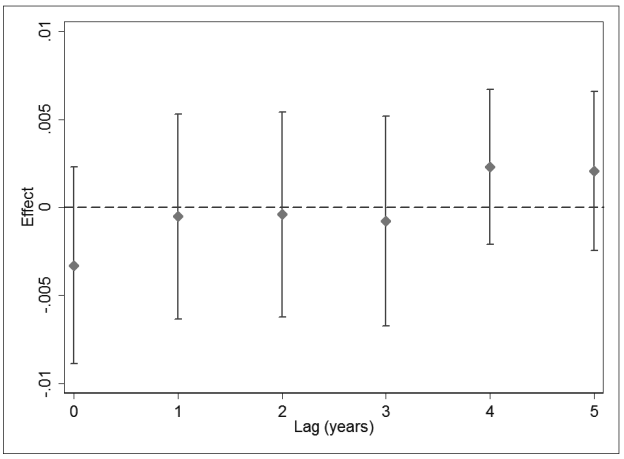


Figure 7.91: Lagged effect of binary trans-gen unbundling on household electricity prices

If separating transmission from generation has little discernable effect on electricity prices, the same cannot be said for the effect of overall vertical unbundling. Figures 7.92 and 7.94 suggest a positive relationship between overall vertical separation and increasing electricity prices,

especially for households. Figures 7.93 and 7.97 both suggest that increasing overall vertical separation is associated with increasing electricity prices. The effect, however, does not appear to be large, amounting to no more than a 5% increase.

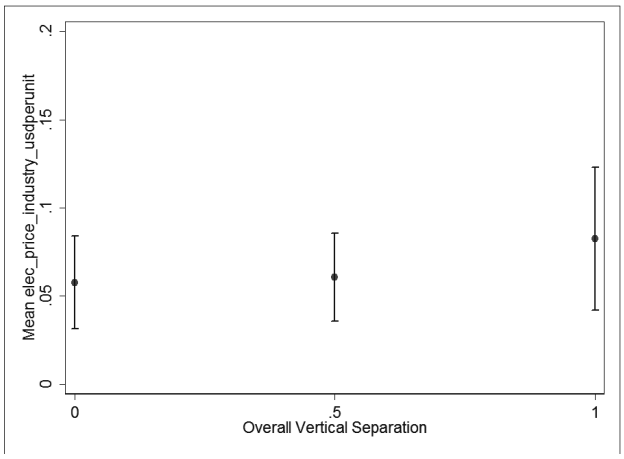


Figure 7.92: Industrial electricity price (all county-years) against overall vertical separation

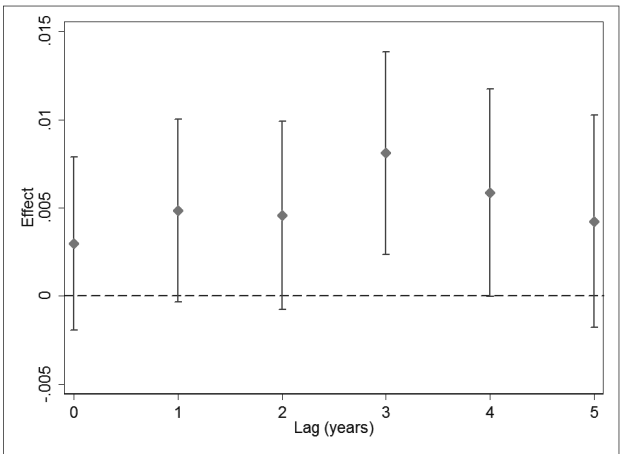


Figure 7.93: Lagged effect of overall vertical separation on industrial electricity prices

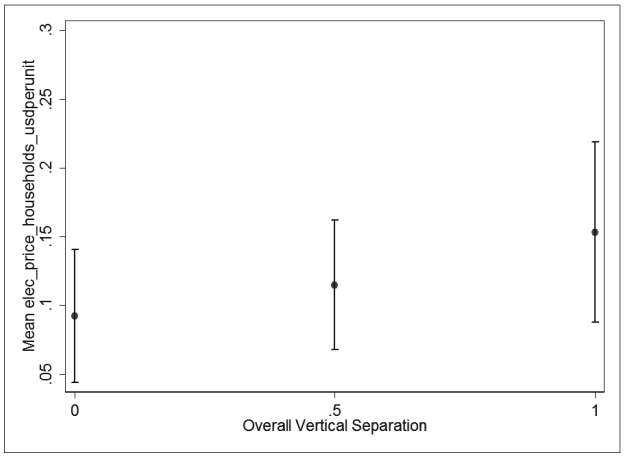


Figure 7.94: Household electricity price (all county-years) against overall vertical separation

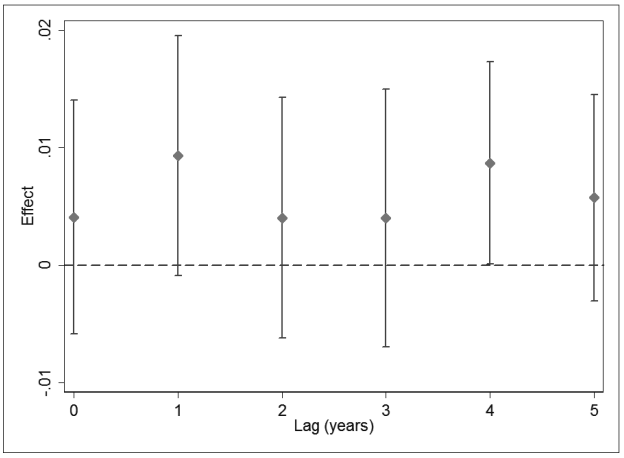


Figure 7.95: Lagged effect of overall vertical separation on household electricity prices

To put this in context, electricity price trends are distinguished by the binary **overall_unbundling** variable shown in Figures 7.96 and 7.98. Industrial electricity prices are largely comparable between the two groups, whereas for household prices, the increase is more marked for vertically unbundled systems. Again, the effect shown in Figures 7.97 and 7.99 is positive and significant at some lags, but is still only a small effect with respect to the overall difference seen in the time-series plot.

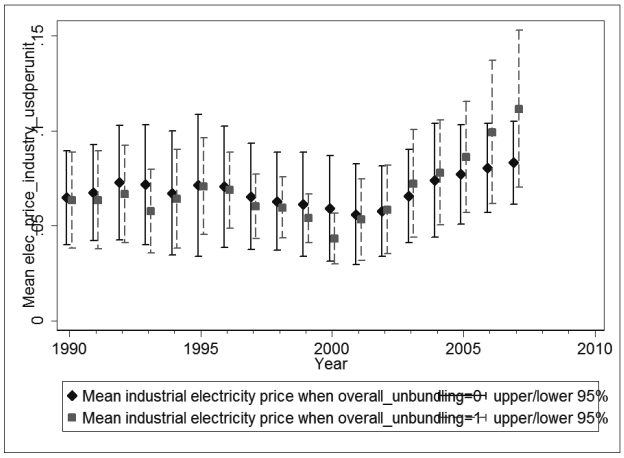


Figure 7.96: Mean industrial electricity price by year grouped into vertically integrated and unbundled or mixed

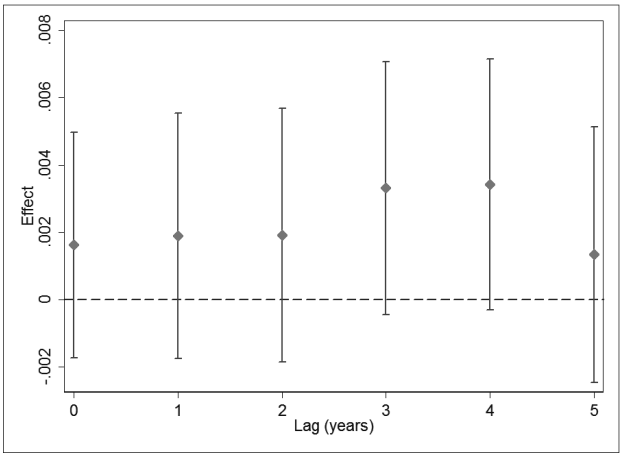


Figure 7.97: Lagged effect of binary overall unbundling on industrial electricity prices

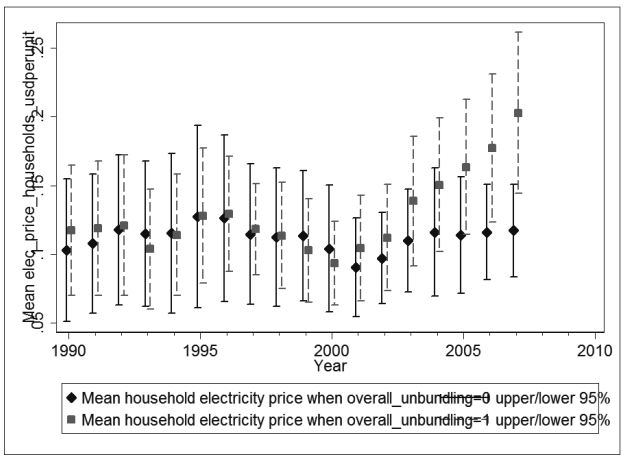


Figure 7.98: Mean household electricity price by year grouped into vertically integrated and unbundled or mixed

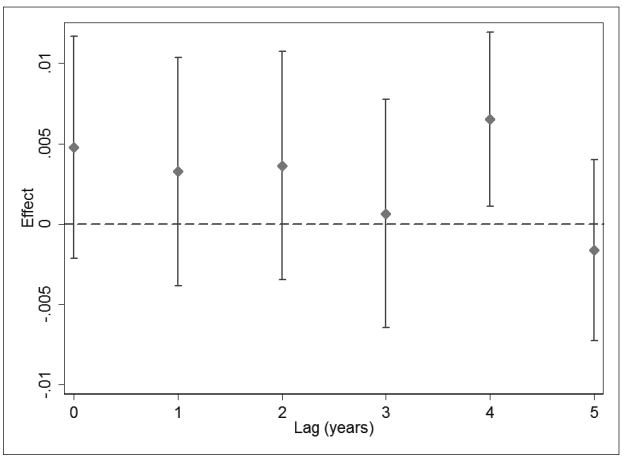


Figure 7.99: Lagged effect of binary overall unbundling on household electricity prices

From this, it can be said that separating transmission from generation has little, if any, effect on electricity prices, whereas there is a small effect if overall vertical integration is reduced. Assuming this effect is real, this would suggest that the real effect lies in the separation of transmission of electricity from its distribution and/or supply, and that the result of that separation is (to a small degree) to increase electricity prices.

7.2.3 Effect of renewable generation and associated policies on electricity prices

This section assesses the relationship between the deployment of renewable generation and the associated renewables policies on gas and electricity prices.

7.2.3.1 Installed capacity of new renewables

A scatter plot showing the relationship between the proportion of new renewables (wind, solar and marine renewables) and the price of industrial and household electricity is shown in Figure 7.100 and Figure 7.102, respectively. Both show a positive correlation, but it is particularly marked in the case of household electricity prices.

Those countries with high proportions of renewables seem to have high electricity prices. As before, it is possible that this is a between country effect – that a country's characteristics give it a propensity to have both a large proportion of renewables and high electricity prices. As Figures 7.101 and 7.103 suggest, however, this is a real association – that increasing the proportion of renewables is associated with an increase in the price of electricity.

Table 7.1: Effect of increasing the proportion of renewable generation on the price of household electricity

lag	effect	se	pvalues
0	0.283	0.091	0.002
1	0.337	0.091	0.000
2	0.346	0.099	0.000
3	0.457	0.104	0.000
4	0.545	0.115	0.000
5	0.520	0.121	0.000

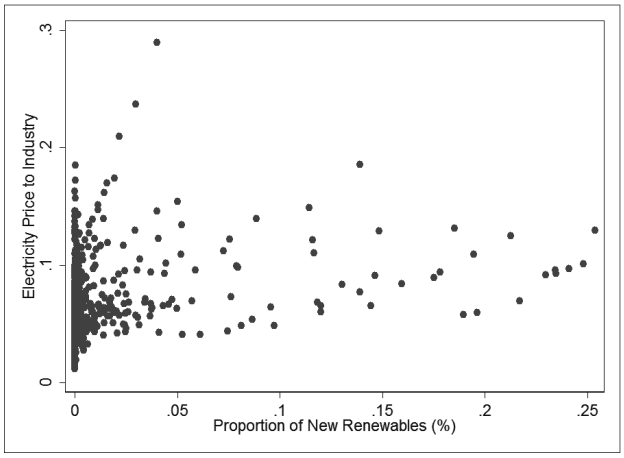


Figure 7.100: Industrial electricity price (all county-years) against the proportion of new renewables on the system

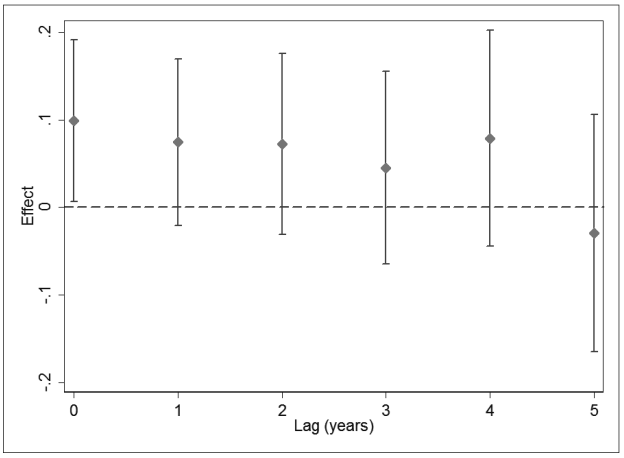


Figure 7.101: Lagged effect of increasing the new renewable proportion on the industrial electricity price

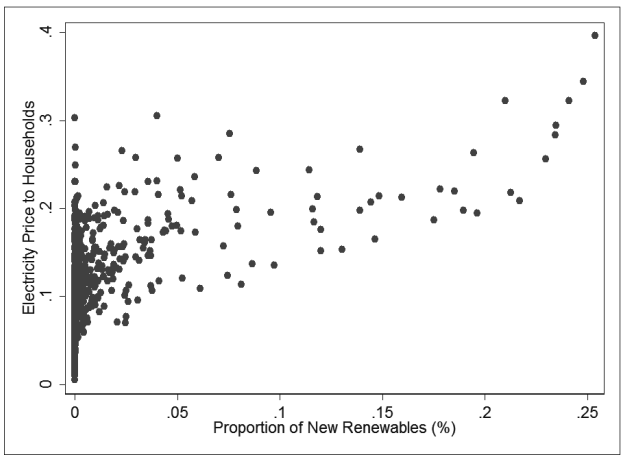


Figure 7.102: Household electricity price (all county-years) against the proportion of new renewables on the system

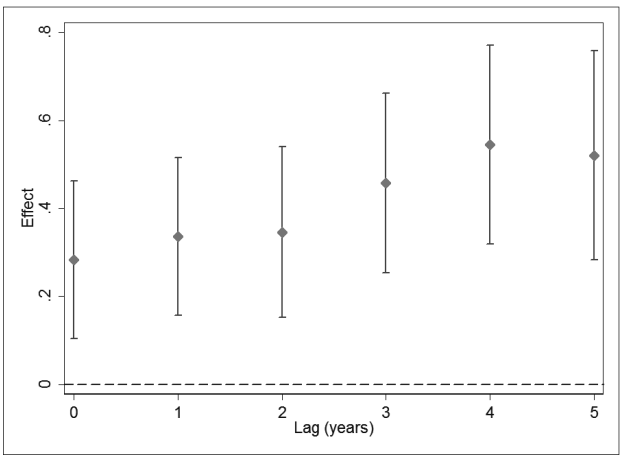


Figure 7.103: Lagged effect of increasing the new renewable proportion on the household electricity price

The underlying values from Figure 7.103 are shown in Table 7.1. Increasing the proportion of new renewables in a given year has the effect of increasing the price of household electricity by 0.3 cents per kWh in the first year. The average electric price in the sample is 11 cents per kWh. Using this figure, a 1% increase in renewable generation increases the cost of household electricity by around 3%. The peak effect of that increase, however, comes after 4 years, by which time the effect of that 1% increase would have been, in total, to increase the price by 0.5c/kWh, or 5%.

7.2.3.2 Renewable electricity support schemes

The following sections investigate whether the effect that renewable generation has on electricity prices differs depending on the nature of the support mechanism in place.

Any renewable support scheme

Figures 7.104 and 7.105 show that overall, countries with a renewable support mechanism tend to have higher electricity prices than those that do not.

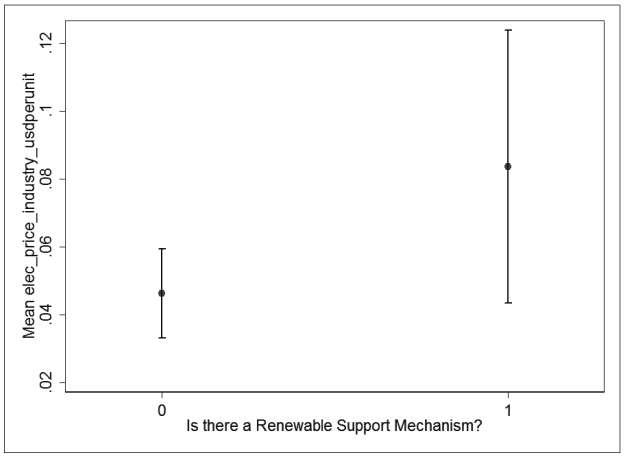


Figure 7.104: Mean industrial electricity price by renewable support

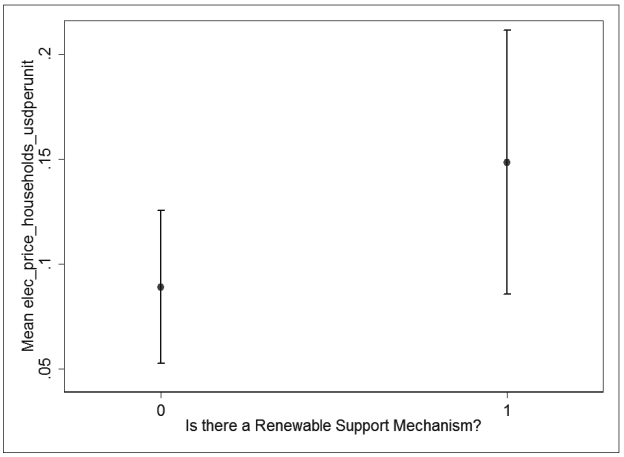


Figure 7.105: Mean household electricity price by renewable support

Figures 7.106 and 7.107 show how this behaviour changes over time. In both cases, countries with renewables support mechanisms have higher prices in all years. In the case of industrial electricity prices, this disparity appears to increase over time, whereas for household electricity prices the magnitude of the difference varies over time.

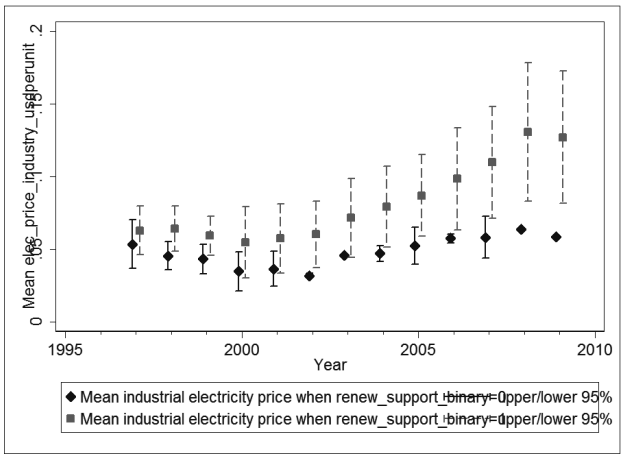


Figure 7.106: Mean industrial electricity price by renewable support and by year

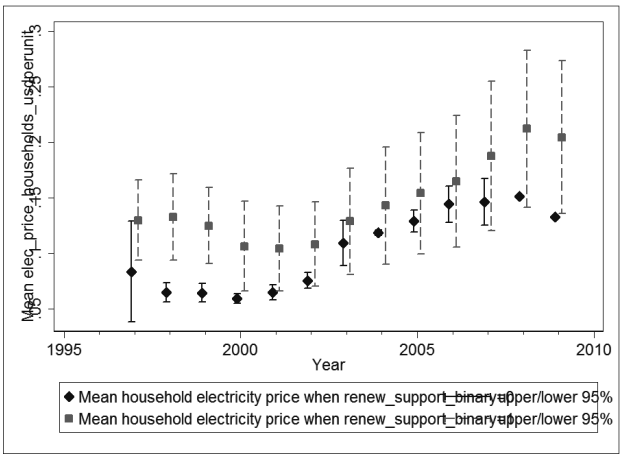


Figure 7.107: Mean household electricity price by renewable support and by year

The observed effect is shown in Figures 7.108 and 7.109. Whereas the proportion of new renewables was directly associated with price increases, this does not appear to be the case for the renewables policies designed to bring about the renewables deployment. There is some suggestion that five years after the introduction of a renewables support mechanism there is some effect. The industrial electricity price at a lag of 5 years, for example, shows an increase of 1 cent per kWh – an increase of around 9%.

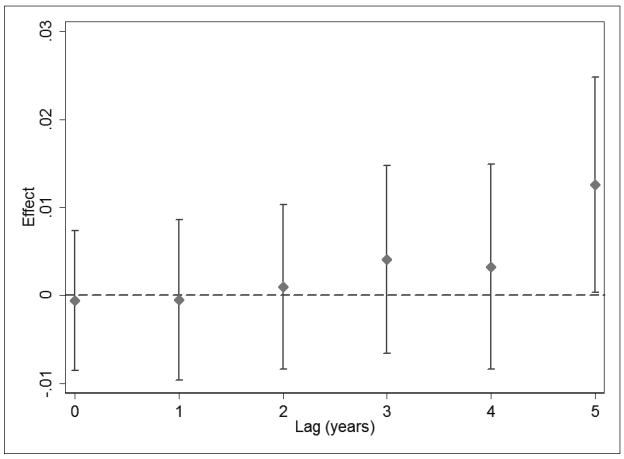


Figure 7.108: Lagged effect of introducing renewables support mechanisms on the industrial electricity price

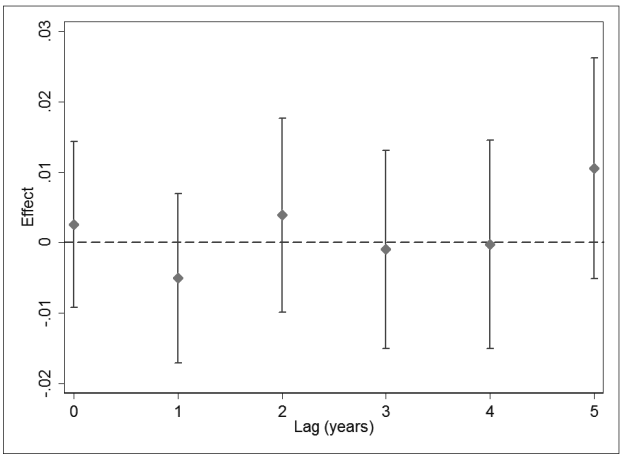


Figure 7.109: Lagged effect of introducing renewables support mechanisms on the household electricity price

In theory, extending the number of lags should be able to test whether this is a real effect. Figures 7.110 and 7.111 show the effect of introducing a renewables support mechanism for lags up to 10 years. Drawing conclusions about these longer-term effects, however, requires that the

renewables policies be in place for a sufficient length of time. At present this is not the case, but there is tentative evidence here that the effect first seen at the five-year lag continues.

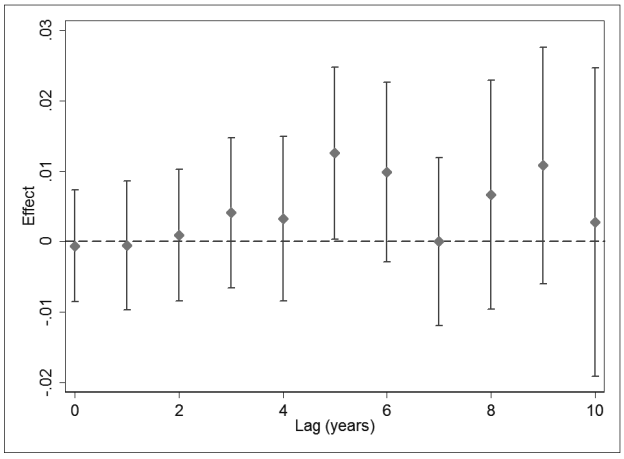


Figure 7.110: Lagged effect of introducing renewables support mechanisms on the industrial electricity price

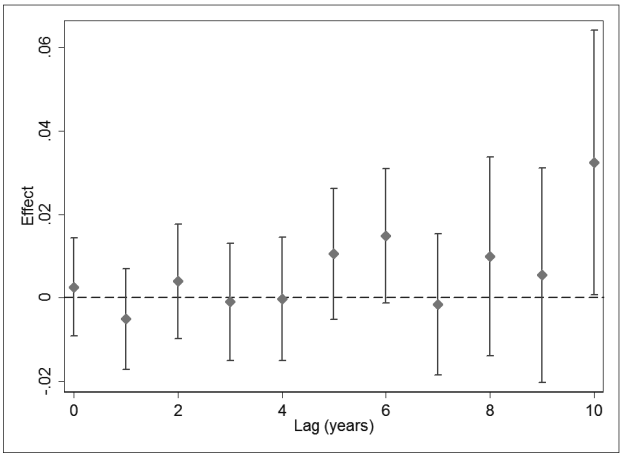


Figure 7.111: Lagged effect of introducing renewables support mechanisms on the household electricity price

Feed-in Tariff

The difference in industrial electricity prices between countries with a FIT and those without is very small for most years, although in the last three years considered this gap appears to have grown (Figure 7.112. The difference is more marked for household electricity prices, where from 2003 onwards FIT-operating countries have, on average, higher and more rapidly increasing electricity prices.

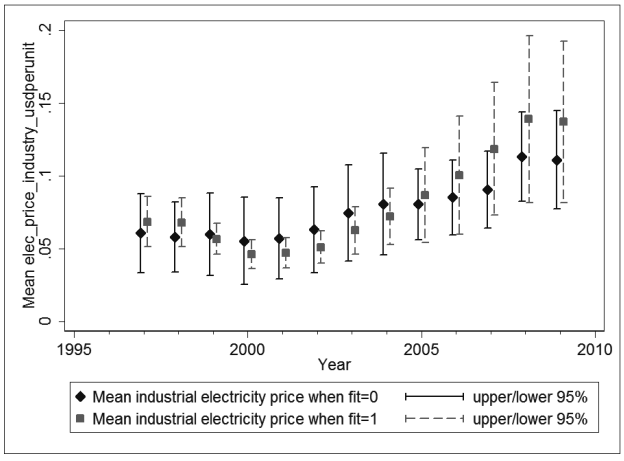


Figure 7.112: Mean industrial electricity price by FIT and by year

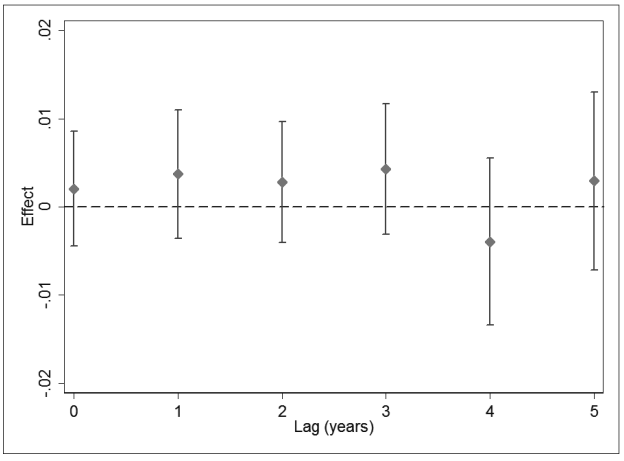


Figure 7.113: Lagged effect of introducing a feed-in tariff on the industrial electricity price

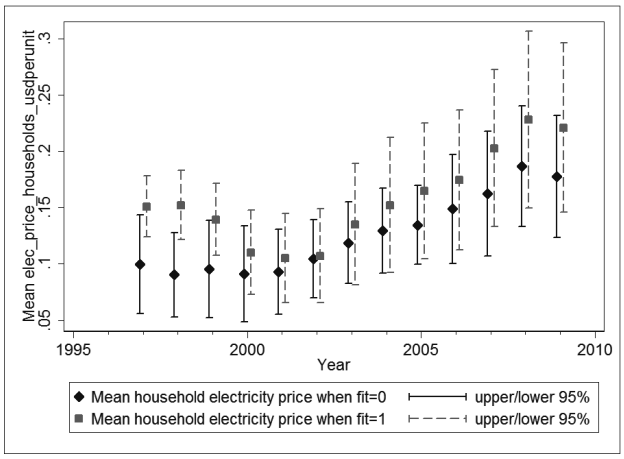


Figure 7.114: Mean household electricity price by FIT and by year

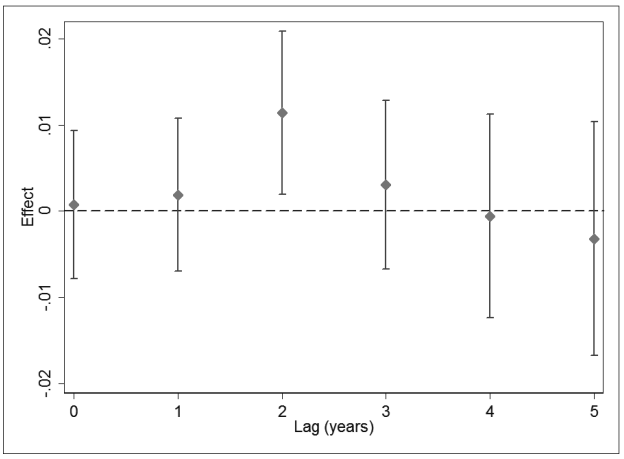


Figure 7.115: Lagged effect of introducing a feed-in tariff on the household electricity price

The results of the mixed effects model shown in Figures 7.113 and 7.115, however, do not reveal a strong association. The association with industrial electricity prices is positive, but not significant, whereas the effect on household electricity prices is positive and significant at a lag of two years, but is not reflected in the other lags. If there is a positive association between FIT-introduction and electricity prices, therefore, it is small in comparison with the underlying country characteristics that lead both to FIT-introduction and high electricity prices.

Quota / Tradeable Green Certificate / Renewables Obligation

Industrial prices are, on average higher in countries with TGCs (Figure 7.116). The mixed effect model provides some weak evidence that there is an association between TGCs and industrial electricity prices, showing a significant effect at a lag of four years (Figure 7.116). This does not appear to be an outlier, as it is reflected to a lesser extend at the other lag levels.

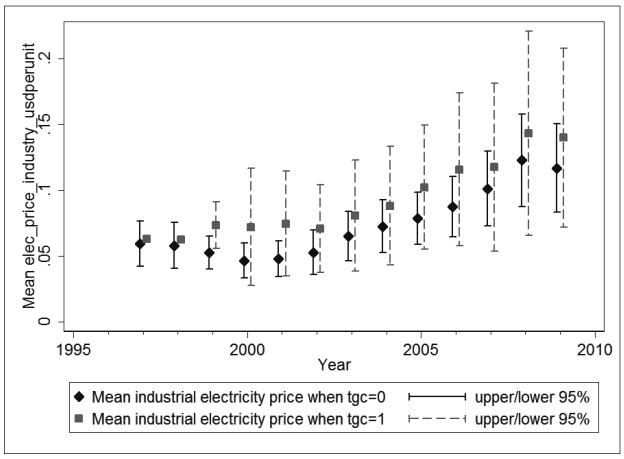


Figure 7.116: Mean industrial electricity price by TGC and by year

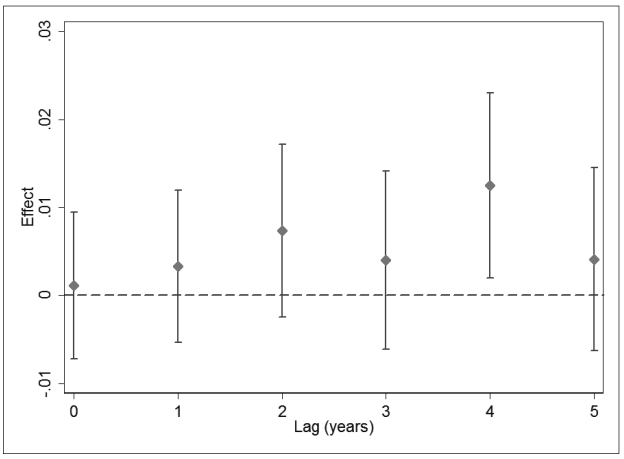


Figure 7.117: Lagged effect of introducing tradeable green certificates (TGC) on the industrial electricity price

There is no real difference for household electricity prices between the two groups when viewed on a year-by-year basis (Figure 7.118). The association shown in Figure 7.119 confirms that there is no discernable relationship between introducing TGCs and the price of electricity to domestic consumers.

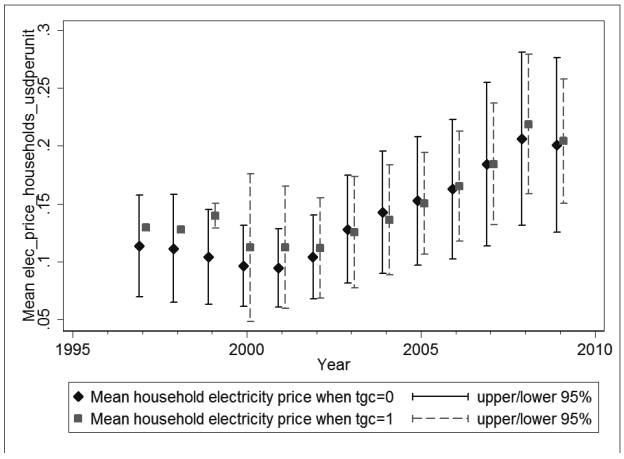


Figure 7.118: Mean household electricity price by TGC and by year

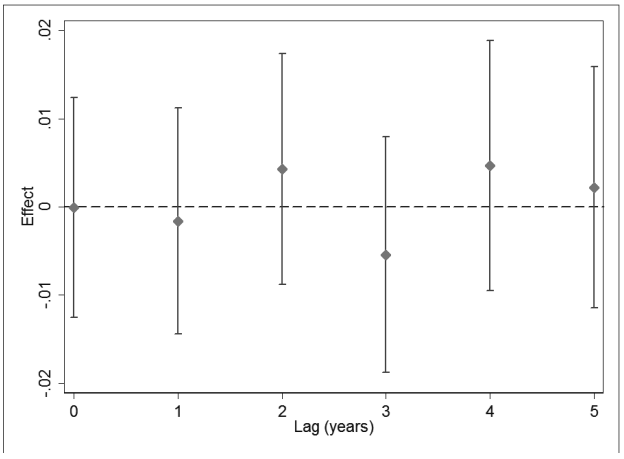


Figure 7.119: Lagged effect of introducing tradeable green certificates (TGC) on the household electricity price

Tendering Process

Systems operating with Feed-in Tariffs or Tradeable Green Certificate have been seen to have higher electricity prices than average, and there is some evidence that, in some cases, introducing

these mechanisms increases the price of electricity to consumers.

By contrast, where tendering schemes for new renewables are in place, the electricity price seems to be below average for both industrial and domestic customers in most years (Figures 7.120 & 7.122).

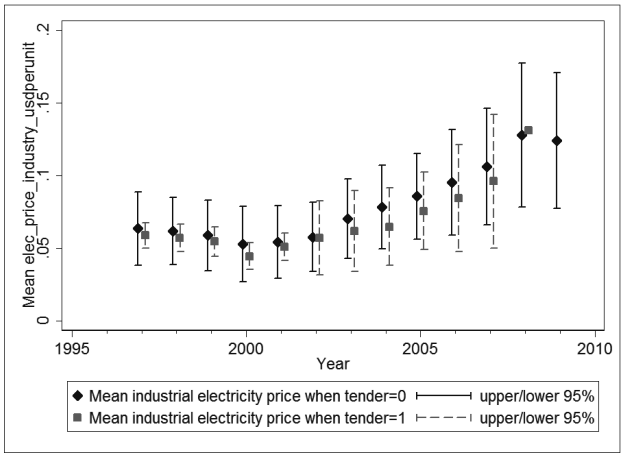


Figure 7.120: Mean industrial electricity price by tendering process and by year

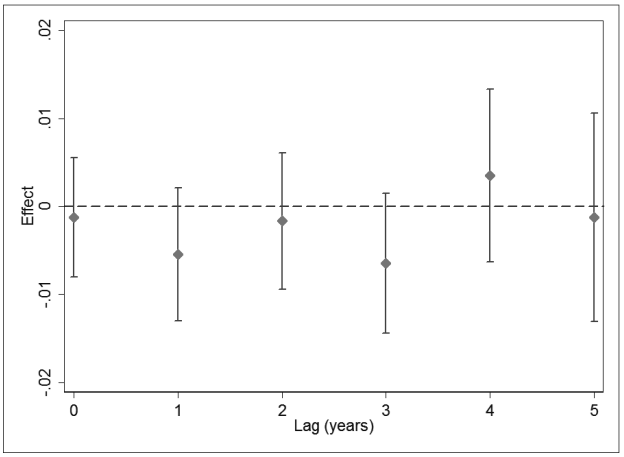


Figure 7.121: Lagged effect of introducing a tendering process on the industrial electricity price

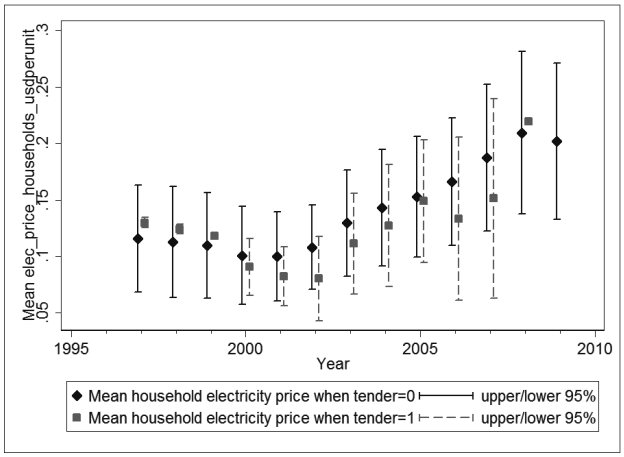


Figure 7.122: Mean household electricity price by tendering process and by year

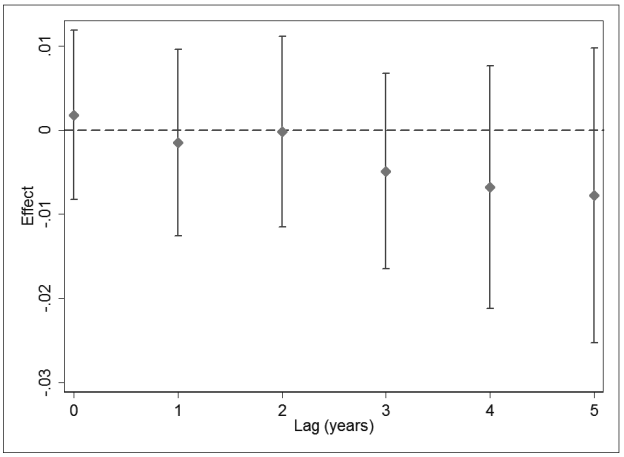


Figure 7.123: Lagged effect of introducing a tendering process on the household electricity price

The evidence that introducing a tendering scheme is weaker, but there is some suggestion in Figures 7.121 and 7.123 that the association is negative, meaning that introducing a tendering system tends to reduce the electricity price.

Renewables Tax Incentives / Investment Grants

This depressive effect on electricity prices is also seen where tax incentives or investment grants have been used to encourage renewables deployment. Industrial electricity prices are slightly lower under such schemes, particularly in later years (Figure 7.124), but it is in household electricity prices that the difference is most evident (Figure 7.127).

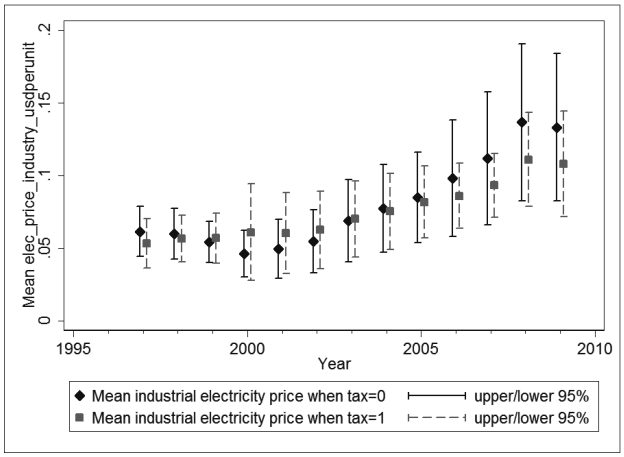


Figure 7.124: Mean industrial electricity price by tax incentive and by year

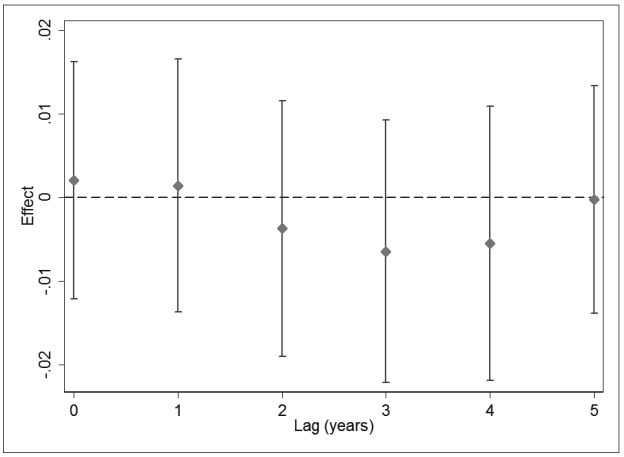


Figure 7.125: Lagged effect of introducing a renewables tax incentive on the industrial electricity price

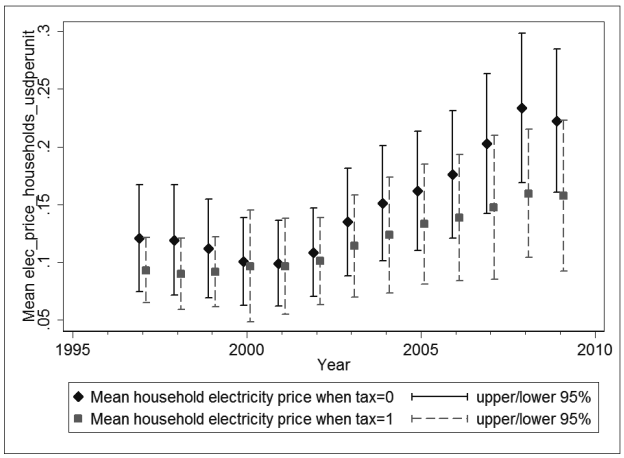


Figure 7.126: Mean household electricity price by tax incentive and by year

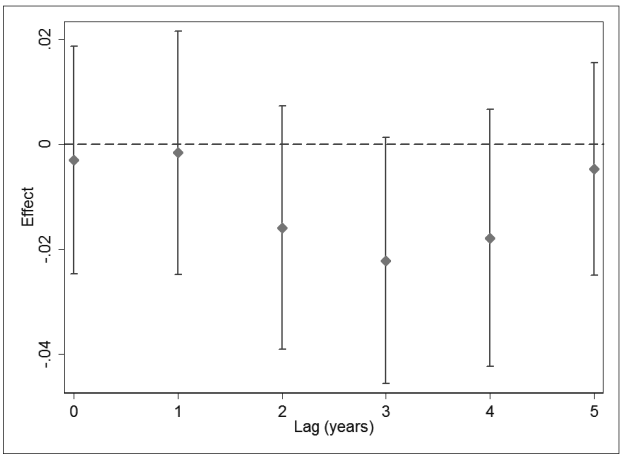


Figure 7.127: Lagged effect of introducing a renewables tax incentive on the household electricity price

The associations shown in Figures 7.125 and 7.127 do not reach the level of significance, but the overall picture is indicative of a slight reduction in electricity prices, particularly for households, between two and four years after these schemes are introduced.

FITs & TGCs vs. Tenders, Tax breaks and Grants

By the standards of evidence required for a full longitudinal study, the evidence of renewables incentive schemes is currently very limited. What the above analyses suggest, though, is that there is some tentative evidence towards the following conclusions:

- Feed-in tariffs and TGC schemes such as the UK's Renewables Obligation have been implemented in countries with above-average electricity prices.
- Once implemented, FITs and TGCs either have no effect on electricity prices or have a small upward effect.
- Tendering process, tax breaks and investment grants are more often implemented in countries where the price of electricity is below the OECD average.
- Once implemented, these schemes tend to decrease the electricity price. In the case household electricity prices, tax breaks for renewables seems to result in a reduction of up to 2c/kWh in the price of electricity.

These conclusions say nothing of the overall cost effectiveness of introducing these different measures. It is more likely that whereas the costs associated with FITs and TGCs tend to be passed onto consumers, tenders and tax breaks tend to be absorbed by central governments.

7.2.4 Conclusions

This chapter has focussed on two indicators that measure society's exposure to an electricity system disruption. The impact of privatisation and liberalisation, it would seem, are less important than the wider economic changes that the countries under investigation have undergone. In nearly all the countries the per-capita demand for electricity has been rising. At the same time, the expansion of the service industries in these same countries has led to a reduction in the per-GDP energy intensity.

By far the most important predictor of price, it would seem, is the expansion of the renewable sector. This is perhaps unsurprising, as such technologies are (in general) currently more expensive than alternative, more well-established, technologies. What may be of more concern to policymakers is that domestic customers seem to be more susceptible to price rises than are the industrial consumers. Combined with the increasing domestic demand for electricity, and the

further planned expansion of the renewables sector, there seems to be a need to ensure that households are not adversely affected. This could be done either by ensuring price stay at a manageable level for consumers, or by enabling them to reduce their demand for energy. The policy proposals for each of these strategies, and their implications, are discussed further in Part III. The next chapter, however, addresses *energy independence*: an indicator that is not a perfect measure of a country's energy security, but one that brings a useful perspective to the concept of resilience.

8

Energy Independence

Energy independence does not necessarily ensure security of supply. Most disturbances experienced by an electricity system originate within national borders. However, in the sense that resilient system design is concerned with preparing for unforeseen or unquantifiable events, there is an argument to be made for not being overly reliant on systems and institutions beyond one's regulatory control.

This concept can be quantified in various ways, but for the purposes of this analysis, an indicator was chosen that reflected the extent to which the fuels on which a given electricity system relies are imported from outside national borders. The Import Dependence Indicator (IDI) reflects both the proportion of a fuel that needs to be imported for electricity production and the extent to which the electricity system is reliant on that fuel, and is defined as follows:

$$\text{IDI} = \frac{1}{T}\left(\frac{C_g I_g}{P_g + I_g} + \frac{C_c I_c}{P_c + I_c} + \frac{C_o I_o}{P_o + I_o}\right) \tag{8.0.1}$$

where C is the installed capacity, I is the imported fuel and P is the amount of fuel produced indigenously; g, c and o refer to gas, coal and oil, respectively, and T is the total installed capacity in a given country.

These fuels have been chosen partly because their associated datasets are sufficiently complete, but also because most other fuels represent only a small proportion of any country's fuel mix (e.g. peat). One notable exception is uranium for nuclear reactors. The data required to include uranium in the IDI is not available. Furthermore, the cost of uranium contributes only a small amount to the running costs of nuclear reactors, and the physical amounts required for each unit of electricity are small when compared with coal or gas. This means that physical availability and price fluctuations are less likely to have an impact on the availability or price of the resulting electricity generated.

Where a country has a high proportion of renewables, the IDI will indicate low energy dependence as the contribution of gas, coal and oil to the overall installed capacity will be reduced.

8.1 Changes to the IDI over time

The IDI indicator requires a number of different sources of data, namely, installed capacity by fuel, indigenous production figures and fuel import amounts. Not all countries report these figures, so the sample of countries is smaller here than in previous chapters. Figure 8.1 shows how the IDI has changed over time.

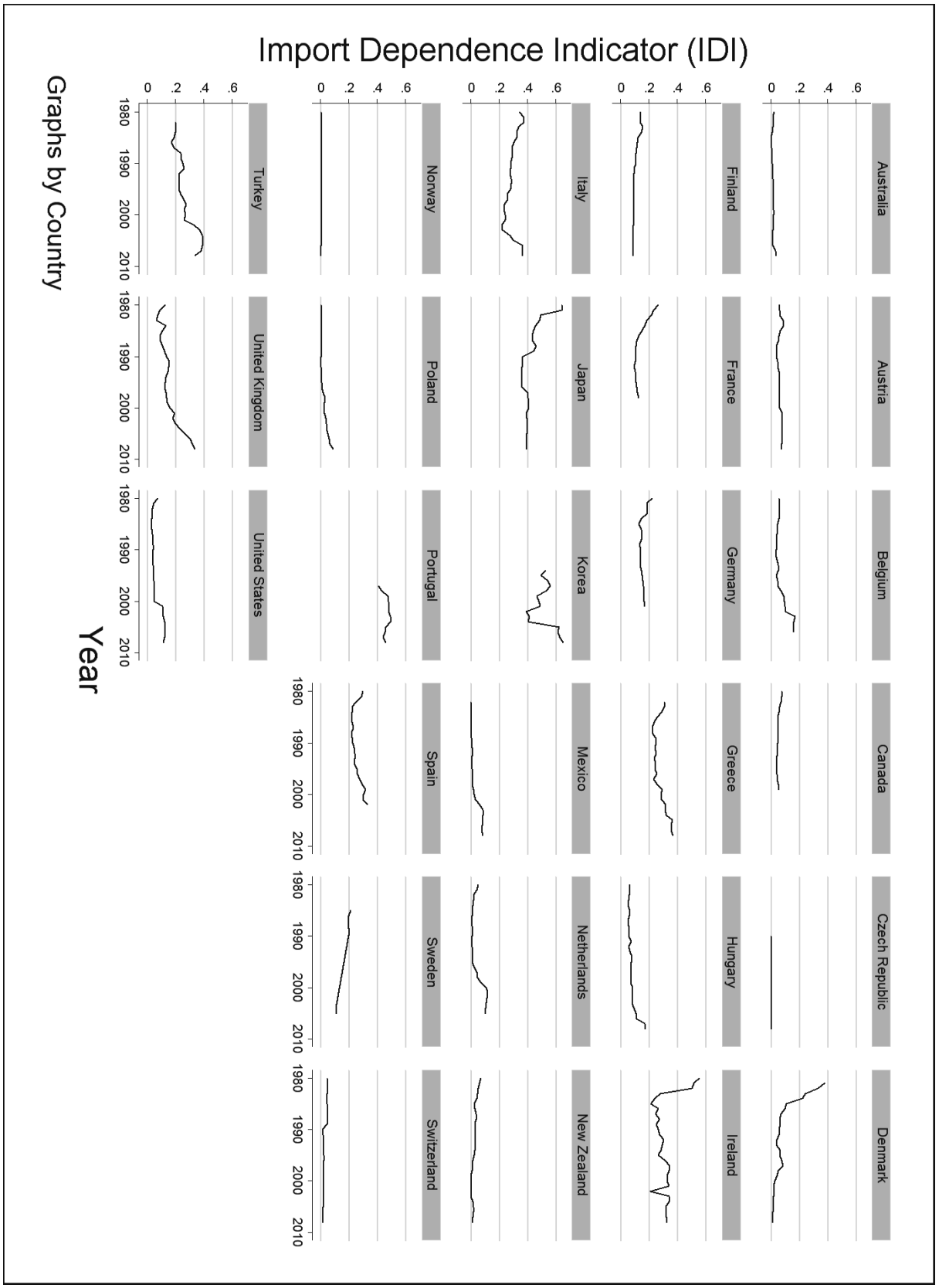


Figure 8.1: IDI for all OECD countries

IDI can be driven in two ways. An increase in IDI can either arise because:

1. For a given generation mix, the amount of the associated fuel that needs to be imported increases. This can arise because indigenous production dwindles or a competing industries divert an increasing amount of fuel from electricity generation;

2. For a given level of fuel imports, the amount of that fuel type required for electricity generation increases.

The UK's IDI has increased fairly steadily since the beginning of the 1980s, as can be seen by Figure 8.2.

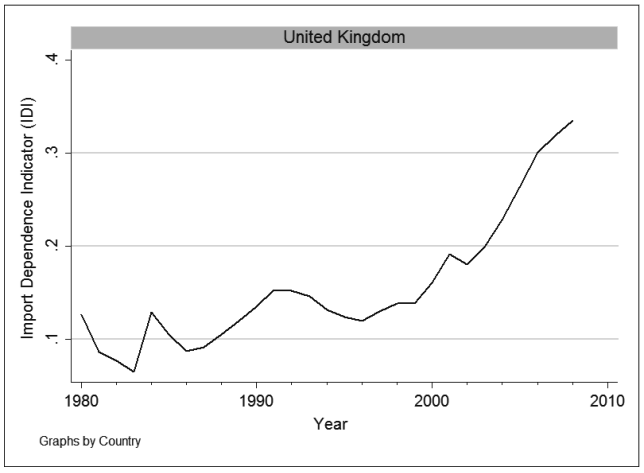


Figure 8.2: IDI for the UK

The natural gas component of the IDI remains low and level until 2000, as shown in Figure 8.3. Figure 8.4 reveals that during this period the proportion of gas generation increases, but the corresponding demand for gas is met by increasing levels of indigenous production, meaning that the gas import dependence remains relatively unchanged. From 2000 onwards, however, the amount of indigenous gas production begins to fall, and the level of imported gas increases to fuel the still-increasing numbers of gas-fired generators. The resulting effect is a sudden shift in the gas IDI from flat to steeply increasing (Figure 8.3).

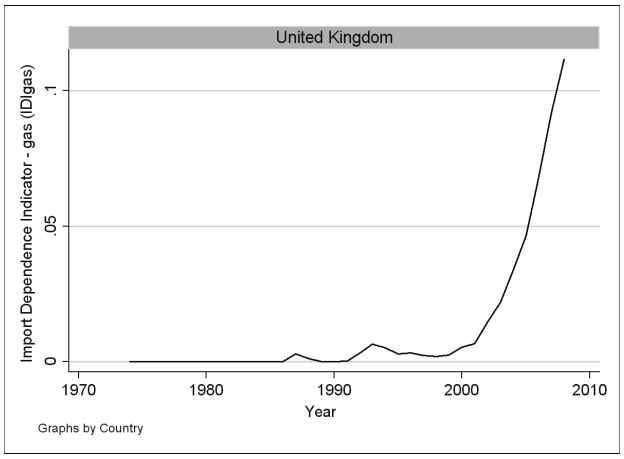


Figure 8.3: UK IDI for gas

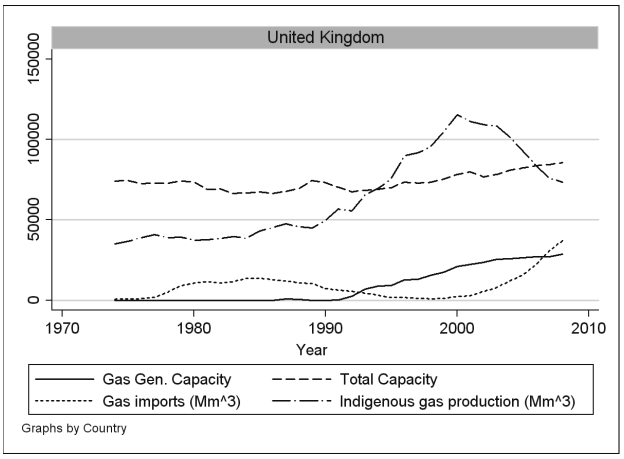


Figure 8.4: UK gas generation, imports and indigenous production

The IDI's coal component has twice the effect on overall IDI than the gas component. Its increase is more steady over the period in question (Figure 8.5). This increase is driven both by a significant decline in the levels of indigenous coal production and a corresponding increase in the amount of coal imported annually. Over this time, the installed coal-fired generation capacity has decreased, but not at a rate low enough to offset the decline in indigenous production.

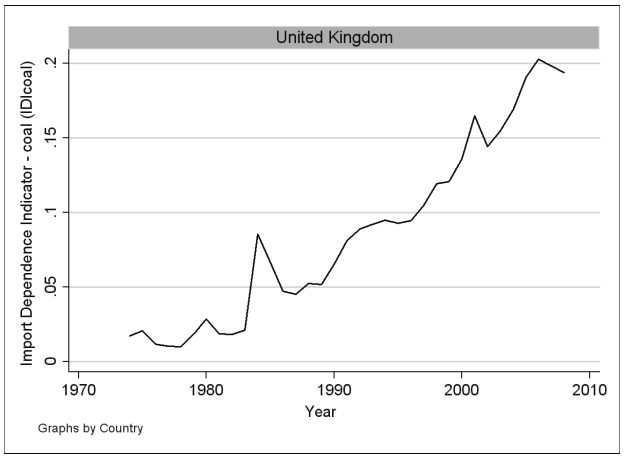


Figure 8.5: UK IDI for coal

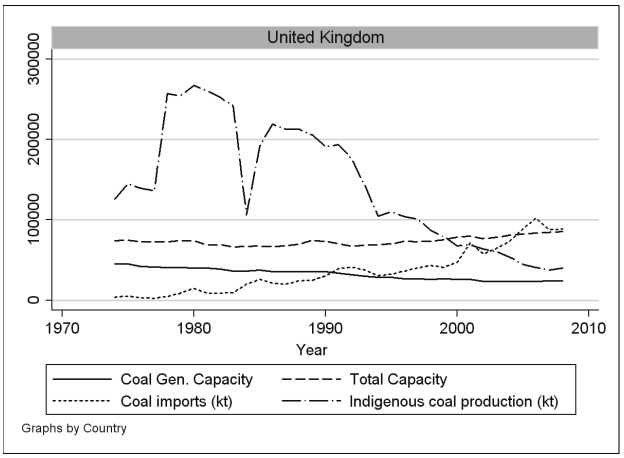


Figure 8.6: UK coal generation, imports and indigenous production

Since 2000 the indigenous oil production has declined, and the import levels have increased, thereby putting an upward pressure on the UK's oil IDI. However, the contribution made by oil-fired generation to the UK electricity mix has been in decline over this period, and particularly since the early 1990s. Whilst oil import dependence has increased, therefore, the net effect is a

decline in the direct exposure of the UK electricity system to extra-national oil shocks.

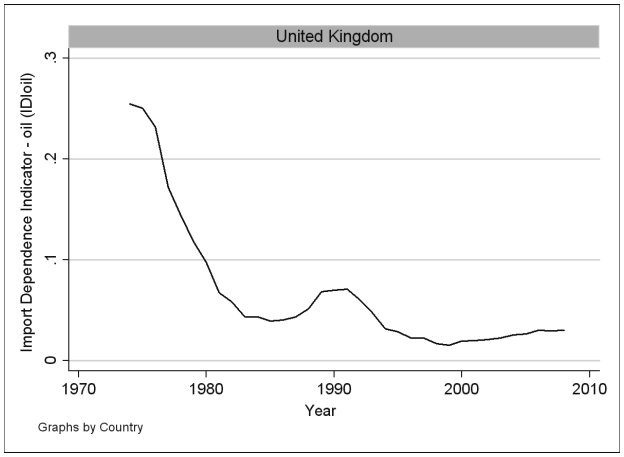


Figure 8.7: UK IDI for oil

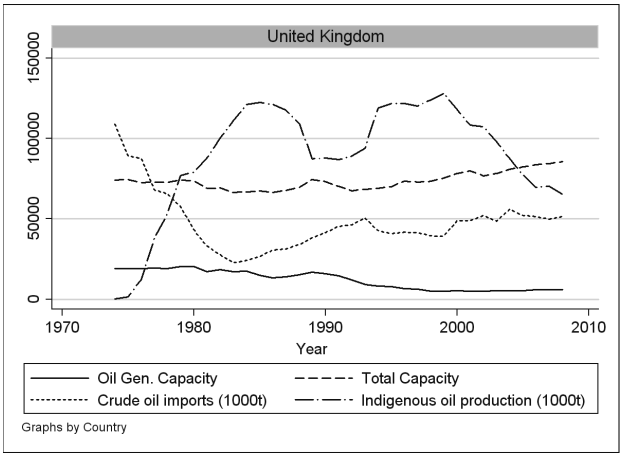


Figure 8.8: UK oil generation, imports and indigenous production

8.2 Effect of liberalisation and privatisation on IDI

This section asks whether different liberalisation measures are causally associated with a change in the IDI in the OECD countries.

8.2.1 Effect of overall liberalisation

As Figure 8.9 shows, there appears to be little, if any, correlation between overall liberalisation and IDI when considered over all country-years. The results of the mixed effects model shown in Figure 8.10 similarly reveal no association between the two variables.

8.2.2 Effect of the creation of a liberalised pool on IDI

As can be seen from Figure 8.11, countries with a liberalised pool have very similar IDIs, on average, to those without. On a year-by-year basis, as shown in Figure 8.12, the overall trend for both liberalised and non-liberalised systems is slightly towards increasing energy dependence. In most years, countries with higher levels of energy dependence tended to be those without a liberalised pool. This difference was increasing year-on-year in the 1990s, so that countries with

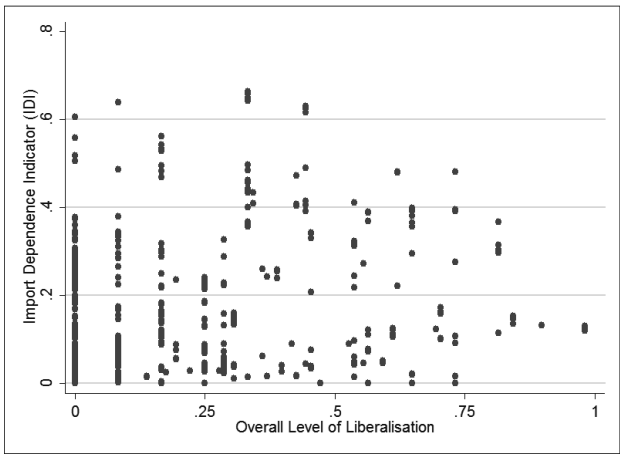


Figure 8.9: IDI (all county-years) vs overall liberalisation

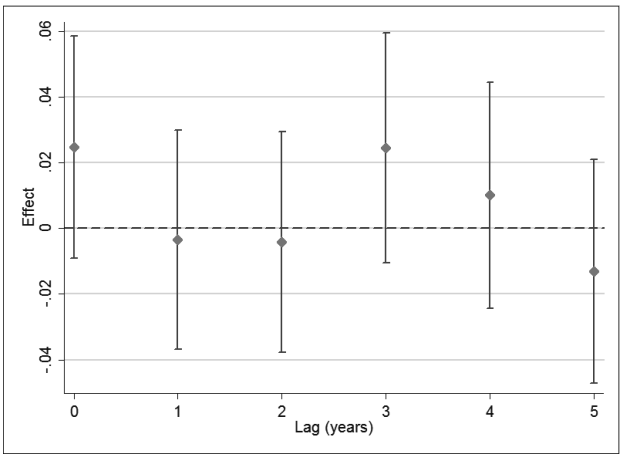


Figure 8.10: Lagged effect of overall liberalisation on IDI

a liberalised pool saw an overall decline in IDI, whereas for those without, the IDI increased. By 2007, however, the difference between the two groups has reduced to zero.

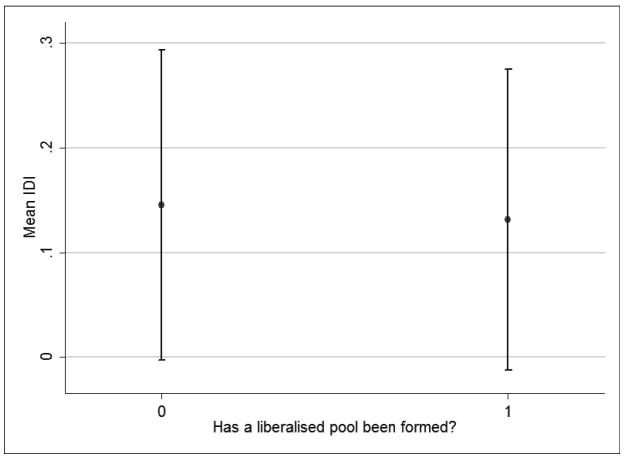


Figure 8.11: The overall mean IDI with and without a liberalised pool

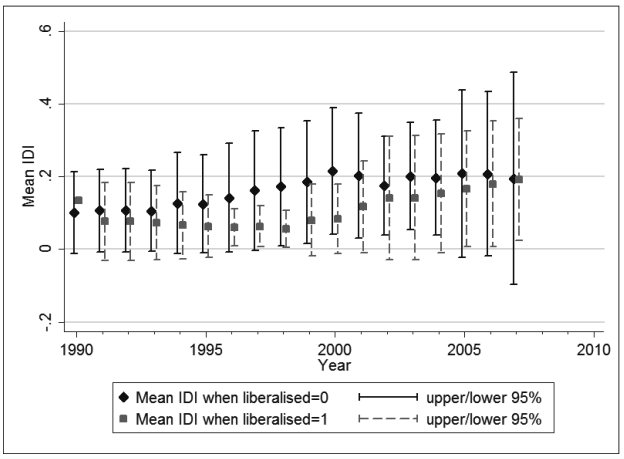


Figure 8.12: The mean IDI by year, with and without a liberalised pool

Figure 8.13 addresses the causal question: does introducing a liberalised pool, all other things being equal, cause a change in the level of energy dependence for a given electricity system? In the year in which liberalised pools are introduced the association is positive, but not statistically significantly so (at a 5% significance level). Over the subsequent five years, however, the apparent effect decreases until by year 5 there appears to be a significantly negative effect of 0.014 (p=0.029).

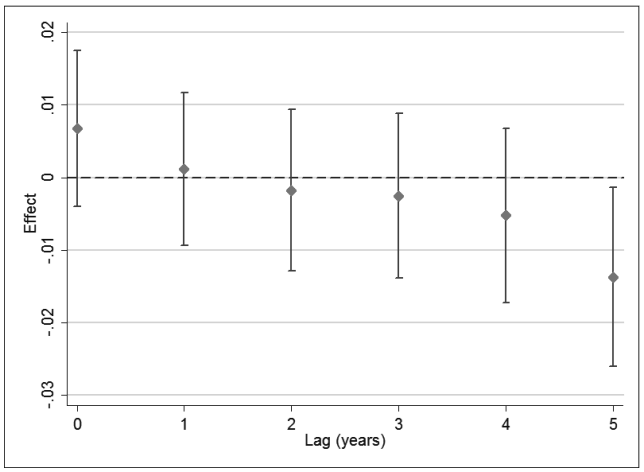


Figure 8.13: Effect of the creation of a liberalised pool on IDI

This would suggest that there is a small year-on-year cumulative effect of introducing a liberalised pool that tends to result in an electricity system that is less reliant on imported fuels.

8.2.3 Effect of the ownership arrangements on IDI

A plot of the mean IDI against ownercode (Figure 8.14) reveals a broadly positive correlation between the degree of privatisation and the degree of energy dependence. This trend, however, is not consistent over all levels of privatisation, so strong conclusions should not be drawn about this relationship.

The mixed modelling analysis (Figure 8.15) reveals no association between increasing the degree of private ownership and the resulting IDI.

The binary variable, **privatised**, shows the difference between the more privatised systems and the more nationalised ones (Figure 8.16). The by-year plot shows that for all years under analysis, countries with mostly privately-owned electricity companies also tend to have higher levels of import dependence, as indicated by the IDI (Figure 8.17).

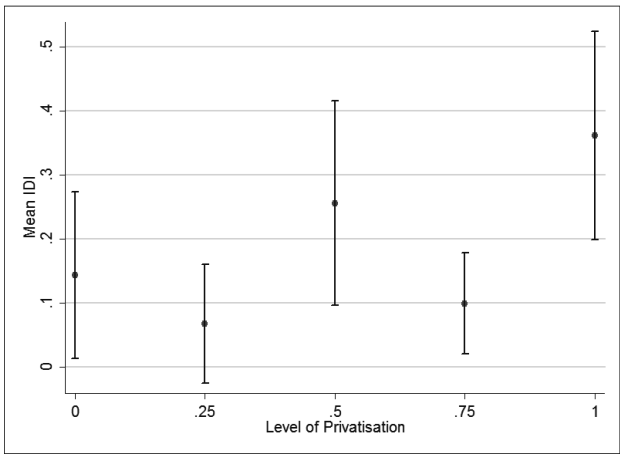


Figure 8.14: IDI (all county-years) against the degree of private ownership

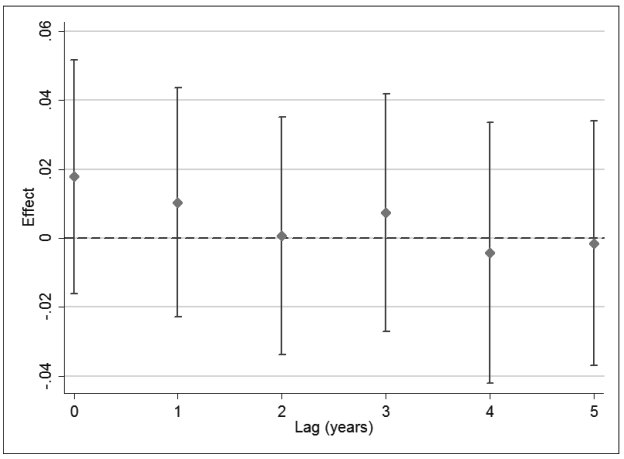


Figure 8.15: Effect of the ownership arrangements on the IDI

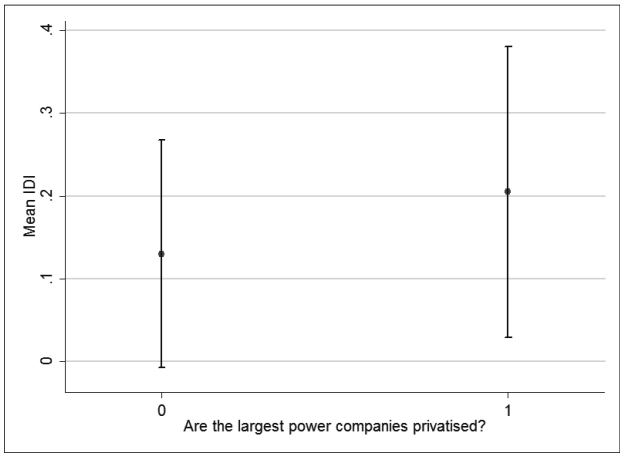


Figure 8.16: Mean IDI by privatised

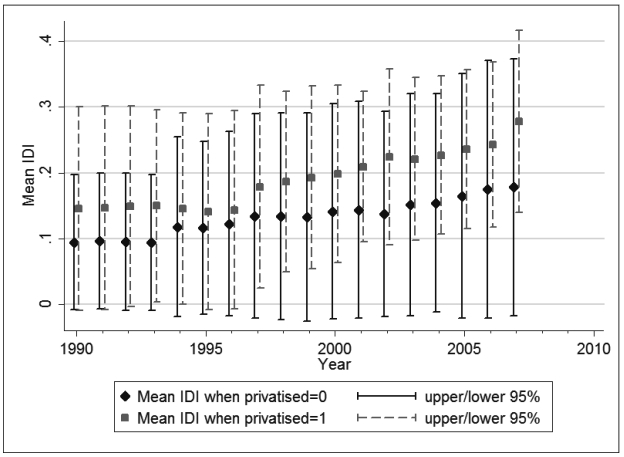


Figure 8.17: Mean IDI by whether privatised and by year

Again, however, there is little evidence that privatising an electricity system changes a given country's energy import dependence (Figure 8.18). It can only be said, then, that those countries that already have an above-average dependence on fuel imports are the ones more likely to undergo privatisation.

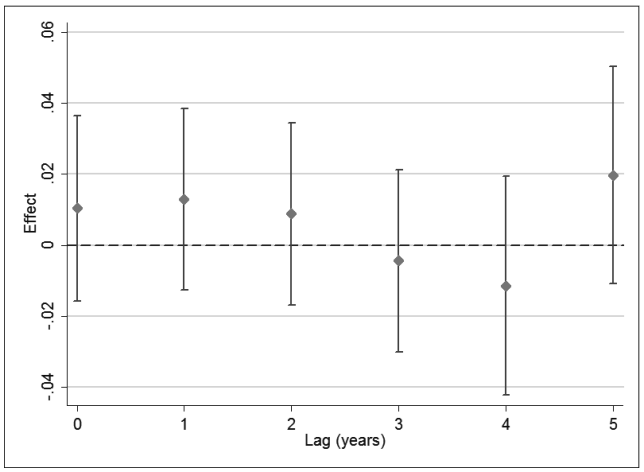


Figure 8.18: Lagged effect of privatised on IDI

8.2.4 Vertical Separation

There is very little difference in IDI between countries with differing levels of separation between their transmission and generation sectors. The overall difference shown in Figure 8.19 shows the three categories to have similar average IDIs, and the results of the mixed effects model shown in Figure 8.20 reveals no significant within-country association.

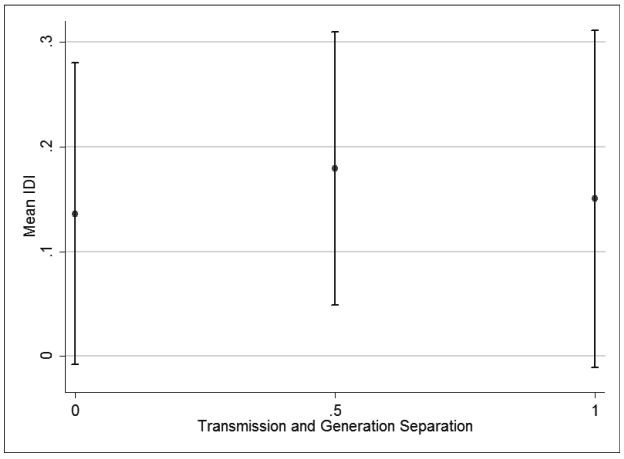


Figure 8.19: IDI (all county-years) against the degree of transmission-generation separation

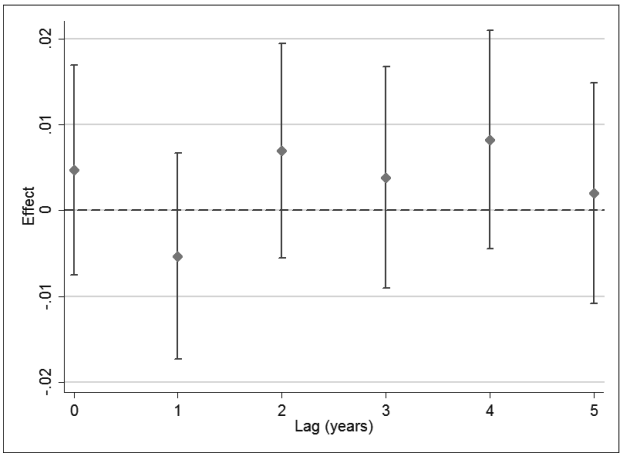


Figure 8.20: Effect of a change to the degree of transmission-generation separation on the IDI

Similarly, the yearly IDI plots for the binary **transgen_unbundling** shows little difference between integrated and unbundled transmission and generation systems.

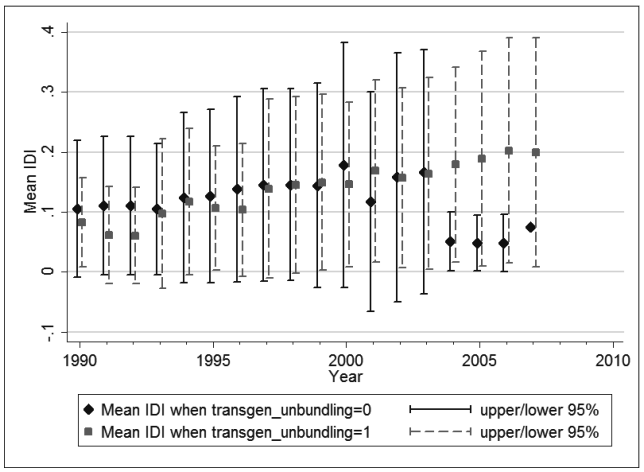


Figure 8.21: IDI by year against whether transmission and generation are integrated (0) or not (1)

For overall vertical separation, there is slightly more of a suggestion that vertically unbundled systems are more likely to have a lower IDI, as shown by Figure 8.22 and by Figure 8.24. The mixed effects model, however, does not provide evidence that this relationship is causal (Figure 8.23).

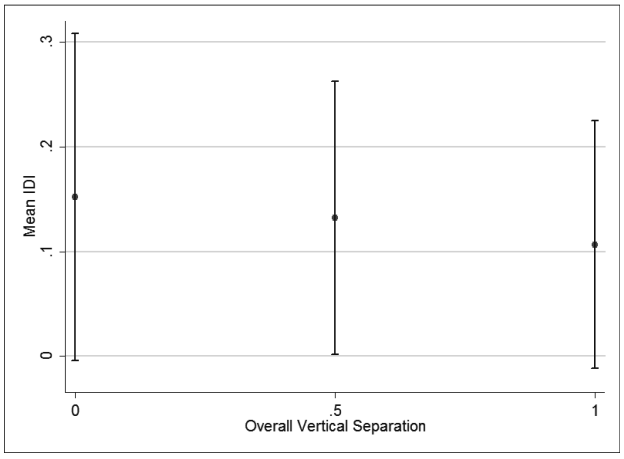


Figure 8.22: IDI (all county-years) against overall vertical separation

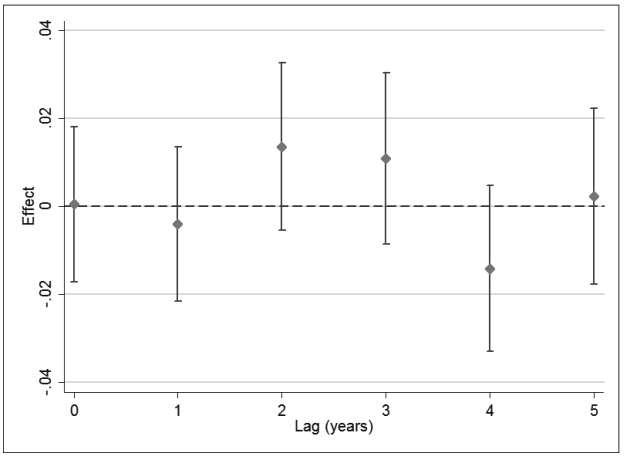


Figure 8.23: Effect of a change to the degree of overall integration on the IDI

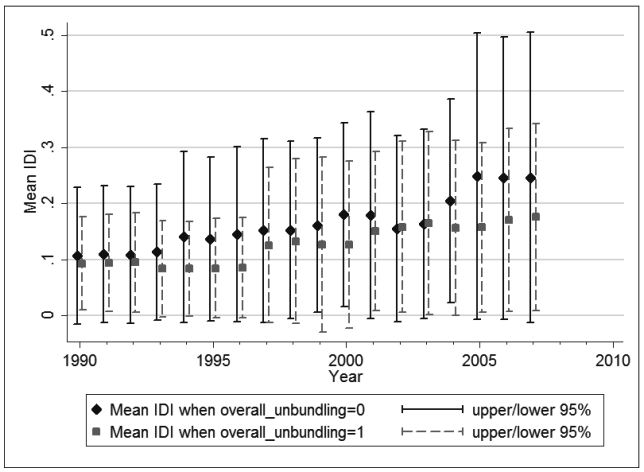


Figure 8.24: IDI against whether the system has undergone vertical unbundling in a given year

8.3 Effect of renewable generation and associated policies on system diversity

Using the same methods applied above, this section assesses the relationship between the deployment of renewable generation and the associated renewables policies on energy import dependence.

8.3.1 Installed capacity of new renewables

Figure 8.25 shows a scatter plot of IDI against the proportion of installed renewables. No obvious association emerges from this plot.

For the mixed effects model, no significant association is seen in any lags, although the effect of increasing the proportion of new renewables has a consistently negative effect on IDI. If this were indicative of a true association it would mean that increasing the proportion of wind, solar and marine generation reduced an electricity system's dependence on foreign fuel imports.

Although not quite significant at the 5% level, the lag at five years shows an effect of -0.70 (s.e.=0.38, p=0.066). Were this to apply specifically to the UK, the increase from an IDI of 0.1 to 0.3 experienced between 1989 and 2003 would have been reduced by 0.7 had an additional 10% of renewables been installed.

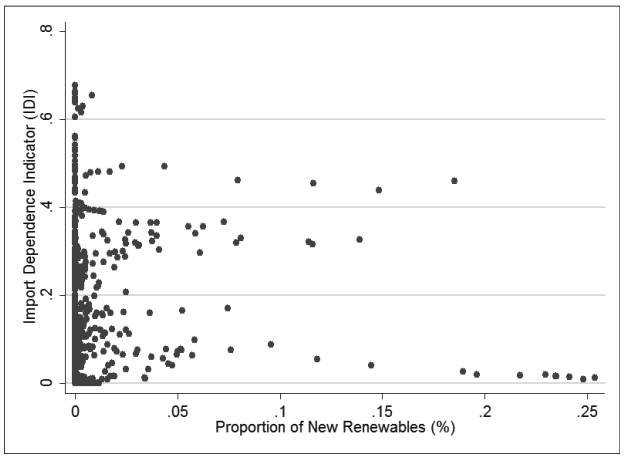


Figure 8.25: IDI (all county-years) against the proportion of new renewables on the system

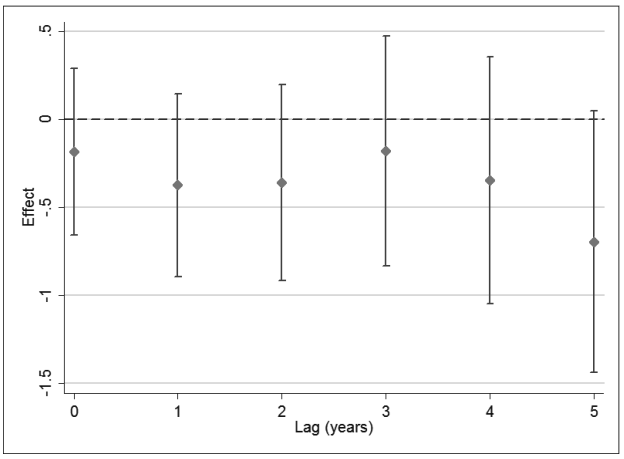


Figure 8.26: Lagged effect of increasing the new renewable proportion on the IDI

8.3.2 Renewable electricity support schemes

The following sections investigate whether the provision of support for these new renewables has an effect on IDI.

Any renewable support scheme

The overall difference in diversity and the difference seen on an annual basis (Figures 8.27 and 8.28, respectively) show that countries with renewable support mechanisms have consistently higher levels of fuel import dependence.

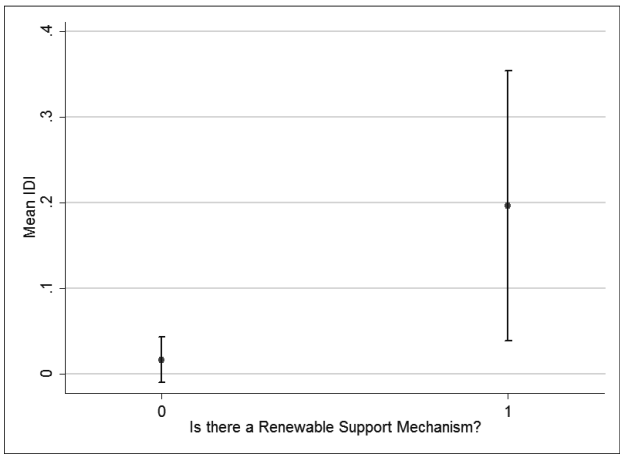


Figure 8.27: Mean IDI by renewable support

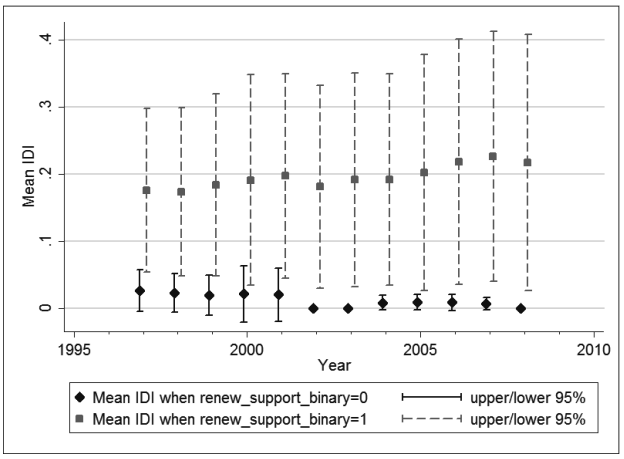


Figure 8.28: Mean IDI by renewable support and by year

The outcome of the mixed effects model, however, finds no significant effect of introducing such a policy on IDI within the timescales considered for this analysis (Figure 8.29).

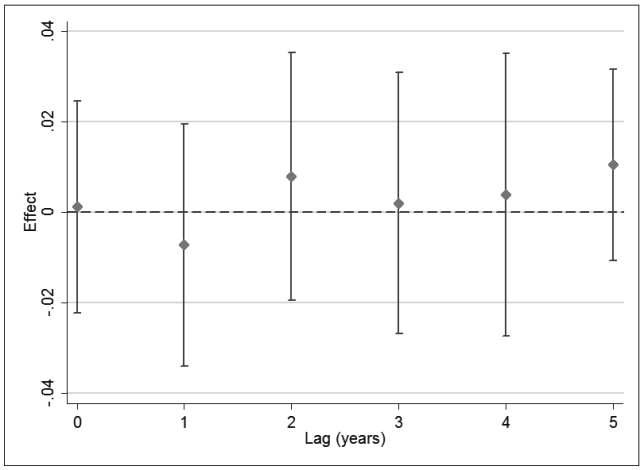


Figure 8.29: Lagged effect of introducing renewables support mechanisms on the IDI

The difference between the two groups, then, is more likely to arise from system characteristics that lead to the decision to introduce a mechanism for expanding the renewables sector. It is possible, for instance, that having a high level of fuel import dependence provides the political motivation to support forms of generation that are less reliant on foreign fuels. In other words, IDI would be a predictor of the decision to incentivise renewables.

Alternatively, there could be an unmeasured national characteristic that predicts both high IDI and renewable policy implementation. Countries that are reluctant to rely on fuel imports may, for example, be the same countries that are unwilling to implement policies such as low-carbon incentives, which are designed primarily to benefit extra-national individuals.

Feed-in Tariff

As with renewables mechanisms more generally, countries with a Feed-in Tariff tend, on average, to have higher levels of energy import dependence than those without (Figure 8.30).

The mixed modelling analysis, however, shows no effect of introducing an FIT (Figure 8.31), suggesting that those countries that bring in a FIT scheme, on average, tend to have a higher IDI prior to that decision being made.

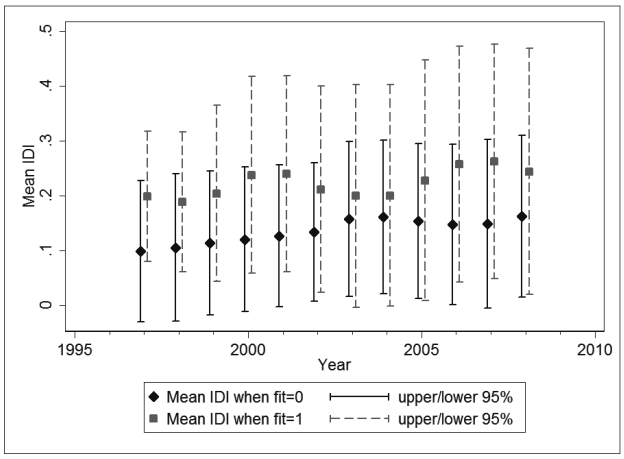


Figure 8.30: Mean IDI by FIT and by year

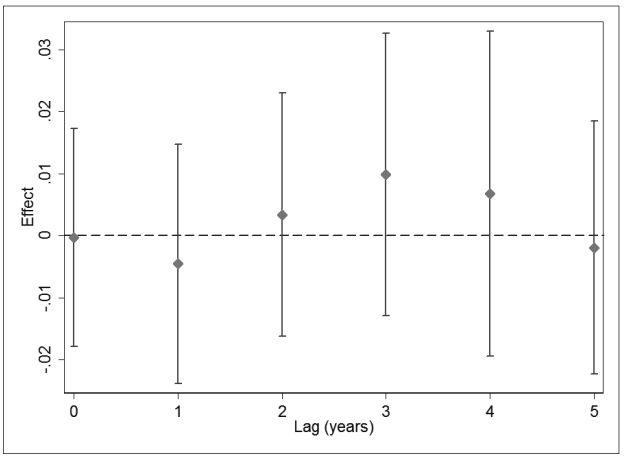


Figure 8.31: Lagged effect of introducing a feed-in tariff on the IDI

Quota / Tradeable Green Certificate / Renewables Obligation

There is very little to distinguish between the IDIs in countries either with or without a TGC mechanism (Figure 8.32). The mixed effects model reveals a slightly positive association, but at no time is the effect significant.

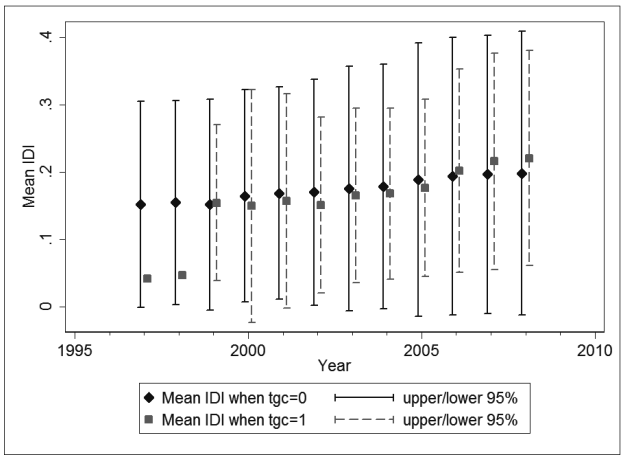


Figure 8.32: Mean IDI by TGC and by year

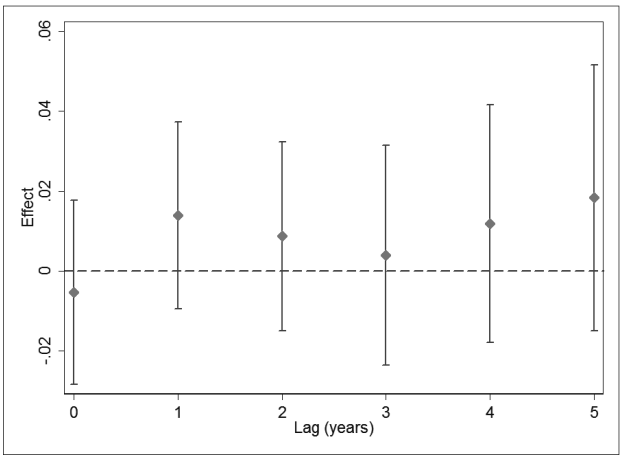


Figure 8.33: Lagged effect of introducing tradeable green certificates (TGC) on the IDI

Tendering Process

As can be seen by the absence of standard error bars, from 2003 onwards in Figure 8.34, only one country had both a renewables tendering process and sufficient data to determine the IDI (with the sole exception of 2005). Strong conclusions about the effect of tendering processes on the IDI are therefore unlikely.

Nevertheless, countries that have a tendering scheme have higher energy import dependence than those that do not. The mixed effects model shows no significant association, although the effect, if any, appears to be negative.

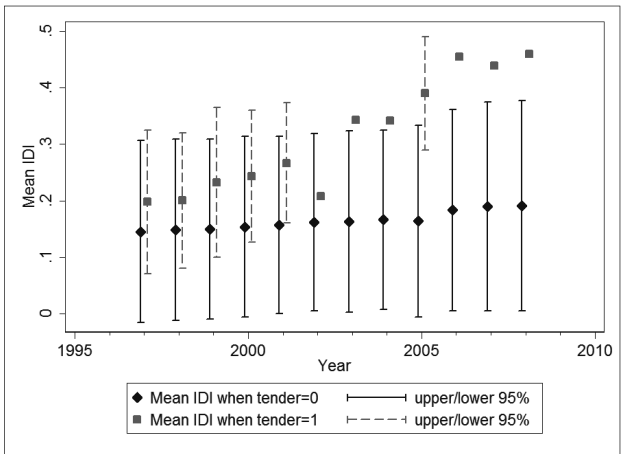


Figure 8.34: Mean IDI by tendering process and by year

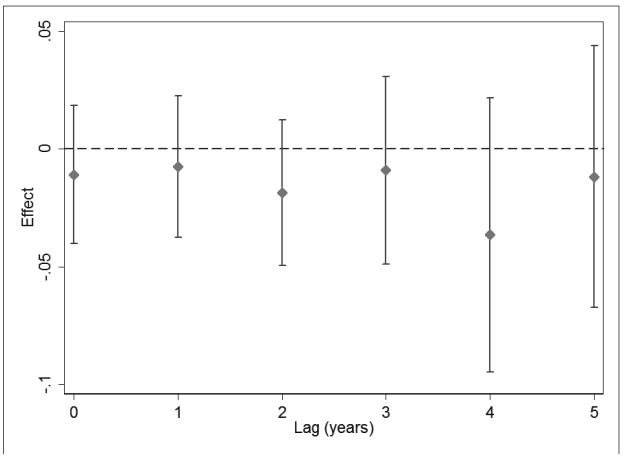


Figure 8.35: Lagged effect of introducing a tendering process on the IDI

Renewables Tax Incentives / Investment Grants

There is almost no difference in IDI between countries with or without tax incentives or investment grants (Figure 8.36). Nor is there an observable effect of introducing (or retracting) such schemes on the IDI.

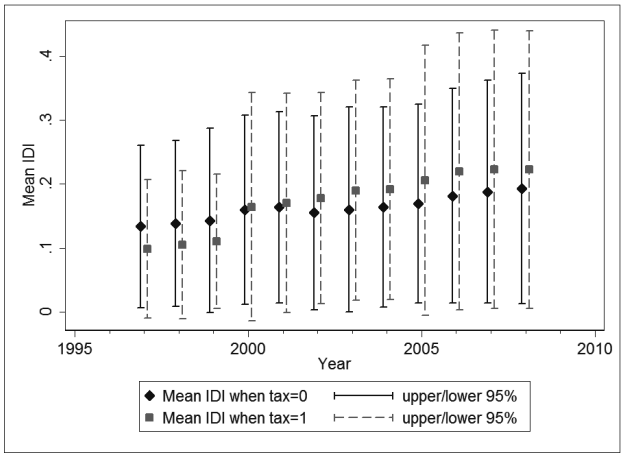


Figure 8.36: Mean IDI by tax incentive and by year

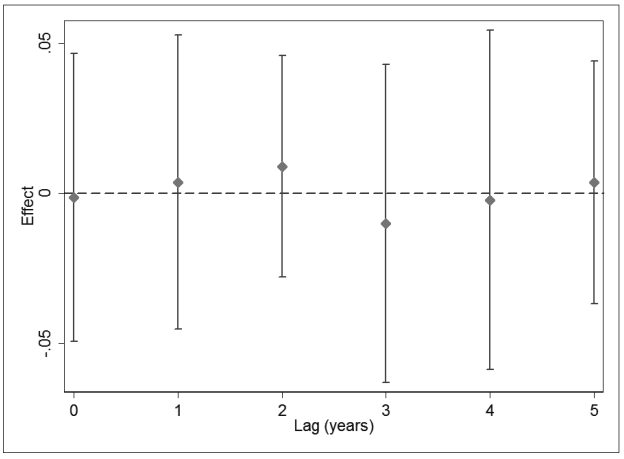


Figure 8.37: Lagged effect of introducing a renewables tax incentive on the IDI

8.3.3 Conclusions

The UK's dependence on foreign imports to fuel its electricity system has been increasing now for a number of decades. It is unsurprising, therefore, that some commentators have raised concerns about this fact. It remains to be shown, however, that such dependence represents a real risk to the UK's security of supply.

In general, this increase in dependence appears to be unrelated to liberalisation or privatisation, although the case of the UK may be viewed as a notable exception to this trend. As for the claim that an expansion in the renewables sector will reduce reliance on foreign imports, this appears to be supported. Perhaps most telling, however, is that the countries that chose to push for renewables expansion most strongly were those that already had a high reliance on imported fuels. The implementation of such policies, therefore, is indicative of governments' concerns about security of supply. Disentangling this underlying drive from the effect of the policy intervention itself will always be difficult.

Part III attempts to bring together these various indicators of resilience and to relate the findings of this research to the most recent UK policy developments.

Part III

Assessing Future Policy Options

9

UK resilience trends and the role of liberalisation and renewables

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The analysis presented in Part II illustrates a number of different indicators of electricity system resilience, and the relationship of those indicators initially to liberalisation and later to the introduction of policies to reduce the reliance on fossil fuels. In many cases there is either no discernable effect. This is not to say that such interventions have no impact on the outcome; rather, the underlying variability in these indicators is too large to identify the role played by specific interventions.

At any given moment in time the difference in resilience between, say, a liberalised system and a monopolistic system could be explained in three distinct ways:

1. Liberalisation caused the difference in the resilience indicator;
2. The resilience indicator caused (or contributed causally to) the decision to liberalise;
3. An unmeasured variable (e.g. GDP, institutional maturity, political stability) is drives both the decision to liberalise and the difference in the resilience indicator.

For many countries there is a difference between their resilience indicators at the point they introduce privatisation, liberalisation and low-carbon policies. This would be suggestive of points 2 and 3 above, which is to say that (whether causal or not) the underlying difference in resilience is predictive of the decision to liberalise. In some cases, however, there is additional evidence that once the intervention (such as liberalisation) has occurred, a further change in the resilience indicator can be measured. It is this additional change that describes the post-intervention association, from which it would be plausible to conclude that intervening caused a change in the resilience indicator.

The following sections summarise and expand on the findings of Part II, attempting to understand the mechanism at work where a relationship between liberalisation and resilience is found and, where no such effect is observed, to explain why this might differ from existing theories of liberalisation.

9.1 Derated Generation Margins

9.1.1 The role of liberalisation

The ability of a privatised and liberalised system to deliver sufficient new build has been one of the primary concerns regarding the security of the electricity system in the UK (Surrey, 1996). As Figure 9.1 shows, however, the decline in margins in the UK was at its most steep in the 1970s and the first half of the 1980s. From 1973 to 1986 the reserve margin dropped from 59% (its highest level since 1933) to 16%.

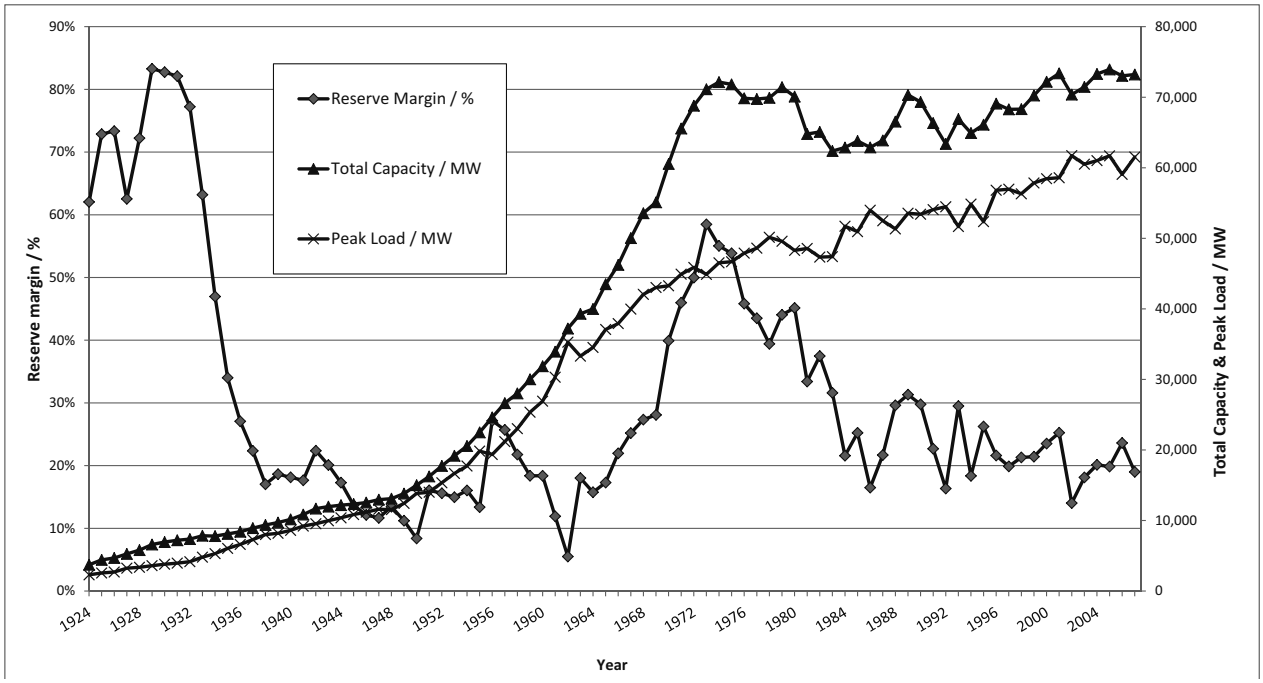


Figure 9.1: UK Reserve Margins 1924 – 2007

As the analysis of Chapter 5 shows, countries that first chose both to liberalise and privatise had lower margins than those that did not. One of the reasons for undergoing liberalisation was because of a belief that there was excess electricity generation that was not economically justified (Newbery, 2004). The findings of this research do not contradict this as such, but they do show that whilst the desire to reduce the system's 'gold-plating' may have been a motivating factor, there were many countries with higher margins that did not choose to liberalise.

In an article written prior to the privatisation of the UK electricity sector, Kay and Thompson (1986) gave a number of different reasons that the UK Government may have had for privatising and liberalising the state-owned entities:

> One purpose is to improve the economic performance of the industries concerned. Another is to resolve the persistent problems of management and control which have made the relations between government and nationalised industries one of the unhappier elements of British public administration... The Treasury is greatly interested in the revenue which can be obtained from privatisation. Although the objective is rarely articulated, privatisation may also be seen by the government as a means of disciplining the power of public sector trades unions. A final objective is the promotion

of a kind of popular capitalism through wider share ownership.

A desire by Government to resolve difficulties in its relationships with both the management and the unions associated with the state-owned industries appears to have been a factor in the decision to privatise, as was the need to improve the public finances. Improving the economic performance of these industries appears, therefore, to be just one of a number of reasons for the decision to liberalise and privatise. As David Newbery (2001) argues, however, "the emphasis in Britain was on ending state ownership, not on liberalising the network utilities", citing the example of British Telecoms, which "was privatised as a de facto monopoly".

When it came to the power sector, it was argued by economists such as Vickers and Yarrow (1988) that it was not privatisation, but liberalisation, and the increase in competition that arose as a result, that would lead to the largest benefits. This view was reflected in the decision to unbundle the electricity generation sector concurrently with privatisation (Newbery, 2001).

Whether or not this increased efficiency resulted in a reduction in consumer electricity prices is discussed in Section 9.3.1, but in terms of reserve margins, there is little evidence that either privatisation or the introduction of competitive elements have significantly contributed to the decline that has occurred since 1990. Newbery (2001) argues that profits in the power sector were higher in the five years after privatisation than they would have been in the counterfactual world in which the system remained nationalised. If this is true, it can be concluded that such profits did not arise because of a change in the way in which the decision to construct new capacity was made.

The other intervention investigated in this research was the vertical unbundling of the electricity supply chain. As with the indicators that referred to privatisation and the creation of a liberalised pool, those countries that unbundled transmission from generation tended to have lower margins than those that did not. Rather than being a statement about the effect of vertical unbundling, it is possible that this finding is more a reflection of the fact that unbundling tends to occur as part of an overall liberalisation package. The data are insufficient to control for such confounding, so the effect of such a correlation cannot be easily eliminated.

In terms of the impact that liberalisation and privatisation had once they had been implemented, there is little evidence that there was any effect. There are some tentative grounds for saying that separating transmission from generation and decreasing the overall vertical integration reduced the level of the system margin. This would suggest that vertical separation has more of an effect

on reducing margin than horizontal separation. This is in agreement with the argument made by Newbery (2001) that "increased competitive pressure on generation is needed to reduce costs and that requires separating generation from transmission and distribution."

9.1.2 The role of new renewables

The evidence suggests that renewable generation and the policies surrounding it have a more significant impact on margins than any aspect of liberalisation or privatisation. As will be discussed, however, there are interactions between renewables expansion and the liberalised markets that may impact on questions of resource adequacy.

Because of the non-dispatchable nature of renewables such as wind and solar generators, additional backup generation in the form of coal or CCGT has to be held, meaning that the overall margin will increase with increasing levels of renewables (Zhang and Chowdhury, 2009). The data strongly support this theory, showing that an increase in renewable generation is strongly predictive of an increase in the absolute margin.

What is less apparent is whether the amount of additional dispatchable generation is sufficient to maintain the desired Loss of Load Probability (LOLP). For this measure, the 'capacity credit' of a renewable generator, rather than its absolute capacity, is a more appropriate measure of its ability to contribute to system security (Boyle, 2008). By estimating the average effective capacity of the new renewables added to the system, it was shown in Chapter 5 that the derated margin (which attempts to account for the non-dispatchable nature of renewables) still increases as the proportion of new renewables goes up. This additional security comes at a price to consumers, as is discussed below, but in terms of a strict definition of security in terms of LOLP, it appears that the margins are maintained or even increased. An increase in the proportion of new renewables seems to have at worst a benign influence on the derated margin, and perhaps a protective one.

This finding does not necessarily lead to the conclusion that renewables increase the resilience of the electricity system. As was discussed in Chapter 3, the LOLP measure itself has come under some scrutiny, particularly with the expansion of the renewables sector. The UKERC report on the Costs and Impacts of Intermittency, for example, refers to a debate as to whether LOLP and similar measures of reliability "fully capture the changes that arise when intermittent sources of are added to the network" (UKERC, 2006).

All forms of generation are prone to periods of unavailability (both planned and unplanned). The characteristics of wind variability, however, are different from conventional plant. In particular, wind farm outputs are potentially highly correlated during 'cold snap low wind' events (UKERC, 2006). "Large-scale variability" would arise from an anticyclone covering most or all of the country, resulting in low or zero wind speeds (Laughton, 2008).

Such *common mode failures* (Laughton, 2008) are generally agreed to be rare, assuming that the grid region is sufficiently large, but as the UKERC (2006) report notes, a number of studies have used relatively short weather data sets, which would tend to under-report the probabilities. The report cites work by Sinden (2005), however, which uses longer-term weather data and concludes that such events would be extremely rare in the case of the UK.

The potential for such High Impact Low Proability (HILP) events presents some concerns about maintaining adequate supply levels. This may be particularly problematic under a market-based system that relies on private investment. DECC noted in a call for evidence in 2009 that there may be a need for some reserve to be held centrally to accommodate such rare periods of supply unavailability (DECC, 2009b):

> It has been suggested that there could be a case for an additional reserve – essentially, a number of MW that could be called on as a last resort, when other options had been exhausted, perhaps to deal with high-impact low-probability events. This could be controlled by National Grid or by another body... There are situations where an emergency reserve might be useful — for example, prolonged periods of low output from wind generation, or rare but serious events that mean that a significant proportion of the electricity generation capacity in GB is unavailable.

The potential impacts of such an intervention, along with other proposed policy changes, is discussed in Chapter 10. It also highlights, however, the point that the risk that a renewables expansion would have on margins depends to a large extent on the policies that bring about that expansion. Again, the historic performance of renewables policies on this measure have been assessed in this research.

9.1.3 Renewables policies and system margins

The overall introduction of a renewables support mechanism (of any design) resulted in a slight increase in the derated margin, but the results do not appear to be significant. These interventions were separated into Feed-in Tariffs, Tradeable Green Certificates, Tendering processes and tax incentives for investment. The introduction of these latter two — tenders and tax breaks — led to a reduction in the derated margin by as much as 7%. This suggests that these mechanisms tended to encourage renewable generation at the expense of other forms of conventional power.

Tradeable Green Certificates did not lead to this depressive effect, but neither is there evidence that derated margins were increased as a result of their introduction. This would suggest that any additional renewable capacity brought on as a result of the TGCs resulting in a corresponding loss (or deferred investment) in the corresponding amount conventional generation.

The most striking effect was seen in those countries that introduced a Feed-in Tariff. Within one year of introducing the FIT, the average effect was an increase of over 5% in the margin – an effect that was sustained over the five subsequent years, meaning that it is unlikely to be an anomalous result. It cannot be ruled out that countries that chose to introduce an FIT were different in some relevant but unmeasured parameter from those countries that chose an alternative mechanism. The primary suggestion, however, is that FITs have been more successful in achieving their primary objective of encouraging new renewables without displacing other forms of generation.

A direct comparison of TGCs with FITs shows that FITs have been more successful in terms of maintaining or improving margins. If this additional capacity results in an increased electricity price to consumers, this difference could be attributed to the more interventionist approach of the FIT scheme. In fact, as will be discussed below, the evidence suggests that whilst both schemes have resulted in increased electricity prices, it is the TGC mechanisms that have led to the largest price increases.

It became apparent in conducting this analysis that there was a large underlying variation in countries' system margins and their underlying peak loads and installed capacities. It would be impossible to control for all the causes of this variation, particularly since the data set is of limited size. GDP and electricity price had the potential to affect both the level of demand and the amount of investment in new capacity, so these variables were investigated.

GDP was found to be strongly correlated with both peak load and the derated generation capacity and this association was likely to be causal. An increase in the productivity of the wider economy

was associated with an increased demand for electricity and a subsequent increase in the amount of new-build generation capacity. This presented the potential for a mis-match to arise as demand outstripped supply. There was some evidence that demand increased occurred more rapidly than installed capacity following an increase in GDP, and that subsequently the demand dropped more quickly than power stations were being retired. On further examination of the evidence the association did not, however, result in a disparity between peak load and derated capacity, meaning that the effect of GDP on the derated margin was negligible.

Conversely, the price of electricity had only a small effect on both peak load and derated capacity in absolute terms, well within the confidence interval. This small effect, however, was sufficient to show a positive overall effect on the derated margin, meaning that an increase in electricity price was associated with a subsequent increase in the system margin.

9.2 System Diversity

The diversity of an electricity system was here defined in terms of the number of different types of generator and the balance of those different types in the overall generation mix. Specifically, the Shannon-Wiener Index (SWI) was used, which increases with increasing diversity. The hypothesis under investigation in this thesis is that liberalising the electricity generation sector (which is to say, increasing the diversity of ownership) would result in an increase in the diversity of generation technologies.

There are benefits to individual operators to diversify their generation portfolios to some extent. For example, a private company with a generation portfolio comprising only nuclear power is very exposed to the variation in electricity prices, since there is no opportunity to take advantage of correlations with fuel prices. The privately-owned nuclear generator could diversify by constructing, say, a number of CCGT plants. By aligning its portfolio more closely with the national generation mix, the company is protected against price fluctuations. In the UK, for example, gas and electricity prices are highly correlated so a decline in electricity price tends to be associated with a decline in gas price, and hence operating costs (Roques *et al.*, 2008).

These price-based risk calculations are not so important in state-owned monopolies, as the government shareholder can exert control over electricity tariffs. Whilst the price risk is not an issue, such single-fuel configurations are susceptible to physical risks. There are numerous examples of countries whose electricity supply has been threatened because of too high a dependence on

a single generation technology (IEA, 2005b,c,d). Where price risks can be managed through risk management strategies, the lessons from *resilience* thinking show that it is not sufficient to protect against the known, quantifiable risks. This is especially true in the case of complex entities such as power systems. To return to Part I, the reason that *diversity* is a key indicator of resilience is that it protects against both the know and unknown risks – both the quantifiable and the unquantifiable uncertainties.

9.2.1 Liberalisation and privatisation

The analysis revealed that increasing levels of overall liberalisation (which includes measures of privatisation and vertical unbundling) are correlated with increasing levels of diversity: more liberalised systems are more technologically diverse. Furthermore, an increase in liberalisation within a given country, on average, increases the diversity. The act of liberalising a system, therefore, leads to an increase in diversity. It was thought possible that GDP was correlated both with liberalisation and diversity, which would induce an association between the two. Indeed, a correlation between GDP and SWI was found, but after controlling for GDP the effect of overall liberalisation on SWI remained.

Again, overall liberalisation was broken into its composite variables: there was very little to distinguish the diversity of the liberalised and non-liberalised groups; nor did vertical integration explain the difference in diversity. The largest difference in diversity was seen between those countries that had privatised and those that had not. The same was true when using the mixed effects model to test for the impact of privatising the system. The effect on diversity was three times higher for privatisation than it was for liberalisation.

This finding means that the technological diversity of the generating mix is increased the most by transferring the ownership of the power system assets from public to private hands. This process, more than the unbundling of generation and transmission assets, and more than the creation of a liberalised trading pool, is the component of 'overall liberalisation' that leads to an increase in the diversity of the generation mix.

The fact that privatisation, rather than increasing competition, seems to be the best predictor of increasing diversity reveals something about the underlying mechanism. If liberalisation had been the driver of increased diversity, this would have suggested that there would be a competitive pressure to diversify a company's generation portfolio. The fact that there is no significant

correlation between liberalisation and diversity implies that no such driver exists, or that it is counterbalanced by some other mechanism. Once such mechanism is suggested by Roques *et al.* (2008):

> A perfect market should motivate individual investment decisions leading to the socially optimal fuel mix, but the conditions for this to hold are strong... In particular, herd behaviour (in which investors observe others' decisions, and assume they are based on superior information that justifies imitating their choices) may encourage investment in one or two dominant technologies...

The Roques *et al.* (2008) paper argues that whilst market liberalisation would hypothetically lead to an optimally diverse generation mix, this relies on the assumption of perfect foresight and perfectly rational price and risk behaviour. Since these conditions are never met, the observed lack of correlation between diversity and liberalisation is unsurprising.

Nonetheless, there remains a significant correlation between privatisation and diversity. Returning to an earlier argument, privatisation of the generation sector tends also to result in a loss of electricity tariff controls. Even if newly-formed private entities do not operate in a fully 'rationally' competitive manner, they are exposed to price fluctuations that they need to manage. One approach is to diversify the fuel mix of their generation plant. Some of this will be done through the buying and selling of existing assets, but this diversification will also be reflected in the choices for new-build generation capacity.

9.2.2 Renewable electricity generation

Increasing the contribution of an otherwise under-represented technology to the electricity mix will increase the overall diversity of the system. This is perhaps a simple statement of fact, but it does rely on the assumption that the effect is not countered by a corresponding reduction of diversity elsewhere in the system.

The analysis of the evidence conducted for this thesis does indeed show that the addition of new renewable generation to the grid has the immediate effect of increasing diversity. This effect, however, is reduced very quickly, suggesting that any diversity gains for adding a new form of generation are lost as other plant is then retired. Increasing the UK's generation diversity is not the primary driver for expanding the renewables sector, but it would nonetheless be desirable

from the point of view of the resilience of the overall system. Furthermore, it should be noted that the chosen diversity indicator most likely underestimates the value of renewables as it ignores the 'disparity' metric, which describes how 'different' two technologies are from each other. Nevertheless, it is in the interests of system resilience to understand whether this tailing off in diversity can be mitigated to leave a lasting net benefit.

What the analysis of renewables policies shows is that where such incentives are in place, there is evidence that this drop-off is slowed to some extent. Comparing the two groups (those with renewable support and those without) shows a clear difference in the diversity of the two groups. The mean SWI in groups with renewable support is approximately equal to 1, whereas the mean SWI of the groups with no support mechanism is 0.5. The effect of introducing a support mechanism leads to an increase in SWI of 0.3, suggesting that much of the sustained difference between the two groups can be attributed to the presence of the support mechanism.

These results, therefore, are somewhat ambivalent about the hypothesis that adding renewables to the system increases system resilience by means of increasing diversity. There is certainly an initial increase in SWI following an increase in the renewables proportion, but it is less clear that this is not offset over time by a subsequent change elsewhere in the generation mix. There is some evidence, however, that the use of policy intervention can have more of a lasting positive effect on the diversity of the system. Again, the SWI indicator fails to value how dissimilar renewable generation technologies are from the existing stock in terms of their fuel consumption, their physical design and their network characteristics. Furthermore, the levels of renewable penetration remain low and relatively novel, so the drop-off effect should not be overstated.

9.3 Energy Intensity & Prices

Energy intensity is a measure of the extent to which a society or an economy is dependent on the electricity system. It is one proxy for the exposure of that economy to the collapse of the electricity system should it occur. In this research, both the economic electricity intensity (kWh/GDP) and the per-capita electricity intensity (kWh/capita) were analysed.

The UK's economic energy intensity has been in steady decline over the past 30 years, whereas, apart from a drop in the last three years, the electricity consumed per person in the UK has steadily increased over the same time period.

The price of electricity to both industry and households has increased since 1980, and has seen a particularly steep rise since the beginning of the 21st century. The UK's economic productivity is protected to some extent against this rise since the per-GDP electricity consumption has decreased. For households, this is not the case: the high prices, combined with the increasing dependence on electricity, makes consumers more vulnerable both to price spikes and physical supply shortages.

Many of these changes in the intensity of electricity use and its price can be attributed to wider economic changes such as the decline of manufacturing in many of the OECD countries and the increase in commodity prices in the global markets. This research considered whether, first, privatisation and liberalisation were protective or exacerbating factors, and second, the extent to which the recent expansion of the renewables sector has contributed to the changes.

9.3.1 Liberalisation and privatisation

As has been mentioned before, there were a number of reasons – some ideological, some economic – for the privatisation of the UK electricity sector. One central reason, however, was the belief that liberalised, competitive utilities would operate more efficiently, and crucially, that the efficiency savings that resulted would be passed onto consumers.

The overall liberalisation indicator does not appear to have any relationship with the electricity demands of either the economy or individuals within society. Furthermore, whilst there are differences between countries that chose or did not choose to introduce a liberalised pool or to privatise, this difference does not appear to be a causal one. This contrasts with the effect that this indicator had on the electricity price, which for both industrial and domestic consumers increased as a result of increasing overall liberalisation.

On the 'liberalised pool' indicator the evidence suggest that those countries that introduced a pool early tended to have both higher economic electricity dependence (kWh/GDP) and individual electricity demand (kWh/capita). Conversely, countries that privatised their electricity systems had comparable levels of per-capita electricity consumption but consistently and significantly lower per-GDP electricity consumption.

The impact of creating a liberalised pool and privatising the electricity assets has a minimal effect on the electricity prices. Any effect of these interventions on energy intensity does not therefore seem to operate via a price mechanism. There is, however, evidence that vertically

unbundling the power sector tends to increase both domestic and industrial electricity prices. Again, this runs counter to the view that unbundling should lead to increased competition and thereby result in lower prices for consumers. These data suggest that countries that chose instead to allow power companies both to supply and to distribute and transmit electricity, had lower price increases than those that opted for more aggressive unbundling.

There may be two factors at play to explain the either neutral or perhaps adverse effect of liberalisation on electricity prices. First, whilst there is evidence from the literature that the efficiency of operations did increase in the power sector as a result of privatisation and liberalisation (Newbery, 2001), the resulting savings are not necessarily passed on to consumers. Second, countries with a state-owned power sector have are more likely to subsidise the price of electricity (Bacon, 1995). By shifting some of the burden of electricity from consumers to taxpayers, this may inflate the perceived efficiency of state-owned operations, and correspondingly depress the perceived savings resulting from increased competition.

9.3.2 Renewable electricity generation

Costs associated with renewable electricity generation technologies tend to be higher than those for incumbent technologies. A study by Parsons Brinckerhoff (2010), for example, produced the following breakdown of estimates of levelised costs by generating technology:

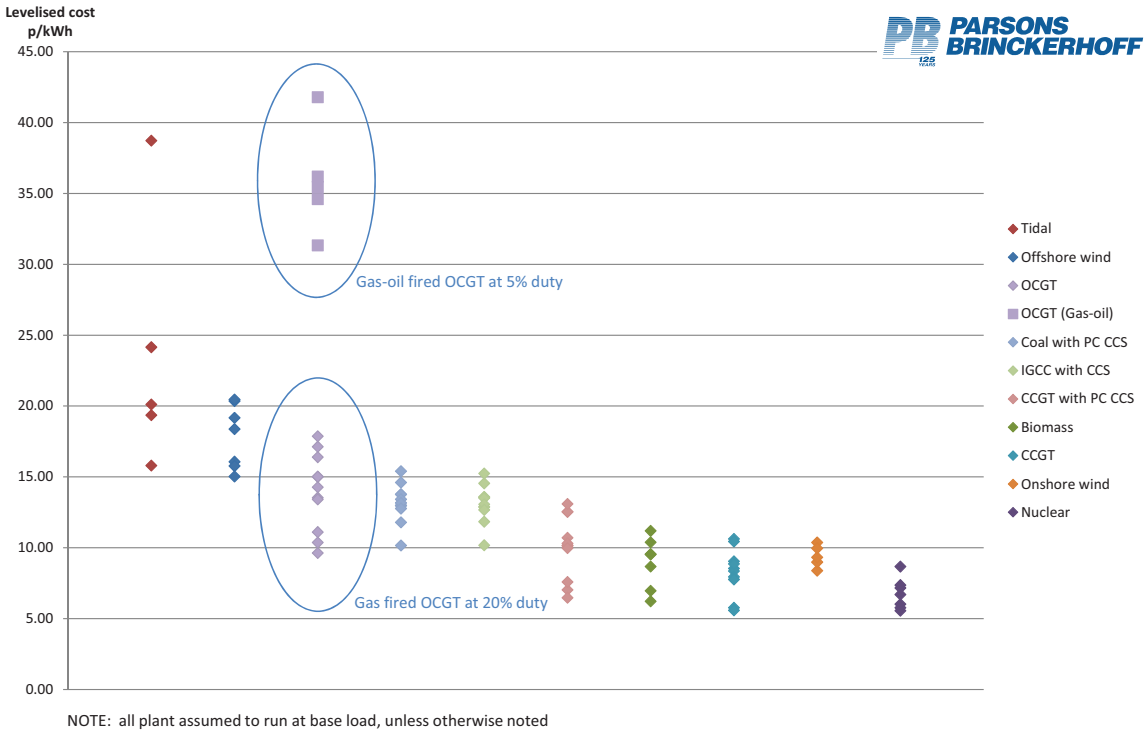


Figure 9.2: Estimate of 2010 levelised costs by generating technology

These estimates take into account a projection for future carbon prices but, with the exception of onshore wind and biomass, the costs of new renewables is significantly higher (and more uncertain) than the cheapest conventional alternatives (nuclear and CCGT).

The analysis conducted for this thesis shows that an increase in the proportion of new renewables onto the electricity system has a depressive effect on both per-GDP and per-capita electricity consumption. The most likely cause of this is via the price of electricity. This is confirmed by the analysis of renewables penetration on electricity price. An increase of 10% in the proportion of renewables increases industrial electricity prices by, on average, 1 cent (US) per kWh of electricity. For households this figure is between 3 and 5 cents for the same increase in renewables. Householders, therefore, appear to take more of the price increases associated with renewables, and this has been reflected in the reduction in an otherwise upward trend in domestic electricity intensity.

9.4 Energy Independence

The Import Dependence Indicator (IDI) reflects the amount of fuel required for generating electricity in a given country, and the proportion of that fuel that has to be imported. There is no single trend across the OECD, but the UK's IDI has been steadily rising over the past thirty years. This has arisen because of a decline in the indigenous production of both coal and gas, and in particular as a result of an increasing reliance on gas-fired generation. The renewables sector is intended to deliver some degree of energy independence, but as yet the levels are too low to have a strong effect on the IDI.

9.4.1 Liberalisation and privatisation

Taking the OECD as a whole, the analysis of the data reveal some small effects of liberalisation and privatisation on the IDI, but none of them are strong enough to suggest there is any real relationship between privatisation or liberalisation and energy import dependence.

The fact that there is no overall effect across the OECD countries does not mean that privatisation and liberalisation had no impact in the UK. As was discussed previously, one of the motivating factors for privatising the electricity was to diminish the power of the unions, and in particular to decrease the country's reliance on coal. The decline of the UK coal mining industry has been more rapid than the closure of coal-fired power plant. As a result, of the fuel commodities required for the UK's electricity production, coal was the most significant contributor to the UK's increasing import dependence. Initially, this increase in dependence on imported fuels was mitigated to some extent by the 'dash for gas' that followed privatisation. The contribution of gas to the IDI was at first neutral, as production from the North Sea was sufficient to meet the demand from new CCGT plant; once these gas supplies began to decline from 2000 onwards, however, the continued expansion of gas generation drove up the UK's import dependence.

Not included within the IDI measure is any sense of the diversity of fuel imports or the means to stockpile those fuels. The increased use of Liquified Natural Gas (LNG), and the diversification of the gas network would improve the resilience of the UK's current electricity generation mix to supply disruption, as would an increased use of gas storage. Nor should it be concluded that an increase in IDI is necessarily bad from the point of fuel security. It is, however, a reflection of the country's exposure to adverse events beyond its control. As such it is one measure of the resilience of the national system to events whose probability of occurrence cannot be changed,

and whose impacts must be mitigated.

9.4.2 Renewable electricity generation

The introduction of renewables, it has been argued, reduces a country's dependence on imported fuels, thereby increasing a nation's energy security. As was observed with the measure of diversity, the true effect of introducing a new generating technology depends on the subsequent response of the rest of the market, and the intuitive benefit can be offset by a change in another generating technology.

In the case of IDI, it seems that there is some evidence that introducing renewables reduces import dependence, and that the effect is sustained. Even more noticeable is the underlying difference in IDI between those countries that introduced a renewable support mechanism and those that did not. The IDI in countries that introduced renewable support was, on average, an order of magnitude higher than those that did not. Further investigation revealed that it was countries with FITs or tendering processes in particular that exhibited higher IDI levels.

An number of factors could explain this, but one likely explanation is that it is those countries that were particularly conscious of their reliance on foreign fuel were more inclined to use renewable generation as a means of reducing this reliance. Of the four renewable support mechanisms, FITs and tendering represent the two most interventionist approach. Tendering, in particular, is a quantity-based approach to delivering new generating plant. FITs take much of the future electricity price risk away from investors, and have proved to be successful in their aim of delivering the required new build.

It is possible however, that the apparent success of FITs and tendering is a manifestation of 'regression to the mean'. If countries with high IDI, for whatever reason, were more likely to opt for these policy mechanisms, the natural fluctuation in IDI for each country will tend to mean that high values decrease over time. This phenomenon may explain the apparent success of a number of policy interventions. A policy to reduce electricity prices, for example, is likely to be implemented when prices are considered to be above-average. A subsequent decline in prices could occur either because of market forces correcting the anomaly, or because the policy is indeed effective. The purpose of a multi-country statistical analysis is to distinguish between these two explanations. Where the explanatory variable is dependent to some extent on the outcome variable (as in the case where FITs and tenders are more likely in high IDI countries),

a large proportion of this 'regression to the mean' effect may remain.

This chapter has attempted to understand how privatisation, liberalisation and renewables policies have historically affected the resilience of electricity systems. In the next chapter the findings of this, and previous, chapters are discussed in the context of UK policy. A number of policy changes are being proposed for the regulation of the UK's electricity system. Some directly address issues of security; others do not, but may impact on security indirectly. The intention is to understand how the historic experience of the OECD countries should best be used to inform these policy proposals, and to understand what adverse (or beneficial) impacts on resilience may be expected.

9.5 Conclusions: What role have policy changes had on electricity system resilience?

This chapter attempted to consolidate the statistical analysis on the resilience indicators in order to understand first, what trends can be seen in the UK and the OECD countries and second, what role privatisation, liberalisation and the expansion of the renewables sector have played in those trends.

Resilience trends

Based on an aggregate view of the resilience indicators identified, the UK's electricity system has experience decreasing resilience overall since the 1980s. Although not universal, this trend was also seen in the wider OECD. The trend has not, however, been the same for all indicators:

- *Capacity margins* have seen a particular decline in the UK, but this has to a lesser extent been a trend visible in most OECD countries.
- *Diversity* of generation technologies has increased considerably in the UK, driven by a large increase in the use of natural gas for electricity generation. Except for countries dominated by large hydro plant, this trend towards increasing diversity is replicated across the OECD.
- *Per-capita energy intensity* has increased in the UK and OECD countries as demand for electricity services increases with income. The UK's *per-GDP energy intensity*, by con-

trast, has declined, along with other OECD that have reduces the contribution from their industrial sectors and moved more towards being a service industry. Where the manufacturing industries remain an large part of an economy, however, the per-GDP intensity has increased.

- *Electricity prices*, both industrial and domestic, have increased above inflation levels across the OECD, including the UK. The domestic sector seems to have been particularly affected by these rises, and the rate of increase has been climbing since the early 2000s.
- *Import dependence* has varied across the OECD, but the UK trend is clearly defined. It has been increasing since the 1980s as indigenous coal stocks declined. Through the 1990s the 'dash for gas' in generation was matched by an increase in domestic gas production. However, since 2000 the need for imported fuel to supply the UK electricity generation fleet has accelerated.

Testing the association with policy change

Impact of privatisation and liberalisation

The data were analysed to assess impact of privatisation and liberalisation on the derated system margin. No effect could be seen, suggesting that if there was a relationship, it could not be a strong one. What was seen, however, was that countries that chose to liberalise already tended to have lower margins. This conflicts somewhat with the narrative that privatisation was primarily seen as a necessary remedy to excessive margins and 'gold plated' systems. This may have been a factor in some of the decisions, but there were countries with similar or larger margins that did not choose that policy route.

There was similarly little evidence for liberalisation affecting a country's energy intensity. Countries that had privatised consumed 40% less electricity per unit GDP, on average, but this is more attributable to the fact that countries that had wound down their industrial sectors tended also to undergo electricity reform, rather than privatisation causing any change in the use of electricity in the economy. Little effect was seen of privatisation on import dependence. This is not to say that there were not specific cases where a link can be found (the UK itself being a notable example), but the the relationship is not a universal one, and as such cannot be seen as a general effect.

Prices were generally increasing over the period of interest, but one might have expected liberalisation to have provided a buffer against these rises as industrial efficiency resulted in lower bills. In fact, the evidence points in the opposite direction, showing an increase in both industrial and domestic electricity prices in the years after liberalisation. This effect is on top of the underlying trend of increasing prices seen across the OECD.

Although low margins are now a concern for a number of countries' electricity systems, one of the rationales for privatising these systems was to allow seemingly excessive margins to be reduced. That privatisation and liberalisation seem not to have contributed to a decline in margins suggests that this goal was not achieved for these reasons. Further, the 'gold plating' under nationalisation was thought to be driving high prices, but if there is any effect on prices it is only to contradict this hypothesis. Rather, the impact of privatisation and liberalisation seems secondary to the other many changes that these energy systems were undergoing.

The exception to this is the relationship between privatisation and diversity. There is some evidence to suggest the diversity of investors arising from liberalisation drove the increased diversity of generating technologies. However, perhaps because of a herd mentality (Roques *et al.*, 2008) this effect was smaller than may have been expected. Rather, it was privatisation – the transfer of ownership from public to private hands – that seems to have driven generation diversity. The tendency of national operators to select a small number of generation technologies (such as nuclear generation in France) is manageable when tariff controls can protect consumers against the volatility of the power price. However, privatisation has tended to be occur alongside a reduction in such tariff controls. Under such conditions, there is an incentive on private operators to diversify their own portfolios, partly perhaps by the acquisition of existing plant, but also in the choice of new-build generating technologies.

A summary of the effects of liberalisation and privatisation is given in Table 9.1. This also summarises the effect of low-carbon policies on the resilience indicators, which have perhaps had a more significant effect that the preceding years of privatisation and liberalisation.

	Derated Margins	Generator Diversity	Energy Intensity	Price (ind. & domest.)	Import Dependence (IDI)	Summary
UK trend	Bumpy decline, flatter since 1980 but still declining	Increased considerably since 1980	Per-GDP decreasing as move to services. Per-capita increasing.	Bumpy increase over time with rapid acceleration since early 2000s. Dom prices higher than ind.	Increase since 1980s (coal mainly). Dash for gas from 1990 matched by production till 2000 then rapid IDI increase	With the exception of diversity and per-GDP intensity, all other indicators are suggesting a lowering of resilience for the UK
OECD trend	Declining but not in all cases	Increasing, except large hydro countries	Per-GDP: UK, USA, Norway, Ireland decrease, Greece, Portugal, Mexico increase. Per-capita universally upward.	Steadily increasing over the past two decades (in real terms i.e. 1990 prices) and the rate of increase has gone up	Mixture of trends. Denmark's has declined, as has New Zealand's. Greece, Spain, Turkey and US has increased	Mixed story across the OECD. Again, diversity tends to increase, but margins are declining. Price is universally increasing as is per-capita intensity
Overall liberalisation	No effect overall or on subset. However, for countries that chose to privatise, liberalise or vertically unbundle, derated margins tended to be lower	Overall liberalisation tends to increase diversity, even controlling for GDP	No relationship either per-GDP or per-capita	Increase in industrial and domestic prices in the years after liberalisation	No discernable effect or underlying difference	Overall liberalisation has improved diversity but there may have been a price increase. Little effect on margins or the other metrics
Liberalised pool		Weak positive association	Mean intensity has been declining in lib countries but only weak effect	No effect but liberalised countries tended to have lower prices in early years	Liberalised countries tend to be less import dependent and eventually lib causes a decrease	Liberalisation component has had weakly positive effects on diversity, intensity and import dependence
Privatisation		Strong positive effect, 3 times larger than overall lib	Privatised countries 40% lower per-GDP intensity but no causal effect seen. No per-capita difference, but increasing in both groups	No effect but privatised countries had higher prices typically	Privatised countries tend to be more import dependent, but this is not an effect of privatising. The reverse might be true - import dependence leads to privatisation	Impact of privatisation limited to improving diversity, but this has been a strong effect
Vertical Separation		No effect of any sort of vertical unbundling	No good evidence that unbundling has any effect, nor is difference seen	Trans-gen separation gave small (5%) but significant increase in price esp. domestic	No difference or effect can be seen	Almost no effect on resilience seen, but maybe an increase in prices
Renewables proportion	Renewables increased absolute margin and even derated margin to some extent	Initial positive effect, but it it not necessarily sustained in future years	Increased renewables leads to small per-GDP drop, but strong downward effect on per-capita intensity	V. strong effect, particularly on domestic: 1% renew increase gives 5% price increase after 4 years	As expected, import dependence decreases with increasing renewables	Renewables have been positive for resilience on all metrics except for price
Overall renewable support	No effect, but renewable support more likely if margins are low	It is more that diverse systems tend to implement renewable support	"Support" countries tend to have lower intensity on both measures, but only weak evidence that this is causal	If policy has an effect it is a lagged one. Certainly less immediate than the installation of renew capacity itself	No effect, but stong evidence that renewable support tends to be offered if IDI is high	The implementation of policy measures overall had little effect
FIT	FIT seems to increase derated margin by 5%. Margins were also higher to start with in FIT countries	Diversity higher in FIT countries but no effect of their introduction	Same for FIT & RO countries. These countries less intensive, but only a weak effect of the intervention	FIT & RO typically implemented in countries with high prices. Have either no effect or a small upward effect	FIT countries tend to have higher IDI, but no causal effect	Feed-in tariff improved derated margins. A small decrease in intensity corresponds to a small increase in prices
Quota/ RO/ TGC	No effect on margin. But TGC countries had lower margins, as did the countries that tendered or had grants. Negative effect seen probably more because margins recovered after they stopped	First RO countries had low diversity but inconsistent and no effect seen			No difference or effect can be seen	Renewable Obligation-type mechanisms did not damage the derated margin but did not help.
Tendering		Tendering sporadically applied. No effect visible	No evidence of difference or causal effect	Typically used in countries with lower electricity prices. May be weak depressive effect on prices	Data too limited to draw conclusions	Almost no effect could be seen, but the sample was small
Tax incentive/ Grant		More widespread. Countries typically more diverse but no effect seen	Very small difference between groups but no effect seen	Slight reduction in prices seen, particularly domestic	No difference or effect can be seen	Almost no effect could be seen, but the sample was small
GDP	Strong causal effect on capacity and demand, but no overall effect on margin	Increase in GDP has effect of increasing diversity	-	-	-	GDP greatly affected capacity and demand, but the net effect on margins was small. GDP did however increase diversity
Electricity price	Price increase reduces demand and increases capacity. Individual effects not significant but significant enough to increase margin	-	-	-	-	Electricity price had small impact on capacity and demand but was enough to show up as an effect on margin
Summary	Majority of difference occurs before liberalisation. Overall_lib itself shows no effect. Renewables did not increase derated margin unless FIT. GDP affected capacity and load but not margin, whereas price did increase margin.	More liberalised systems also tend to be more technologically diverse. Overall_lib further increases diversity even after controlling for GDP, but this is more to do with privatisation than liberalisation.	Per-capita intensity has been increasing across the OECD. Per-GDP has declined for those countries moving to service industries. Little if any effect from overall_lib, but intensity is pushed down by new renewables, probably via price increases	Real prices increasing in nearly all countries, and rate of increase has been going up. Overall_lib seems to have increased prices, which is unexpected. Impact of renewables is more significant though. Role of policy here is not clear but likely to be weak.	Mixed across OECD. UK has increasing IDI for 20 years. Increased coal use with declining indigenous production, followed by dash for gas and declining North Sea production. Adding renewables to the system results in lower IDI as expected but no policy stands out	Key:
						Detrimental effect
						Weakly detrimental effect
						No measurable effect
						Weakly positive effect
						Positive effect

Table 9.1: Summary of policy impacts on resilience

Impact of renewables expansion

The primary purpose of renewable generating technologies is to reduce the use of fossil fuels for electricity generation. Arguments have been made, however, that security could be harmed by reducing the effective capacity on the system. Conversely it has also been argued that such technologies would be beneficial to overall system security by diversifying the electricity mix and reducing the dependence on imported fuels. This research has been able to test each of these claims.

First, an increase in renewable generation can be shown to increase the effective derated margin on the system. This approach, in principle, accounts for the variability inherent in non-dispatchable plant such as wind and solar technologies by using their 'capacity credit' rather than their nameplate capacity. The renewables expansion has, therefore, been beneficial in providing additional capacity. This is particularly so in the case of countries that have used a Feed-in Tariff mechanism to encourage investment. In practice, there remains some uncertainty about the precise measure of 'capacity credit' for a given electricity system, but there seems to be little reason for concern, and certainly not at the levels of penetration seen to date.

The case made for renewables providing diversity of generation seems less strong, however. Although the initial effect of introducing more renewable capacity onto the system is to increase diversity, this effect seems to wear off as older plant is retired. However, the reduction in import dependence was a visible and sustained result of increased renewables. In this way, although renewable generation in itself presents uncertainties, its inclusion in the generation mix reduces dependence on fuel supplies beyond the control of national borders and institutions.

Renewables, then, improve the effective margin on the system and reduce the dependence on imports. However, this seems to come at a cost in the form of electricity prices. An increase of 1% in the level of renewables on the system is associated with a 5% increase in domestic electricity prices. If the ability to afford electricity is to be considered an important indicator of resilience, then, the benefits of renewables need to be tempered by this observation.

That renewable generation seems to have inflated prices historically does not preclude the possibility that future fuel prices will rise and that renewable technologies will become more affordable. However, as the expansion of the renewables sector increases, policies to prevent an adverse impact on fuel poverty may be required if societies are to remain resilient to future increases in the cost of generating electricity.

The conclusions of this chapter do not present a single story for the impact of either liberalisation or the expansion of the renewables sector on electricity system resilience. Apart from diversity, liberalisation has had surprisingly little effect on resilience – a fact that will be relevant to ongoing policy discussions about the future of the UK system. Perhaps more important has been the way in which liberalisation has been done and the underlying characteristics of the country in which it has been implemented. Further, the introduction of large-scale renewables projects has been the more significant factor for the resilience of electricity systems in the past decade, and this trend is likely to continue.

The largely positive impact of such expansion on the resilience of these systems should be encouraging to policymakers, but the evidence also suggests that these benefits can be transient if not managed through appropriate policies. The following chapter considers the proposals being put forward by the UK Government and attempts to understand these proposals in the light of their historical context.

10

Assessing future policy in the light of the historical analysis

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This chapter considers the most recent UK policy documents, and attempts to review their proposals and findings from a "resilience" perspective. The Electricity Market Reform (EMR) consultation (DECC, 2010a) provides a particular focus for this chapter because of its direct significance for policy change; however, other relevant policy documents are considered and discussed:

- The UK Low Carbon Transition Plan (DECC, 2009c)
- The UK Renewable Energy Strategy (DECC, 2010c)
- Ofgem's Project Discovery (Ofgem, 2010)
- Energy Market Assessment (DECC, 2010b)

In particular, this chapter focuses on the Electricity Market Reform (EMR) document's proposals, which are "designed to ensure that low-carbon technologies become a more attractive choice for investors, and adequately reward back up capacity to ensure the lights stay on." The reform proposals discussed in the EMR consultation include:

- Carbon price support (CPS)
- Feed-in tariffs (Premium, Fixed, Contract for Difference (CfD))
- Targeted capacity mechanism
- Emissions Performance Standard (EPS)

10.1 Generation System Margin

The findings of this thesis are broadly that, despite some initial concerns, the history of privatisation and liberalisation has not been detrimental to system margins in the OECD countries. The Electricity Market Reform (EMR) consultation document agrees with this finding in the specific case of the UK, where it states that the "market has performed well" and has "delivered the almost 30GW of gas generation currently in operation and maintained an adequate capacity margin".

The concern for the margins in the generation system, then, are not based on historic performance, but rather express concern about the impact of delivering the UK's other energy policy objectives. As the EMR puts it, "as the UK progresses in decarbonising the electricity sector, the Government will need to ensure that electricity supplies continue to be secure" (DECC, 2010a). It goes on:

> Over 19GW of nuclear, oil, coal and gas plant is scheduled to close over the coming decade as stations reach the end of their design lives and due to the effects of environmental legislation. Over 20 GW of new capacity is either in construction or development and will therefore enable the UK to maintain secure supplies for the time being. However modelling shows that de-rated capacity margins will reduce in the latter part of the decade from circa 20% to below 10% and we need to ensure that the market design provides the right investment signals for both new baseload gas

> plant and the additional flexible plant that is required to ensure system balancing in the latter part of this decade and into the 2020s (DECC, 2010a).

Similar concerns are expressed in the Low Carbon Transition Plan (2009) report about the intermittency of renewables such as wind, particularly if plans for higher levels of penetration to 2020 are achieved. If the market provides the adequate price signals, the theory is that market participants will invest in the appropriate levels of conventional generation to exploit periods of high electricity prices when the intermittent sources of electricity are unavailable. Levels of renewables penetration across the OECD remain relatively low in comparison with the UK's future targets, so predictions about market behaviour at high penetration levels are based more on theory than experience. As the LCTP states: "Since our electricity system has never experienced this level of plant intermittency and price volatility before, there is a lot of uncertainty as to how prices will behave in reality" (DECC, 2009c).

Ofgem's Project Discovery (2010) questions whether existing arrangements will deliver the price increases required to make the economic case for building new CCGTs viable. The reduced load factor for these plants that would arise as a result of the additional renewables would mean that the electricity price would need to rise to make the case for investment. This, the report concludes, would require supply scarcity (in the form of low margins) to ensure that prices were sufficiently high. This conclusion, it argues, provides the justification for further intervention in the market as the renewables penetration levels increase.

> An alternative outcome is that CCGT investment may not be forthcoming because investors become concerned about the risk of future government intervention to address these issues (e.g. promotion of CCS and nuclear) and thus of stranding assets in the future. In this case, the system would experience a reduced level of security of supply in the 2016-2020 period before new CCS/nuclear plant comes on stream (Ofgem, 2010).

The analysis conducted for this thesis showed that there was little evidence that either liberalisation or privatisation has had a detrimental impact on countries' ability to delivery sufficient levels of capacity to meet demand. Furthermore, the experience of building new renewable capacity to date has had a positive effect on margins, providing a protective level of system security, even when the contribution made by variable generation is derated appropriately.

This may be a situation where the past is not especially useful for predicting the future. The main difference between now and the past 20 years is that a rapid new-build programme is needed in the UK, and this has to be done whilst attempting to meet a number of environmental objectives. In the EMR report by the Energy and Climate Change Select Committee, it argues:

> . . . it is not clear that the policies introduced in the EMR Consultation would increase the overall capacity margin in the next ten years because of the lead times involved in building new low-carbon plant and the low "de-rated" capacity of wind power (ECCC, 2011).

The argument here is that, whilst the expansion of renewables has not in the past necessarily reduced derated margins, wind power is perhaps not the optimal way to add capacity rapidly to the system. The evidence from this thesis shows that, historically, the UK's choice of a Renewables Obligation (RO) as the means by which to deliver new-build renewable generators may explain in part why it is not seen as likely that margins can be significantly increased without substantial change. The Feed-in Tariff mechanism, by contrast, is the only incentive mechanism that has a track record of adding renewables whilst resulting in a net benefit to the overall derated margin.

Nevertheless, past experience of these policy mechanisms remains limited, and there will continue to be large uncertainty about how best to implement the measures. Particularly as the proportion of electricity delivered by non-dispatchable plant increases, the behaviour of the system and of investors becomes less certain still. At current levels, the amount of wind on the system is manageable under existing operational arrangements, but increasing levels will need to be managed by increasing levels of balancing plant:

> At present, there is very little wind on the system and therefore dealing with its intermittent nature is not a problem. It will only cause problems once there is a much greater penetration on the system. At the moment, levels of intermittent renewables are forecast to reach the scale at which balancing starts to be a problem around 2020." (ECCC, 2011)

Delivering both the wind capacity itself, and the additional balancing plant to maintain the overall margin, has potential risks. The three other main proposals will affect these risks in different ways:

10.1.1 Emissions Performance Standard (EPS)

The Emissions Performance Standard (EPS) proposed by the government consultation would set a limit on the per-kWh CO_2 emissions allowed for a power plant. In responses to the consultation, this proposed measure has come under some criticism (ECCC, 2011), primarily because it is seen by many to be redundant, given the other proposals being put forward. Indeed, the DECC consultation itself acknowledges that the EPS would be a "regulatory backstop" within a "package of reforms to prevent the construction and operation of new unabated coal-fired power stations" (DECC, 2010a).

Some contributors have further argued that the EPS would contribute an additional, unnecessary layer of regulatory uncertainty. The HoC 2011 report cites evidence that the EMS proposals "could in fact undermine policy certainty and credibility, thus introducing a negative impact on investment in low-carbon capacity". This counterintuitive conclusion, the report argues, arises from the recognition of two possibilities:

1. The Welsh Power Group, in its response, expressed concern that an EPS could, over time, be made increasingly stringent. By potentially being applied to future gas-fired plant, this could provide a source of investment uncertainty.
2. RenewableUK's concern was that an EPS that did not align with the CO_2 targets and the Committee on Climate Change's emission reduction pathway would lead to "mixed messages".

It is not clear whether these specific objections are valid, but it seems likely that the EPS, as currently proposed, is unlikely to contribute to the decarbonisation of the UK electricity system. It has already been noted that investor uncertainty is one of the key concerns for delivering the UK's required level of new build. If the EPS has little or no upside, the potential downside of adding further to this uncertainty seems unnecessary.

10.1.2 Carbon price support (CPS)

The introduction of a carbon price floor is intended to provide some stability to the carbon price, and thereby reduce the risk seen by investors in new renewables whilst also discouraging the construction of high-CO_2-emitting plant. In conjunction with the EPS, the construction of

new UK coal plant is made very unlikely in the future. One of the rationales here is that the carbon price is highly sensitive to policy decisions, and so is inherently linked to Government decision-making:

> Carbon price uncertainty is predominantly driven by wider regulatory uncertainties and the Government might therefore be better placed to manage some carbon price risk (HM Treasury, 2010).

The mechanism is, however, technology non-specific; as a result it will likely benefit all forms of low-carbon generation, including nuclear power. Whilst increasing the attractiveness of new nuclear plant for investors may benefit the overall margin, the proposed increase in non-dispatchable plant will require corresponding plant with fast ramp rates to mitigate the additional variability — this is most likely to be CCGT.

For investors in gas plant there is a need to see stability in the spread between gas and power prices. The Treasury report argues that although carbon prices have been volatile, the volatility of the gas price is much greater:

> While the carbon price is an important factor affecting investment decisions, the gas price is a larger source of uncertainty. Gas prices have historically been more volatile than carbon prices (HM Treasury, 2010).

A carbon price floor may encourage renewable generation and strongly discourage coal plant, but there remains an uncertainty about the ability of the proposed market and regulatory environment to deliver the CCGTs needed to balance the system. For this and other reasons, a capacity mechanism has been proposed, which is discussed below.

10.1.3 Targeted capacity mechanism

The EMR consultation (DECC, 2010a) proposes a capacity mechanism as a means to ensure that security of supply be maintained whilst meeting other energy policy objectives, saying: “it is necessary to introduce a capacity mechanism in order to provide greater assurance of the future security of electricity supplies” (DECC, 2010a, p.86). The need for such a mechanism is twofold: first, it is now thought uncertain whether a purely market-based system would deliver

the sorts of price signals needed to deliver large amounts of new capacity with sufficient speed; and second, that the specific mix of flexible plant required to balance the increasing levels of non-dispatchable plant requires targeted intervention.

On this first point, Ofgem's Project Discovery report (Ofgem, 2010) argues that "by providing an additional capacity revenue stream this may reduce the investment risk and lower the cost of capital (Ofgem, 2010)". A particular concern for potential investors in CCGT plant is that they will be under-utilised, and that price spikes will be inadequate to recoup the initial investment. A capacity mechanism may alleviate some of this risk by offering a secondary means by new plant can generate revenues.

A DECC memorandum on the EMR consultation reiterates this view:

> 'The Government believes some form of capacity mechanism is necessary to ensure security of supply in future. Analysis suggests that as levels of low carbon generation increase, the price signal alone may not be sufficient to incentivise adequate levels of the additional flexible backup capacity required to run for only a few hours operation a year (DECC, 2011).

This also highlights the need for flexible capacity, which is not incentivised by any other proposed intervention. The capacity mechanism is, in part, intended to perform this role:

> Support for low-carbon technologies such as wind and nuclear energy (through the Feed-in Tariff) will skew the system in favour of generation that cannot easily or reliably respond to short-term peaks and troughs in demand. The proposed capacity mechanism is intended to counteract that difficulty by paying plant for being available to generate, because it is likely to generate for much shorter periods during the year and find it hard to recover its fixed costs from energy sales." (ECCC, 2011)

It has been argued before in this thesis that, unlike the electricity itself, the 'energy security' component of the electricity system exhibits some collective good characteristics, at least in some spacial dimensions: system security is non-rival (security is not part of a zero-sum game in which one must lose for another to gain) and non-excludable (it cannot be given to one consumer but denied to his neighbour). For this reason, security will tend to be undersupplied, which is why a grid operator has always required the additional purchase of various balancing services. The

retaining of additional capacity is an extension of this idea. Indeed, as the Energy and Climate Change Select Committee reports:

> The Welsh Power Group also proposed an extension of the role of the SO as a central buying agency for more reserve capacity to balance increasing intermittency. National Grid agreed that "the mechanisms currently employed by National Grid as System Operator to procure 'balancing services' could also be extended or amended to provide additional 'back-up' capacity (ECCC, 2011).

Of the five investigated, system margin is the indicator about which most concern has been expressed in the policy literature. Undoubtedly margins have declined in the UK since privatisation began, but that is not necessarily sufficient evidence to support the idea that privatisation or liberalisation caused this change. Indeed the analysis of OECD countries found no consistent effect on any of the liberalisation indicators. It cannot be concluded, however, that privatised systems will therefore continue to deliver adequate margins. Indeed, there are good reasons to believe that the rapid capacity expansion required in the UK will not be achieved without some sort of intervention.

The UK's electricity system has in the past benefited from adequate (some have argued excessive) margins, so relatively little new-build capacity was needed. The next twenty years are unlikely to reflect the past twenty years, however. The closure of a large amount of renewable plant, the implementation of the LCPD, and the need for new generation that meets the government's environmental objectives have the potential to leave a supply shortfall.

On the question of renewables, the statistical analysis showed that the net effect of expanding the renewables sector was to increase a system's margin. An increase is not necessarily of overall benefit, as non-dispatchable plant such as wind requires additional backup capacity to achieve a given level of LOLP. By analysing the derated margin, an estimate of the real contribution of new renewables to system security was made, and it was found that renewables still provided a net benefit.

There was, however, a caveat on these results: in some cases the initial benefit of increasing the proportion of new renewables was dissipated over time as older plant was eventually displaced. The speed of this tailing-off appears to depend on the policy that brought about the renewables expansion. The sample size available was small, and should be interpreted with caution, but it appears that where renewable generation was introduced primarily as a result of a tendering

process, or through specific tax breaks, the derated margin actually decreased by 7%. Where Tradeable Green Certificates were used (such as the Renewables Obligation), there was no effect on the derated margin. The only policy that saw a benefit in terms of the margin was the Feed-in Tariff schemes. These saw an sustained increase of 5% to the derated margin, suggesting that the new renewable plant was able to be added to the system without displacing the existing conventional plant.

The proposals in the EMR agree with the findings of this thesis that there is little reason to suppose that liberalised markets have been unsuccessful in maintaining the desired levels of system margin. However, they also reflect a large amount of uncertainty for the future. This reflects both the relatively short time horizons under which liberalised electricity markets have operated, and the new challenges of ageing networks, increasing demand and the need to deliver on carbon-reduction commitments.

The UK government has a range of strategies it could adopt. At one extreme is the 'do-nothing' option where the existing market and regulatory mechanisms are deemed to be capable of maintaining adequate levels of reliability. Perhaps the opposite extreme would be some form of direct state investment in the electricity generation sector, or a return to state-owned and centrally planned operation. In between these two extremes lie policy actions such as those aimed at addressing regulatory problems and overcoming market barriers, as well as more direct interventions such as the reintroduction of a system of explicit payments for the provision of capacity.

A significant additional layer of complexity is that markets do not just respond to price signals and market information: they also respond to actual or anticipated policy actions. Generating companies will thus base their investment decisions on both market appraisal and assessments of the direction of future government policy (Gross *et al.*, 2007a). One consequence of this is that companies may choose to delay investment until the policy landscape is clearer, which could have significant implications for investment and hence system margin. This uncertainty might suggest that a 'wait-and-see' approach is most appropriate, allowing policies to be adjusted in light of any new developments. The danger is that this creates a self-fulfilling prophesy of anticipated, then real, intervention: if investors believe that the government might intervene in the market it would be prudent for them to exercise the option to wait. If all investors wait, then policy intervention becomes inevitable: "frequent revision of policy could lead to the worst possible outcome – no investment at all while players wait for the situation to become clear" (Scott and Watson, 2006)

The British market was one of the first to liberalise, and it still enjoys a higher degree of competition than the rest of Europe and most of the rest of the world. The British 'experiment' with liberalisation delivered efficiency gains and cost reductions during the 1990s. Since then, policy goals have changed, and both security and environmental commitments will require considerable investment and re-engineering. It remains to be seen whether the more limited set of levers policymakers have available under the liberalised arrangements will be sufficient to balance the benefits of the market in delivering higher efficiency and lower costs against the risk that the market will not deliver the levels of supply security which the UK has hitherto enjoyed.

10.2 System Diversity

The findings of this thesis show that, even after controlling for GDP, an increase in the overall level of privatisation and liberalisation is positively associated with an increase in diversity. Further analysis revealed that this was explained primarily by the measure of 'privatisation'. It was not the increase in competition that induced an increase in the diversity of the generating mix, but rather the transfer of ownership from the state to private hands.

The Electricity Market Reform consultation (DECC, 2010a) states the Government's ambitions for diverse electricity generation as follows:

> Our mix of electricity generation capacity should be diverse, so that problems with one technology or fuel do not lead to the failure of the entire electricity system. Diversity can be technological (a wide range of electricity generation technologies) and geographic (primary fuels imported from a wide range of countries). Diversity can also address uncertainty as it helps to address the issues around technology costs maturing at different rates over time, and so reduces the overall costs we might face if we put our faith in only one or two technologies.

One of the consistent arguments in favour of low-carbon technologies is that it would increase the diversity of the generation mix, and to reduce exposure to global commodity prices. This sentiment is illustrated by the Energy Market Assessment:

> Developing sources of low-carbon energy will help to diversify energy supply so as to

> strengthen the UK's resilience to any geopolitical instability or global price volatility (DECC, 2010b).

Analysis of the data for this thesis revealed that, indeed, the addition of new renewables increased the diversity of a generation system. By looking at the lagged effects, however, it also showed that such increases could rapidly dissipate as old plant then closes. This diversity drop-off can be mitigated through the use of policy interventions, but the evidence is not sufficiently strong to say which mechanisms are best placed to achieve this effect. The conclusion, therefore, is that diversity is not a guaranteed result of increased investment in renewables, and that governments should consider carefully their interventions to maximise the benefit to the generation mix.

This seems to be reflected in the policy literature. Ofgem's Project Discovery report, for example, notes that there is a risk in introducing Capacity Tenders of reducing the diversity of the generation mix: "if tenders are highly specified in terms of technology, the benefits of diversity on security of supply may be undervalued" (Ofgem, 2010). Following Jim Skea's work on valuing diversity (Skea, 2010) it may be possible to design a tendering mechanism that incentivised generating technologies that were dissimilar to the existing stock, but this has not been proposed in recent policy proposals. The Ofgem report highlights similar problems with the notion of capacity mechanisms, saying "the Central Energy Buyer may undervalue the diversity that a more competitive market may deliver"

Project Discovery (Ofgem, 2010) notes that the introduction of a carbon price floor, while achieving low carbon investment, could also improve the diversity of the generation mix by reducing the proportion of gas-fired generation. It also notes, however, that such a mechanism would likely lead to the early closure of coal-fired power stations. The Redpoint analysis conducted for the EMR, however, suggests that the driving effect of the carbon price floor would be to encourage new nuclear, which would not necessarily lead to an increase in system diversity:

> ... nuclear is favoured over CCS when the investment incentive is purely based on a market-wide price signal, as is the case under Carbon Price Support. This is because it is assumed to be lower cost and to mature earlier (Redpoint, 2010).

The report goes on:

> Under Premium Payments, Fixed Payments and Contracts for Difference there is a greater proportion of CCS since we assume that it would receive targeted support

> at a level that bridges the different funding gaps. As a result these options tend to promote a more diversified, but (initially) more expensive generation mix (Redpoint, 2010).

Under this analysis, then, the FIT has the most potential to deliver a diversified system. It seems clear that the net effect on diversity of any of the proposed policy mechanisms is uncertain, and depends on the specifics of how those interventions are targeted. The findings of this research seem to show that diversity is encouraged by privatising a system, and that this benefit can be maintained under appropriate policy regimes.

A resilient system is one that can cope well with a wide variety of unforeseen adverse scenarios. As has been discussed in previous sections, an electricity system, and in particular a privatised electricity system, is susceptible to adverse events that fall under the categories of 'uncertainty' and 'ignorance' (Grubb *et al.*, 2006). Diversity provides a hedge against a wide range of adverse scenarios. A system with a large number of disparate technologies makes a system resilient for a number of reasons. First, if the generation mix runs on a number of different fuels, an adverse event cutting off the supply of one of these fuels is unlikely to affect all generators. Second, any adverse-event that is technology-specific (such as droughts forcing certain generators to shut down as a result of a lack of coolant) is minimised if the affected technology represents only a small proportion of the overall technology mix.

In contrast with generation system margins, which have been considered by many commentators to be threatened by privatisation, diversity drew little of such attention. The 1995 White Paper, "The Prospects for Nuclear Power in the UK" ((DTI, 1995), cited in (Helm, 2002)), states, for example:

> "the government cannot identify any reasons why the electricity market should not of its own accord provide an appropriate level of diversity"

In the years since 1980 the diversity of the UK's electricity system has steadily increased. This has been caused largely by the increased use of natural gas for electricity generation, but the trend has not been consistent across the OECD countries. This thesis attempted to discern some general relationships between regulation and diversity:

- Will the real market (as opposed to a theoretical idealised market) deliver adequate levels of diversity?

- What regulations, if any, are necessary to ensure that this diversity can be achieved?

The statistical analysis found that the overall indicator of privatisation and liberalisation appeared to have little if any effect on the diversity of OECD electricity systems. However, when these indicators were considered individually the 'privatisation' indicator seemed to lead to an increase in diversity. In other words, the technological diversity of the generating mix is increased most by transferring the ownership of the power system assets from public to private hands. This, more than the unbundling of generation and transmission assets, and more than the creation of a liberalised trading pool, is the component of 'overall liberalisation' that leads to an increase in the diversity of the generation mix.

The fact that privatisation, rather than increasing competition, seems to be the best predictor of increasing diversity reveals something about the underlying mechanism. If liberalisation had been the driver of increased diversity, this would have suggested that there would be a competitive pressure to diversify a company's generation portfolio. The fact that there is no significant correlation between liberalisation and diversity implies that no such driver exists, or that it is counterbalanced by some other mechanism. Once such mechanism is suggested by Roques *et al.* (2008):

> A perfect market should motivate individual investment decisions leading to the socially optimal fuel mix, but the conditions for this to hold are strong... In particular, herd behaviour (in which investors observe others' decisions, and assume they are based on superior information that justifies imitating their choices) may encourage investment in one or two dominant technologies...

The Roques *et al.* (2008) paper argues that whilst market liberalisation would hypothetically lead to an optimally diverse generation mix, this relies on the assumption of perfect foresight and perfectly rational price and risk behaviour. Since these conditions are never met, the observed lack of correlation between diversity and liberalisation is unsurprising.

It has been argued that one benefit of promoting a strong renewables sector is that it delivers the additional benefit of increasing the diversity of the overall system. The analysis of the evidence conducted for this thesis does indeed show that the addition of new renewable generation to the grid has the immediate effect of increasing diversity. This effect, however, is reduced very quickly, suggesting that any diversity gains for adding a new form of generation are lost as other

plant is then retired. These results, therefore, are somewhat ambivalent about the hypothesis that adding renewables to the system increases system resilience by means of increasing diversity. There is some evidence, however, that the use of policy intervention can have more of a lasting positive effect on the diversity of the system.

The policy interventions proposed in the EMR have the potential to affect electricity system diversity in different ways, and there remains some uncertainty about whether the resulting system following a policy intervention would emerge as being more or less diverse. Both Capacity Tenders and Capacity Mechanisms may prove to be too technology-specific and, as a result, dissuade a variety of technologies from being developed. A carbon price floor could increase diversity by reducing the proportion of gas-fired plant (Ofgem, 2010), or it could favour nuclear, in which case diversity could remain fairly stable (Redpoint, 2010). The Redpoint report also argues that FiTs may be the option that results in greater diversity.

It seems clear that the net effect on diversity of any of the proposed policy mechanisms is uncertain, and depends on the specifics of how those interventions are targeted. The findings of this research seem to show that diversity is encouraged by privatising a system, and that this benefit can be maintained under appropriate policy regimes, but that the best regime is, as yet, uncertain.

10.3 Demand and Prices

Both energy intensity and price are indicators of society's exposure to and reliance on the electricity system. The amount of electricity consumed to generate a country's wealth reflects how much economic loss would occur as a result of an outage. It is by no means a perfect indicator — some tasks may require a small, but critical, amount of electricity in order to function. The per capita GDP indicator reflects individuals' dependence on electrical services, and their exposure to system failure.

As with a number of other countries, the UK's economic energy intensity has been decreasing for a number of years. The OECD's per-capita electricity intensity showed an increasing trend in nearly all cases. The UK showed strong growth over this time period, although it peaked in 2005 and showed a considerable drop in 2009.

The price of electricity to both industry and households has increased since 1980, and has seen a

particularly steep rise since the beginning of the 21^{st} century. The UK's economic productivity is protected to some extent against this rise since the per-GDP electricity consumption has decreased. For households, this is not the case: the high prices, combined with the increasing dependence on electricity, makes consumers more vulnerable both to prices spices and physical supply shortages.

The statistical analysis found no effect of overall liberalisation on the intensity with which electricity is used. Whilst there are differences between countries that chose or do not choose to introduce a liberalised pool or to privatise, this difference does not appear to be a causal one. Similarly, no effect of overall liberalisation was seen on prices. Two possible explanations for this were considered: whilst there is evidence from the literature that the efficiency of operations did increase in the power sector as a result of privatisation and liberalisation (Newbery, 2001), the resulting savings are not necessarily passed on to consumers; second, countries with a state-owned power sector have are more likely to subsidise the price of electricity (Bacon, 1995), so the price reported would not reflect the true price of the commodity. By shifting some of the burden of electricity from consumers to taxpayers, this may inflate the perceived efficiency of state-owned operations, and correspondingly depress the perceived savings resulting from increased competition.

The expansion of the renewables sector was associated with a decrease in per-GDP and per-capita electricity consumption. There is the possibility of confounding here, as the more developed countries tend both to promote renewables and are expanding their service sector. The electricity price indicator is also associated negatively with electricity intensity, meaning that as prices go up the demand for electricity reduces. Finally, it can be shown that as the proportion of renewables on the system increases, so the price of electricity goes up. In this case, then, 'price' can be seen as a resilience indicator in its own right, but it is also the mediator by which renewables expansion reduces demand. Renewable generation increases prices, which in turn reduce demand.

The price paid by consumers for this renewables expansion does not appear to be shared equally between domestic and industrial consumers. The analysis revealed that for an increase of 10% in the proportion of renewable generation on the system, industrial consumers saw, on average, a 1c per kWh increase in their electricity price. For the same 10% increase, however, residential customers saw a 3-5c per kWh increase. This, combined with the contrast between the decreasing per-GDP and increasing per-capita consumption, means that domestic consumers are particularly susceptible to prices associated with an increase in renewable generation.

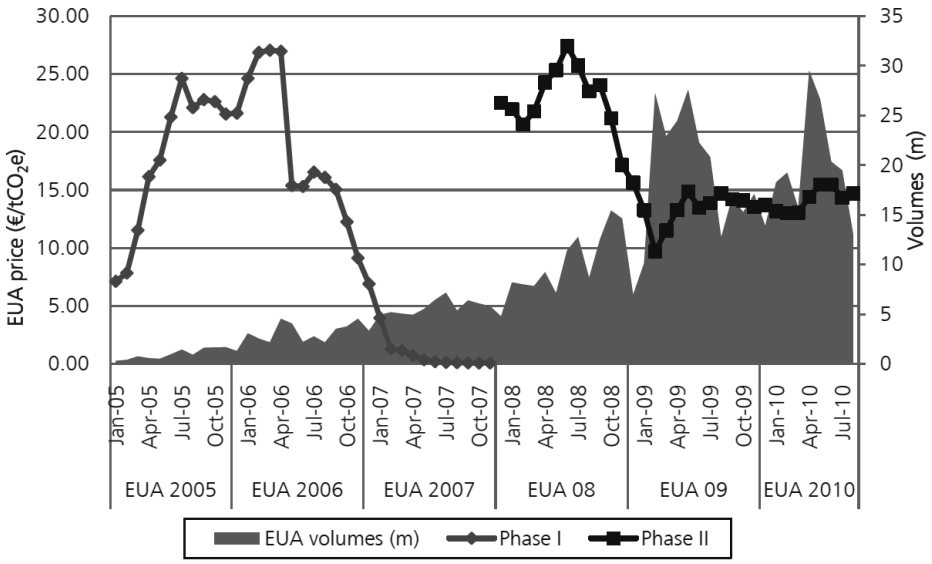
The EMR places a large focus on the price of electricity for consumers: "Competition in retail energy markets is an important means of securing consumer interests. It is vital that retail energy markets work to keep energy prices as low as possible, consistent with the need for investment to meet climate change and energy security objectives (DECC, 2010a)". However, Nick Molho (WWF) pointed out that "the one key area that, unfortunately, is not currently addressed by the electricity market reform is the potential for reducing energy demand in the long term" (ECCC, 2011). Indeed, there is a focus on Demand-Side Response (DSR), whose role the government sees as having "strong potential to assist system balancing and reduce costs", but none of the propose policy measures address overall demand reduction. It has been shown in the international community, however, that an expansion of DSR is associated with an long-term demand reduction as populations become more aware, and in some cases incentivised, to enact lifestyle changes.

Low prices are the overall objective of effective competition, as they have been in nearly every energy policy document to date. The report claims that the UK sees some of Europe's lowest electricity prices, but as has been argued this may have less to do with liberalisation than has been assumed. As margins shrink, such prices are likely to be pushed up; as the EMR observes: "individual bill numbers in any given year are less insightful because they will be affected by other issues in the sector, such as the capacity margin in that particular year which will also affect wholesale prices". Indeed, the statistical analysis of this thesis revealed an association between price and margin. There is therefore an inherent tension when it comes to electricity prices. High prices provide the incentive to build new capacity; a drop in prices dissuades investors, and a drop in margin pushes up prices. This balance is imperfect, however, resulting in long periods of excessively-large, or excessively-small amounts of generation on the system.

The stability of the electricity price will in future years be, at least in part, reliant on a stable carbon price. The EU Emissions Trading Scheme was introduced in 2005. In the first three years of trading (Phase I) the monthly prices of equivalent CO_2 emissions went from a start of €7/tCO_2e to a maximum of €27/tCO_2e. By the time Phase I was coming to an end, the carbon price under the EU ETS was virtually zero (Figure 10.1). Prices recovered following the reallocation in Phase II, but again dropped to a relatively stable position just under €15/tCO_2e.

Incentives for investors and the demands of consumer are in conflict. Where government can intervene, however, is in the volatility of forward power prices. As Figure 10.1 illustrates, the carbon price has been extremely volatile. The carbon price floor would reduce the downside risk for low-carbon investors and, if designed appropriately, could begin to reimburse consumers

when the EU ETS price became sufficiently high.



Source: Department of Energy and Climate Change (based on Point Carbon data), 2010

Figure 10.1: EU ETS monthly prices

Similarly, a form of capacity payment breaks, to some extent, the link between forward power prices and generator investment decisions. The FiT, as opposed to the RO, is seen by Government as a means to reduce price uncertainty to investors, whilst maintaining "exposure to the short-term electricity price signal, incentivising efficient operational decisions by generators".

The analysis conducted for this thesis shows that renewable generation can have a significant effect on the price of electricity, adversely affecting electricity consumers. Mitigating this effect without in turn dissuading further investment in new generation remains a pressing challenge for government.

10.4 Energy Independence

The Import Dependence Indicator (IDI) reflects the amount of fuel required for generating electricity in a given country, and the proportion of that fuel that has to be imported. It reflects the exposure of a country's electricity system to fuel sources outside its regulatory control. The statistical analysis found no link between either liberalisation or privatisation on the IDI. The fact that there is no overall effect across the OECD countries does not mean that privatisation

and liberalisation had no impact in the UK. The decline of the UK coal mining industry has been more rapid than the closure of coal-fired power plant. As a result, of the fuel commodities required for the UK's electricity production, coal was the most significant contributor to the UK's increasing import dependence. Initially, this increase in dependence on imported fuels was mitigated to some extent by the 'dash for gas' that followed privatisation. The contribution of gas to the IDI was at first neutral, as production from the North Sea was sufficient to meet the demand from new CCGT plant; once these gas supplies began to decline from 2000 onwards, however, the continued expansion of gas generation drove up the UK's import dependence.

Many countries have moved from coal to increasing gas dependence. However, the UK gas system was designed to exploit reserves in the UK continental shelf. As a result, Britain has relatively low gas storage levels and a limited number of import routes. Reliance on imported fuel introduces new uncertainties into the electricity sector and, while these are hard to quantify, many argue that the prudent approach is to diversify import routes and to increase the level of gas storage – two strategies that the UK is pursuing. Longer-term policies that seek to diversify investment away from gas-fired plant into nuclear power and renewables are also very clearly motivated by concerns related to diversity of supply as well as by climate policy drivers. In short, Britain faces not a fuel gap per se, but rather a potential, though by no means unmanageable, 'import risk'. In the short term, increasing reliance on imported fuel is inevitable. The main challenge for policymakers is to ensure that the ensuing uncertainties are managed effectively.

One of the key themes that runs through a number of these policy documents is the notion that an expansion of the renewables sector will not only deliver the country's low-carbon objective, but will also increase the security of supply by reducing dependence on imported fuels. In a sense this seems indisputable, but as the Renewable Energy Strategy (DECC, 2010c) notes, an increase in non-dispatchable generators such as wind turbines on the system requires a corresponding increase in back-up capacity. This generation needs to be "from flexible fossil-fuel power stations that are able to switch generation on and off quickly and cheaply (eg CCGTs)". As the report concludes, the UK's "electricity security of supply will remain dependent on secure gas supplies".

> Regarding electricity, we consider one possible outcome is that investment in renewables continues at the current or a somewhat increased pace but is insufficient to meet the 2020 targets. The capacity gap which emerges after 2015 is likely to be filled by new CCGTs. Such an outcome would increase the dependence on imported gas (Ofgem, 2010).

> A large proportion of UK electricity is produced in gas-fired power stations, therefore the security of gas supply has an effect on the security of electricity supply. Since the 1990s the UK has moved from being self-sufficient in gas to being increasingly dependent on imports. Over the next decade it will be important to maintain diverse sources of gas supply as well as adequate gas storage infrastructure (DECC, 2010b).

The Energy Market Assessment (EMA) (DECC, 2010b) raises the important point that in terms of the security of the UK's gas generation, it is not only the absolute levels that should be of concern, but also the diversity of import routes. The report goes on to conclude that "the risks of the gas market being unable to meet demand are very low". Analysis of the OECD data reveals that whilst the UK's dependence on foreign gas has increased considerably (Figure 10.2, so too has the diversity of sources from which that gas is obtained (Figure 10.3).

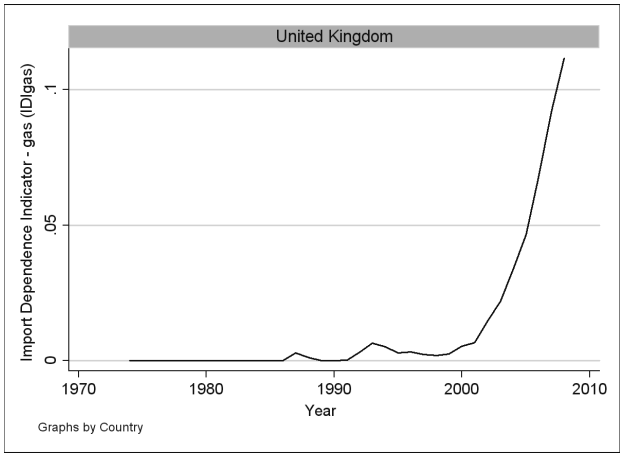


Figure 10.2: UK Import Dependence Indicator for Gas

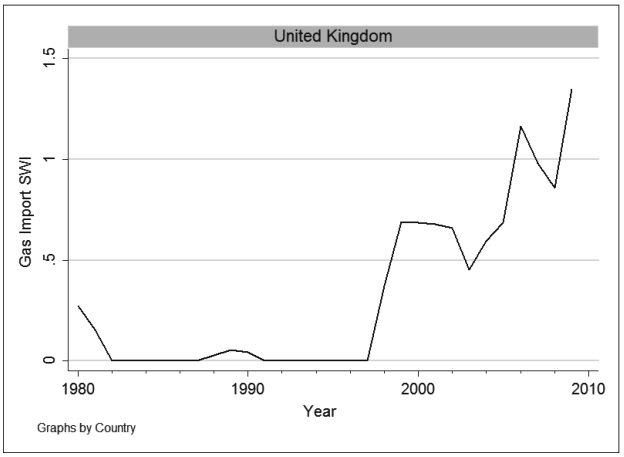


Figure 10.3: UK Gas Import Diversity (SWI)

This seems to concur with the EMA that the risk of a supply disruption large enough to affect electricity supplies is substantially reduced by the large increase in gas import diversity the UK has undergone.

"The UK government (DECC, 2010a) has proposed the unilateral introduction of a carbon price floor via a new carbon tax supplementary to the EU-ETS carbon price, largely in response to power companies and others arguing that the current EU-ETS price is too low" (Blyth and Bunn, 2011). A unilateral move by the UK to support carbon prices could have a number of impacts on the profile of the UK electricity system. The HoC report on the EMR, for instance, notes that whilst the transfer of power via the UK's interconnectors has been fairly balanced, a cross-border price differential would lead to an imbalance.

As the amount of electrical interconnection between the UK and continental Europe increases, issues may arise relating to the interaction of different regulatory regimes between different countries. A paper by Cepeda and Finon (2011) explores the effect of unilaterally introducing a capacity payment when an interconnected neighbour does not do the same. The authors argue that heterogeneous policies intended to ensure capacity adequacy may lead to unintended side effects: distorting the normal functioning of the markets, and thereby impacting on the reliability of supply. This is by no means a reason not to implement such a policy; it does however once again highlight the complexity of electricity system function and the limited experience that system operators have had in addressing the sorts of security concerns that they may now face.

11

Conclusions

11.1 Key findings of the research

The findings of this research can be split into five sections:

- The suitability and usefulness of the concept of 'resilience' for describing electricity systems
- The underlying characteristics that contribute to the resilience of such a system
- How the resilience of the UK and OECD electricity systems has changed over time
- The role that privatisation, liberalisation and the expansion of renewable energy has played in these trends
- What this means for UK electricity policy changes being proposed and already underway

Applying resilience thinking to electricity systems

The first part of this research concerned the concept of *resilience* itself. Arising from the ecological sciences to describe how natural systems cope when exposed to shocks, the concept has since been adopted more widely in the academic and policy literature. More recently it has been used in the energy literature to describe the behaviour of increasingly complex energy systems. In some cases the term seems to be synonymous with 'energy security', whereas in others it is a subset of a wider 'security' concept. The first goal for this research was to understand whether such a concept is useful and necessary given the existing literature on energy security, and whether its use offered any new insights on the way electricity systems should be designed and operated.

Choosing to talk about 'resilience' has, in some disciplines such as ecology, reflected a desire to move away from an approach to system management that focuses on optimisation and efficiency. To drive a system to operate at maximum efficiency is to academics such as Buzz Holling (1973) and Brian Walker a folly — a misguided failure to recognise that we do not understand these systems well enough, and that the future is simply too uncertain (Walker, 2008). For some authors the reason that resilience is useful is that it provides a way of thinking about a system that allows for a degree of uncertainty or ignorance on our part about system behaviour (Stirling, 1994).

The notion that the risks an electricity system faces can be known and quantified has been shown to be incorrect by numerous examples around the world of network failures, fuel disruptions and unplanned outages affecting a large number of generating assets simultaneously. As fuel sources, generation technologies and consumption patterns become more complicated and the grid becomes more overloaded, the potential for unforseen events increases. Designing systems in such a way that they can be expected to cope with unforeseen events is clearly desirable. Some conceptualisations of energy security already refer to such 'unknown unknowns', but within the resilience literature this is a far more prominent theme.

A second approach to conceptualising resilience that has bearing on electricity systems is to see it in tension with the concept of efficiency. Walker (2008) argued, for example, that the goal should be to keep a system in "an acceptable state, albeit not the maximum productivity state, but a resilient state no matter what happens". Charles Redman (2008) took a similar view, arguing that striving for efficiency was only sensible if the system was not going to change. Where systems are more dynamic and less predictable, excessive efficiency-seeking can lead to fragility and vulnerability.

The transformation the electricity system has undergone over the past thirty years is marked. The most significant change over this time has been the decentralisation of planning and operation from the public sector to a privately-owned liberalised system with competing generation plants and electricity suppliers. The demand profiles on the system are in constant flux, the generators each have different designs and operational characteristics, and the generation mix is determined by the decisions of private investors. Whilst the regulator and system operator retain some control over how the system is run, the level of central control has greatly reduced over this period.

More recently, system margins have become more tight (arguably one of the goals of exposing the electricity system the the efficiencies of the competitive market), and the need for new capacity to be added to the system has become more pressing. This whilst also adhering to strict environmental constraints and without making the resulting energy services unaffordable for consumers. Furthermore, UK domestic fuel sources are in decline, and the need for imports has been increasing. Under such change and uncertainty, the concept of 'resilience' provides a focus for considering whether the electricity system has the necessary characteristics to cope with unforeseen changes and adapt to the changes being undertaken.

Characteristics of a resilient electricity system

Based on a review of the resilience literature, a number of aspects of resilience of relevance to electricity systems were identified in this research:

- *Storage* levels in the form of coal stocks and strategic gas storage provides a buffer against physical supply disruption, as well as some protection against spikes in the price of fuel on the market.
- *Grid load* has been shown to be predictive of cascading failures within the electricity system. The more stressed the system becomes, the more likely it is that an underlying, unobserved fault on the network occurs and affects neighbouring components.
- *Learning and training* of the human operators of a system is crucial if they are to react positively to unforeseen events. It is also important to translate the experience of these unforeseen events into Standard Operating Procedures so that a more measured response can be made when such events reoccur.

- *Flexibility* of plant usage can provide protection against shocks in a number of ways. Being able to change the running profile at short notice provides balancing services to the system operator. Fuel switching can allow units to cope with fuel disruptions; the ability to co-fire coal plants with varying proportions of biomass could be one such strategy.
- *Decentralisation* is not necessarily desirable from a resilience perspective. The advantages of restricting the impact of a single large plant failure is clear, but the increased complexity of operating such decentralised systems can add uncertainty around system behaviour. Further, if grid rules designed to protect maintenance staff do not allow such plant to continue operating in the result of a blackout, their potential advantage for system resilience cannot be realised.
- *Indigenous supplies* of fuel are often cited as necessary for secure system operation. There is certainly an argument that domestic supplies reduce reliance on uncertain supplies outside of national borders. However, this still involves concentrating a significant part of the fuel system in a relatively small region, both geographically and politically. Having large amounts of indigenous production can therefore be in tension with having a diversity of fuel sources.
- *Import diversity* therefore should also be seen as important for system resilience. By diversifying the fuels being imported and the routes by which that fuel is delivered, the probability of any single disruption adversely impacting the whole system is reduced.

The above resilience characteristics were seen as important for resilient electricity system operation. However, some of these were not quantifiable, and others did not have sufficient levels of data reported over a large enough period of time in order investigate their behaviour statistically. The following measures were chosen for further investigation therefore not because they necessarily best described a resilient system, but because they had been monitored in multiple countries and over a sufficient length of time to discern their behaviour under different and changing regulatory arrangements:

- The *system margin* needs to be sufficient for a system to cope with unplanned outages or unexpected demand increases.
- The *diversity* of the system needs to be sufficient so that no single fuel supply disruption or design failure is likely to have a large impact on the ability of the system to deliver energy services to consumers.

- The *energy intensity* of a society or economy is an indicator of how dependent it is on the energy supply being maintained.
- The *price* of electricity should be incorporated into any full understanding of 'resilience'. Physical unavailability may be avoidable, but if the price of receiving electricity services is prohibitive for sections of society, this society is not resilient to shocks arising from the electricity system.
- *Import dependence*, a measure of the proportion of fuel needed to generate electricity as compared with the proportion of fuel that can be supplied indigenously, gives an indication of the reliance of an electricity system on external fuel supplies.

Resilience trends

The indicators outlined above were analysed to understand the role that privatisation, liberalisation and the move towards low-carbon electricity generation have had on resilience. Analysis of the underlying trend across the OECD countries showed that the academic and policy interest in electricity system resilience is not unwarranted. Derated margins have been declining steadily since the 1980s, and this behaviour is particularly marked in the UK. Import dependence, which measures both the electricity system's need for fuel and the amount of that fuel that needs to be imported, has been increasing continuously in the UK since the early 1980s. This has been driven by a decline in the domestic coal industry, and the 'dash for gas' which was subsequently followed by a decline in indigenous gas production. This trend has not, however, been uniform across the OECD countries.

The demand for electricity as measured by per-capita consumption has been increasing in nearly all OECD countries, making people increasingly dependent on and therefore vulnerable to electricity systems. Only a subset of economies that have reduced the contribution their industrial sectors in a move towards the service sector have seen a reduction in the electricity intensity of their economic productivity. Compounding the impact of the increasing reliance on electricity systems is the increase in prices that consumers are having to pay for electricity. This has been steadily increasing across the OECD countries, but the rate of increase has been climbing.

The only measured resilience indicator that has been improving over this period is generator diversity. This is true across the OECD countries, except in those countries which have large levels of hydroelectric generation, but the change in the UK has been particularly strong. This

has primarily been driven by the increase in gas-fueled generators, however, so it is not a trend that will necessarily continue in the future.

Resilience, then, as measured by these indicators seems to have been declining in the UK and in the OECD. At the same time, a large proportion of these countries have both undergone some level of liberalisation and privatisation, and have expanded their renewables sectors with varying decrees of policy support. Whether, and to what degree, these trends are related is not immediately obvious, however, and was the subject of this research – to identify the extent to which the changes in resilience seen over this period can be attributed to changes in energy policy.

Effect of policy change

As to the reasons for these observed changes across the OECD, this research attempted to understand the underlying cause, and in particular the role of two factors:

- The privatisation and liberalisation of the electricity sector
- The expansion of the renewables sector and policies to facilitate that expansion

Contrary to expectations, no evidence was found to suggest either that privatisation or liberalisation had caused a reduction in margins, or that margins were particularly high in those countries that chose to transfer these systems from public hands. More important, it seems, has been the subsequent growth in the renewables sector. Even after accounting for the variability associated with non-dispatchable plant such as wind and solar, the effective capacity margin is improved by their inclusion. This effect is particularly strong where a Feed-in Tariff (FIT) mechanism was used to bring about the change. It may be that those countries that opted for this form of intervention were more supportive overall of their renewables sector, or it may be that the mechanism itself is more effective at delivering renewable capacity without displacing existing plant.

The effect of privatisation and liberalisation was not to reduce prices, as perhaps its original proponents might have expected. On top of a background of increasing prices across the OECD, there is some evidence that prices in fact increased more in the liberalised countries and particularly those that vertically unbundled the electricity supply chain. This suggests that any

efficiency gains that may have been made in the operation of the electricity plant was not passed through in the form of lower electricity bills and that vertical unbundling seems not to have reduced prices as might have been expected from the associated reduction in market power. Although no effect was observed on the intensity of electricity consumption, this additional price increase alone would make consumers less able to secure their required energy services and less resilient to further price increases.

The role of renewables here is mixed: the expansion of the renewables sector seems to increase the price that consumers pay for electricity. A 1% increase in the proportion of renewables on the system translates into a 5% price increase. Conversely, those countries that are expanding their renewables sector have seen either a drop, or a reduced growth, in their energy intensity. This may be because renewables expansion is larger in countries with a growing service sector, but it is also likely that the increase in price also has a subsequent depressive effect on electricity demand.

The increase in import dependence in parts of the OECD cannot be explained in general by privatisation or liberalisation as there is no evidence of an overall effect here. This is not to say that the UK's own increasing import dependence is not attributable to such causes. The statistical analysis only reveals that this has not been an effect that has applied consistently across the observed countries. Renewable generation, however, can be shown to be protective against increases in import dependence, which means that a continued expansion of the sector should be an effective way to further reduce the demand on imported fuels.

Diversity, which was the only resilience indicator to show a consistently positive trend in the UK and across the OECD countries, was positively affected by both privatisation and liberalisation. There is some evidence to suggest the diversity of investors arising from liberalisation drove the increased diversity of generating technologies. However, this effect was smaller than may have been expected. Rather, it was privatisation that seems to have driven generation diversity, resulting from the incentive on private operators to diversify their own portfolios, partly perhaps by the acquisition of existing plant, but also in the choice of new-build generating technologies.

As more electricity operators choose to include renewable electricity as part of their diversified portfolios, the evidence suggests that such technologies have the initial effect of improving overall system diversity. This effect is not necessarily sustained and depends on the change to the plant mix as older stations are retired. Nevertheless, the overall effect on system diversity of both privatisation and the subsequent investment in renewables is to improve the diversity of the

generation mix.

11.2 What we have learned: implications for future policy

At the time of writing the UK's 'electricity experiment' has been underway for just over twenty years. From the time the privatisation programme was conceived, to the most recent policy consultations on electricity market reform, the benefits and the risks associated with de-nationalising the power sector have been long debated. This scrutiny is by no means restricted to electricity, but there are certain characteristics of so-called 'critical infrastructures', and power systems in particular, that have given some commentators particular cause for concern. Electricity has been a vital component of modern societies for decades, and this dependence on a well-functioning power system appears to be increasing further.

The findings of this research do not present a clear narrative for the role that privatisation and liberalisation have had in changing the resilience of the electricity system. Apart from diversity, liberalisation has had surprisingly little effect on resilience. Although low margins are now a concern for a number of countries' electricity systems, one of the rationales for privatising these systems was to allow seemingly excessive margins to be reduced. That privatisation and liberalisation seem not to have contributed to a decline in margins suggests that the goal was not achieved for these reasons. Further, the 'gold plating' under nationalisation was thought to be driving high prices, but if there is any effect on prices to be discerned from the data it does not support this hypothesis. Rather, the impact of privatisation and liberalisation seems secondary to the other many changes that these energy systems were undergoing.

Perhaps the lesson here is that privatisation had less effect on changing the electricity system than had been anticipated, and that it is extremely difficult to anticipate how policy changes are going to affect the operation of a complex entity such as an electricity system. A particular challenge for the government of a country with a privatised electricity system is it can never fully understand the associated risks. Such systems are constantly evolving, both in their physical component and in the way that we as consumers use them. The lessons from 'resilience' thinking tell us that such uncertainty will never be eliminated. We can use more nuanced indicators than the LOLP to measure system security – measures that take account of our uncertainty or ignorance about the current system and its future evolution. However, policies must be implemented in such a way that allows for flexibility as we continue to learn more about how

the system and its associated institutions work. Such flexibility can easily lead to regulatory uncertainty and consequently investment delays. Resolving this tension between flexibility and consistency is likely to be key to implementing policies that achieve their stated aims whilst not only maintaining, but enhancing the security and resilience of the electricity system.

If privatisation has had a less than dramatic effect on the resilience of the electricity system, the introduction of large-scale renewables projects has been more significant. The largely positive impact of such expansion on the resilience of these systems should be encouraging to policymakers, but the evidence also suggests that these benefits can be transient if not managed through appropriate policies. The next phase of policy changes, and in particular those being made under the banner of the Electricity Market Reform (EMR) are intended to give strong signals to companies to invest in new renewable and low carbon technologies. The choice of a Feed-in Tariff seems a sensible approach given the positive effect that such schemes have had both on incentivising renewables investment, and maintaining system margins in the process.

However, the potential for such expansion to increase prices needs to be carefully monitored by future governments if society is not to become increasingly reliant on unaffordable energy services. A system as large and as complex as the electricity system is inherently unpredictable for all parties: for consumers, investors and for government. The EMR is intended, in part, to give investors confidence in the future revenue streams arising from their investment, and confidence that future regulatory changes will not lead them to regret those investment decisions. Such reforms will not, however, change the underlying uncertainty inherent to such systems. The challenge for government is to ensure that the risk is not simply passed on to consumers. The resilience of the electricity system needs to be secured, but it must not be done in a way that results in a society dependent on energy services it is increasingly unable to afford.

11.3 Possible future extensions

The possible extensions to this research come in three parts. First, the measurement of those indicators which were chosen as representative of the resilience concept could in some cases be improved:

- The relationship between capacity credit and renewables penetration is part of ongoing research in literature and will, once defined, differ from region to region depending on the

pre-existing generation mix, local climate and the geographical dispersion of renewable generators. This research used a formula to calculate the capacity credit as a function of renewable penetration, but ignored these subtleties. Further, whereas the Voorspools and D'haeseleer (2006) analysis is concerned with wind, this analysis assumes that it is reasonable to extended the formula to cover solar, wave and tidal generation. In further work, the validity of this simplification could be tested and the impact of policy change on the derated margin could be reanalysed to ensure that the conclusions remain sound.

- The use of the Shannon-Wiener Index (SWI) as a measure of diversity is limited because it only accounts for the number and proportion of generating technologies. As a result it ignores *disparity*, which is a measure of the 'difference' between different generating technologies (Skea, 2010). The concept remains qualitative at this stage, but captures the intuitive notion that, for example, two types of nuclear power stations, such as a Advanced Gas-cooled Reactor (AGR) and a Pressurised Water Reactor (PWR) are different technologies, but not as different, say, as an AGR and a wind farm. Work to define disparity more quantitatively is ongoing, and when such a concept is sufficiently defined, a more complete measure of diversity that includes disparity would ideally be used in place of the SWI.

Second, a significant limitation of this research in its current form is the transition from the many and varied aspects of system resilience identified in Chapter 3 to the more restricted quantitative indicators explored in the subsequent chapters. The approach taken to this research was to conduct a thorough statistical analysis. Some quantitative indicators lacked sufficient data to be included, but were nonetheless measurable in principle:

- *Import diversity* can be treated using the same SWI metric as generation diversity. A more diverse number and range of fuel import routes would protect a system against individual disturbances. With an improved data set this measure could be incorporated to give a more complete picture of resilience trends.

- *Grid load*, and other measures of network stress are important for understanding how likely it is that small-scale disturbances on a system will cascade into large-scale blackouts. No systematic data was available on trends in system loading over time and across multiple countries, but in principle this could be performed. This would give a more appropriate weighting to the importance of the grid for the resilient functioning of an electricity system.

Other characteristics of resilience may not be quantifiable, but are nevertheless important for maintaining a resilient system. In particular, the way in which actors communicate with, and learn from, each other across the system has been shown to be important in coping resiliently with failures in human systems such as factories and hospitals (Leveson *et al.*, 2006). The ability of such actors in the electricity system may well have changed during the transition from a centralised nationalised system to the liberalised one we have now. Assessing the impact of such a change may not be a quantifiable exercise, but in order to understand how people actually respond to disturbances could provide an important insight to the resilient operation of the electricity system.

Finally, there is scope for improving the detail afforded to the measures of privatisation and liberalisation. Neither of these is a single policy mechanism carried out in a uniform way across multiple countries. Rather, the process of transferring control of the electricity system has been unique to each country, both in timing and extent, and in the forms of regulation that have been implemented. The policies that are currently under discussion in the UK and in Europe may have some precedents, but their effects will be uncertain. By having a more detailed understanding about the particular mechanisms by which privatisation, liberalisation and regulation have or have not worked, a more robust appreciation of the likely impact of future policy changes on system resilience can be developed.

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Walker, B., Holling, C., Carpenter, S. and Kinzig, A. (2004) Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, **9**(2), 5.

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A

Sources Used in Literature Review

A.1 Energy Journals

A.1.1 Energy

1. Worldwide energy
2. Energy user news
3. Energy journal: International Association of Energy Economists., The
4. Natural gas monthly: Energy Information Administration, Office of Oil and Gas, U.S. Dept. of Energy.
5. Independent energy

6. Energy it.
7. Annals of nuclear energy (online)
8. Annual review of energy (online)
9. Annual review of energy and the environment (online)
10. Applied energy (online)
11. Atomic energy (online)
12. Biomass and bioenergy (online)
13. Energy (online)
14. Energy and buildings (online)
15. Energy and environment (online)
16. Energy and fuels (online)
17. Energy conversion and management (online)
18. Energy economics (online)
19. Energy policy (online)
20. Energy sources: recovery, utilization and environmental effects (online)
21. Energy sources, part A: recovery, utilization, and environmental effects (online)
22. Energy sources. Part B : economics, planning and policy (online)
23. Fuel and energy abstracts (online)
24. High energy chemistry (online).
25. High energy density physics (online)
26. IEEE power and energy magazine (online)
27. IEEE transactions on energy conversion (online)
28. International journal of electrical power and energy systems (online)

29. International journal of energy research (online)
30. International journal of green energy (online)
31. International journal of green energy (online)
32. International journal of hydrogen energy (online).
33. International journal of photoenergy (online).
34. International journal of sustainable energy (online)
35. Journal of energy engineering (online)
36. Journal of energy finance and development (online).
37. Journal of fusion energy (historical archive) (online)
38. Journal of fusion energy (online)
39. Journal of high energy physics (online)
40. Journal of nuclear energy. Part C, Plasma physics, accelerators, thermonuclear research (online)
41. Minerals and energy: raw materials report (online)
42. Proceedings of the Institution of Civil Engineers. Water Maritime and Energy (Archive) (online)
43. Proceedings of the Institution of Mechanical Engineers. Part A; Journal of power and energy (online)
44. Progress in energy and combustion science (online)
45. Progress in nuclear energy (online)
46. Renewable and sustainable energy reviews (online).
47. Renewable energy (online).
48. Resource and energy economics (online).
49. Solar energy (online)

50. Solar energy materials and solar cells (online)
51. Surveys in high energy physics (online)
52. Transactions of the American Society of Mechanical Engineers. Journal of energy resources technology (online)
53. Transactions of the American Society of Mechanical Engineers. Journal of solar energy engineering (online)
54. Wind energy (online)
55. World energy statistics and balances (online)

A.1.2 Power

1. Electric light and power
2. International power generation
3. Power
4. Power engineering
5. International journal of manpower
6. Modern power systems
7. Electric machines and power systems
8. European power news
9. Power economics: policy, markets, finance.
10. Electric power components and systems
11. Electric machines and power systems (online)
12. Electric power components and systems (online)
13. Electric power systems research (online)
14. European transactions on electrical power (online)

15. IEE proceedings. B: Electric power applications (online)
16. IEE proceedings. Electric power applications (online)
17. IEEE computer applications in power (online)
18. IEEE power and energy magazine (online)
19. IEEE power electronics letters (online)
20. IEEE power engineering review (online)
21. IEEE transactions on power apparatus and systems (online)
22. IEEE transactions on power delivery (online)
23. IEEE transactions on power electronics (online)
24. IEEE transactions on power systems (online)
25. IET electric power applications (online)
26. IET renewable power generation (online)
27. International journal of electrical power and energy systems (online)
28. ISLPED : International Symposium on Low Power Electronics and Design (online)
29. Journal of power sources (online).
30. Power engineer (online)
31. Power engineering journal (online)
32. Power technology and engineering (online)
33. Proceedings of the Institution of Mechanical Engineers part A: journal of power engineering (online)
34. Proceedings of the Institution of Mechanical Engineers part A: power and process engineering (online)
35. Proceedings of the Institution of Mechanical Engineers. Part A; Journal of power and energy (online)

36. Transactions of the American Society of Mechanical Engineers. Journal of engineering for gas turbines and power (online)

A.1.3 Fuel

1. Chemistry and technology of fuels and oils (online)
2. Energy and fuels (online)
3. Fuel (online)
4. Fuel and energy abstracts (online)
5. Fuel cells (online)
6. Fuel cells bulletin (online)
7. Fuel processing technology (online)
8. Transactions of the ASME: Journal of fuel cell science and technology (online).

A.1.4 Electric

1. Electric & Gas Utilities Industry Yearbook
2. Electric light and power
3. Electrical world
4. Electric perspectives
5. Electrical wholesaling
6. Electric machines and power systems
7. Electric power components and systems
8. Computers and electrical engineering (online)
9. Electric machines and power systems (online)
10. Electric power components and systems (online)

11. Electric power systems research (online)
12. Electrical communication
13. Electrical engineering (Archiv fur Elektrotechnik) (Historical Archive) (online)
14. Electrical engineering : archive fur elektrotechnik (online)
15. Electrical engineering in Japan (online)
16. Electrical review (online)
17. Electricity journal (online)
18. European transactions on electrical power (online)
19. Ferroelectrics (online)
20. Ferroelectrics letters section (online)
21. IEE proceedings. B: Electric power applications (online)
22. IEE proceedings. Electric power applications (online)
23. IEEE electrical insulation magazine (online)
24. IEEE transactions on dielectrics and electrical insulation (online)
25. IEEE transactions on electrical insulation. (online)
26. IEEE transactions on ultrasonics, ferroelectrics, and frequency control (online)
27. IET electric power applications (online)
28. Integrated ferroelectrics (online)
29. International journal of electrical power and energy systems (online)
30. Natural gas & electricity (online)
31. Natural gas and electricity (online).

A.1.5 Gas

1. Natural Gas Industry Yearbook
2. Oil & Gas Field Machinery & Equipment Industry Yearbook
3. Electric & Gas Utilities Industry Yearbook
4. Gasoline Service Stations Industry Yearbook
5. Pipeline & gas journal
6. Lp-gas
7. Natural gas monthly: Energy Information Administration, Office of Oil and Gas, U.S. Dept. of Energy.
8. American gas: the monthly magazine of the American Gas Association.
9. Gases & welding distributor, The
10. Underground construction: water, sewer, gas & cable.
11. Oil and gas map of Western, Central and Eastern EuropecPetroleum Economist, in association with BNP Paribas ;designed by K. Fuller and P. Bush.
12. Oil and gas map of the Eastern HemispherecPetroleum Economist, in association with Oil and Natural Gas Corporation Limited, India ;designed by K. Fuller and P. Bush.
13. American journal of gastroenterology (online)
14. American journal of gastroenterology (online), The
15. American journal of gastroenterology (online), The
16. American journal of physiology: gastrointestinal and liver physiology (online).
17. Bailliere's best practice & research clinical gastroenterology (online)
18. Best practice and research clinical gastroenterology (online)
19. BMC gastroenterology (online)
20. Current opinion in gastroenterology (online)

21. EMC hepato gastroenterologie (online)
22. European journal of gastroenterology and hepatology (online)
23. Evidence-based gastroenterology (online).
24. Gas separation and purification (online)
25. Gastric cancer (online)
26. Gastroenterologe (online), Der
27. Gastroenterology (online)
28. Gastroenterology nursing (online).
29. Gastroenterology research and practice.
30. Gastrointestinal endoscopy (online)
31. Indian journal of gastroenterology (online)
32. Indian journal of gastroenterology (online)
33. International journal of colorectal disease : clinical and molecular gastroenterology and surgery (online)
34. International journal of greenhouse gas control (online)
35. Journal of clinical gastroenterology (online)
36. Journal of gastroenterology (historical archive) (online)
37. Journal of gastroenterology (online)
38. Journal of gastroenterology and hepatology (online)
39. Journal of gastrointestinal surgery (online)
40. Journal of pediatric gastroenterology and nutrition (online)
41. Natural gas & electricity (online)
42. Natural gas (online)

43. Natural gas (Wiley) (online)
44. Natural gas and electricity (online).
45. Nature clinical practice gastroenterology and hepatology (online)
46. Neurogastroenterology and motility (online)
47. Scandinavian journal of gastroenterology - Supplements (online)
48. Scandinavian journal of gastroenterology (online)
49. Scandinavian journal of gastroenterology (online)
50. Scandinavian journal of gastroenterology (online)
51. Scandinavian journal of gastroenterology. Supplement (online)
52. Techniques in gastrointestinal endoscopy (online)
53. Transactions of the American Society of Mechanical Engineers. Journal of engineering for gas turbines and power (online)

A.1.6 Oil

1. Drugs, Soaps, & Toilet Preps Industry Yearbook
2. Oil & Gas Field Machinery & Equipment Industry Yearbook
3. Paper, film and foil converter
4. World oil.
5. Natural gas monthlycEnergy Information Administration, Office of Oil and Gas, U.S. Dept. of Energy.
6. Oil and gas map of Western, Central and Eastern EuropecPetroleum Economist, in association with BNP Paribas ;designed by K. Fuller and P. Bush.
7. Oil and gas map of the Eastern HemispherecPetroleum Economist, in association with Oil and Natural Gas Corporation Limited, India ;designed by K. Fuller and P. Bush.
8. Acta agriculturae scandinavica. Section B : soil and plant science (online)

9. Applied soil ecology (online)
10. Archives of agronomy and soil science (online)
11. Arid soil research and rehabilitation (online)
12. Biology and fertility of soils (Historical Archive) (online)
13. Biology and fertility of soils (online)
14. Chemistry and technology of fuels and oils (online)
15. Communications in soil science and plant analysis (online)
16. Eurasian soil science (online)
17. European journal of soil biology (online)
18. European journal of soil science (online)
19. Journal of plant nutrition and soil science (online)
20. Journal of soils and sediments (online)
21. Journal of the American Oil Chemists' Society (online)
22. Plant and soil (historical archive) (online)
23. Plant and soil (online)
24. Sciences of soils (historical archive) (online)
25. Sciences of soils (online)
26. Soil and sediment contamination (online)
27. Soil and tillage research (online).
28. Soil biology and biochemistry (online)
29. Soil dynamics and earthquake engineering (online)
30. Soil mechanics and foundation engineering (online)
31. Soil science (online).

32. Soil Science Society of America journal (online)
33. Soil technology (online).
34. Soil use and management (online)
35. Water, air and soil pollution (online)
36. Water, air and soil pollution: focus (online).
37. World oil (online)

A.1.7 Coal

1. Coal Mining Industry Yearbook
2. Organic compounds from coal utilisation
3. Coal preparation (online)
4. International journal of coal geology (online).

B

Resilience Usage in the Energy Literature

#	Author	Title	Periodical	Pub Year
1	Kahn,E.	The Compatibility of Wind and Solar Technology with Conventional Energy Systems	Annual Review of Energy	1979
2	Lovins,A.B.	Soft Energy Technologies	Annual Review of Energy	1978
3	Brooks,H; Hollander,J.M.	United States Energy Alternatives to 2010 and Beyond: The Conaes Study	Annual Review of Energy	1979
4	Shupe,J.W.; Weingart,J.M.	Emerging Energy Technologies in an Island Environment: Hawaii	Annual Review of Energy	1980
5	Fesharaki,F.; Schiltz,W.	Natural Gas Supply and Demand Planning in the Asia-Pacific Region	Annual Review of Energy	1985
6	Goldemberg,J.; Johansson,T.B.; Reddy,A.K.N.; Williams,R.H.	An End-Use Oriented Global Energy Strategy	Annual Review of Energy	1985
7	Schock,R.N.; Fulkerson,W.; Brown,M.L.; San Martin,R.L.; Greene,D.L.; Edmonds,J.	How much is Energy Research & Development Worth as Insurance?	Annual Review of Energy and the Environment	1999
8	Farrell,A.E.; Zerriffi,H.; Dowlatabadi,H.	Energy Infrastructure and Security	Annual Review of Environment and Resources	2004
9	Amin,S.M.; Gellings,C.W.	The North American power delivery system: Balancing market restructuring and environmental economics with infrastructure security	Energy	2006
10	Shackley,S.; Green,K.	A conceptual framework for exploring transitions to decarbonised energy systems in the United Kingdom	Energy	2007

#	Author	Title	Periodical	Pub Year
11	Stirling,A.	Limits to the value of external costs	Energy Policy	1997
12	Helm,D.	Energy policy: security of supply, sustainability and competition	Energy Policy	2002
13	Stern,J.	UK gas security: time to get serious	Energy Policy	2004
14	Owen,A.D.	Oil supply insecurity: control versus damage costs	Energy Policy	2004
15	Watanabe,C.; Kishioka,M.; Carvajal,C.A.	IT substitution for energy leads to a resilient structure for a survival strategy of Japan's electric power industry	Energy Policy	2005
16	Li,X.	Diversification and localization of energy systems for sustainable development and energy security	Energy Policy	2005
17	Grubb,M.; Butler,L.; Twomey,P.	Diversity and security in UK electricity generation: The influence of low-carbon objectives	Energy Policy	2006
18	Greenberg,M.; Mantell,N.; Lahr,M.; Felder,F.; Zimmerman,R.	Short and intermediate economic impacts of a terrorist-initiated loss of electric power: Case study of New Jersey	Energy Policy	2007
19	McCarthy,R.W.; Ogden,J.M.; Sperling,D.	Assessing reliability in energy supply systems	Energy Policy	2007
20	Verma,S.K.	Energy geopolitics and IranPakistanIndia gas pipeline	Energy Policy	2007
21	Amin,M.	Balancing market priorities with security issues	Power and Energy Magazine, IEEE	2004
22	Schainker, R.; Douglas, J.; Kropp, T.;	Electric utility responses to grid security issues	Power and Energy Magazine, IEEE	2006
23	Kirschen, D.S.; Jayaweera, D.; Nedic, D.P.; Allan, R.N.	A probabilistic indicator of system stress	Power Systems, IEEE Transactions on	2004

#	Author	Title	Periodical	Pub Year
24	Salmeron, J.; Wood, K.; Baldick, R.	Analysis of electric grid security under terrorist threat	Power Systems, IEEE Transactions on	2004
25	Lachs,W.R.	A new horizon for system protection schemes	Power Systems, IEEE Transactions on	2003
26	Lachs,W.R.	Controlling grid integrity after power system emergencies	Power Systems, IEEE Transactions on	2002
27	Lachs, W.R.; Sutanto, D.; Logothetis, D.N.	Power system control in the next century	Power Systems, IEEE Transactions on	1996
28	Lachs, W.R.; Sutanto, D.	Battery storage plant within large load centres	Power Systems, IEEE Transactions on	1992
29	Lachs, W.R.; Sutanto, D.	Voltage instability in interconnected power systems: a simulation approach	Power Systems, IEEE Transactions on	1992
30	Nedic,D.P.; Dobson,I.; Kirschen,D.S.	Criticality in a cascading failure blackout model	International Journal of Electrical Power & Energy Systems	2006
31	Scott,D.S.	Template For Sustainability	International Journal of Hydrogen Energy	2004
32	Scott,D.S.	The Tyranny Of Surprise	International Journal of Hydrogen Energy	2004
33	Scott,D.S.	For Better Or Worse?	International Journal of Hydrogen Energy	2004
34	Cropper,M.A.J.; Geiger,S.; Jollie,D.M.	Fuel cells: a survey of current developments	Journal of Power Sources	2004

#	Author	Title	Periodical	Pub Year
35	Bickle,L.W.	Spin-Ins Retain Intellectual Capital, Promote Growth	Natural Gas (Wiley)	1995
36	Smead,R.G.	This Winter to Be Test for Gas Industry	Natural Gas & Electricity	2003
37	Smead,R.G.	Energy Infrastructure Security Has Evolved Since September 11	Natural Gas & Electricity	2004
38	Wills-Dudich,L.	The Gas Industry And Hurricane Katrina: The Untold Story	Pipeline & Gas Journal	2006
39	Smeets,E.M.W.; Faaij,A.P.C.; Lewandowski,I.M.; Turkenburg,W.C.	A bottom-up assessment and review of global bio-energy potentials to 2050	Progress in Energy and Combustion Science	2007
40	Agnolucci,P.	Factors influencing the likelihood of regulatory changes in renewable electricity policies	Renewable and Sustainable Energy Reviews	2006
41	Mulugetta,Y.	Human capacity and institutional development towards a sustainable energy future in Ethiopia	Renewable and Sustainable Energy Reviews	2007
42	Mala,K.; Schlpfer,A.; Pryor,T.	Solar photovoltaic (PV) on atolls: Sustainable development of rural and remote communities in Kiribati	Renewable and Sustainable Energy Reviews	2007
43	Omer,A.M.	Energy, environment and sustainable development	Renewable and Sustainable Energy Reviews	2007

C

Resilience Usage in the Wider Literature

#	Title	Periodical	Pub Year	Resilience Type
1	Resilience in Cognitive Development	Ethos	1975	Human
2	Measuring the Inertia and Resilience of Ecosystems	Bioscience	1978	Ecological
3	The Effect of Management Policies on the Stability and Resilience of British Grey Seal Populations	The Journal of Applied Ecology	1978	Ecological
4	Ecological Resilience of Benthic Insects Subjected to Power Peaking Cycles in the Clearwater River, Idaho	Dissertation Abstracts International Part B: Science and Engineering	1980	Ecological
5	Energy-Flow, Nutrient Cycling, and Ecosystem Resilience	Ecology	1980	Ecological
6	Resilience and inertia in model ecosystems: tests of some hypotheses		1982	Ecological
7	Passage time, resilience, and structure of compartmental models	Mathematical biosciences	1983	Biological
8	Design of resilient processing plantsVI. The effect of right-half-plane zeros on dynamic resilience	Chemical Engineering Science	1985	Dynamic; Process Control; Chemical Engineering
9	A programming model for analysis of the reliability, resilience and vulnerability of a water supply reservoir	Water Resources Research	1986	Water; Ecological
10	Resilience: Concepts and Measures	NASA	1986	Ecological
11	Union Activity and Economic Resilience	C.E.P.R. Discussion Papers	1986	Economic
12	Design of resilient processing plants-IX. Effect of model uncertainty on dynamic resilience	Chemical Engineering Science	1987	Dynamic; Process Control; Chemical Engineering
13	Network Resilience	Siam Journal on Algebraic and Discrete Methods	1987	Network

#	Title	Periodical	Pub Year	Resilience Type
14	The genetics of resistance and resilience to Haemonchus contortus infection in young merino sheep	International Journal for Parasitology	1987	Biological
15	Forest Ecosystem Stability: Revision of the Resistance-Resilience Modeling Relation to Observable Macroscopic Properties of Ecosystems	Forest Hydrology and Ecology at Coweeta, Ecological Studies66, Springer-Verlag	1988	Ecological
16	Effects of nutrient recycling and food-chain length on resilience	American Naturalist	1989	Food Web; Ecological
17	Resilience and local stability in a nutrient-limited resource-consumer system	Bulletin of Mathematical Biology	1989	Ecological
18	Disturbance regimes, resilience, and recovery of animal communities and habitats in lotic ecosystems	Environmental management	1990	Ecological
19	Network resilience - A measure of network fault tolerance	IEEE Transactions on Computers	1990	Network
20	Resilience and development: contributions from the study of children who overcome adversity	Development and psychopathology	1990	Human
21	Network resilience of star graphs: a comparative analysis	Proceedings of the 19th annual conference on Computer Science	1991	Network
22	Analysis and synthesis problems for network resilience	Mathematical and Computer Modelling	1993	Network
23	Resilience of corals to hurricanes: a simulation model	Coral Reefs	1993	Ecological
24	Tillage effects on soil degradation, soil resilience, soil quality, and sustainability	Soil and Tillage Research	1993	Soil; Ecological
25	From Risk to Resilience: A Journey with Heart for Our Children, Our Future		1994	Human
26	Predictive Indices of Ecosystem Resilience in Models of North Temperate Lakes	Ecology	1994	Ecological

#	Title	Periodical	Pub Year	Resilience Type
27	Resistance and resilience in a directly regenerating rainforest: Nicaraguan trees of the Vochysiaceae after Hurricane Joan	Forest Ecology and Management	1994	Ecological
28	A Guide to Promoting Resilience in Children: Strengthening the Human Spirit = Guia de Promocion de la Resiliencia en los Ninos para Fortalecer el Espiritu Humano		1995	Human
29	Experimental Trampling of Vegetation. II. Predictors of Resistance and Resilience	The Journal of Applied Ecology	1995	Ecological
30	Measuring resilience in stochastic systems	Ecological Monographs	1995	Ecological
31	Resilience and the Co-evolution of Ecosystems and Institutions		1995	Ecological
32	Testing predictions of the resistance and resilience of vegetation subjected to extreme events	Functional Ecology	1995	Ecological
33	Achieving Despite the Odds: A Study of Resilience among a Group of African American High School Seniors	The Journal of Negro Education	1996	Human
34	Approximate reliability and resilience indices of over-year reservoirs fed by AR(1) Gamma and normal flows	Hydrological Sciences Journal/Journal des Sciences Hydrologiques	1996	Water
35	Feasibility and implications of breeding sheep for resilience to nematode challenge	International Journal for Parasitology	1996	Biological
36	Resilience: Analysis of the concept	Archives of Psychiatric Nursing	1996	Psychological
37	The concept of family resilience: Crisis and challenge	Family process	1996	Family
38	Toward a definition of family resilience: Integrating life-span and family perspectives	Family process	1996	Family

#	Title	Periodical	Pub Year	Resilience Type
39	Alternatives to resilience for measuring the responses of ecological systems to perturbations	Ecology	1997	Ecological
40	Biodiversity, resilience and the control of ecological-economic systems: The case of fire-driven rangelands	Ecological Economics	1997	Ecological; Economic
41	Responsiveness and resilience of high Arctic ecosystems to environmental change	Opera Botanica	1997	Ecological
42	The trait and process of resilience	Journal of advanced nursing	1997	Human
43	Toward a middle-range theory of resilience	ANS.Advances in nursing science	1997	Human
44	Adverse life events and resilience	Journal of the American Academy of Child and Adolescent Psychiatry	1998	Psychological
45	Concept development of resilience	Journal of Korean Academy of Nursing	1998	Human
46	DNA strand biases and the mutational resilience of genes	Mutation research	1998	Biological; Genetic
47	Flood Insurance as a Management Strategy for UK Coastal Resilience	The Geographical Journal	1998	Economic; Social; Coastal
48	Perceived social support as a protective factor in manifest and emotional resilience	Dissertation Abstracts International: Section B: The Physical Sciences and Engineering	1998	Human

#	Title	Periodical	Pub Year	Resilience Type
49	Resilience and vulnerability: coastal dynamics or Dutch dikes?	Geographical Journal	1998	Coastal; Ecological
50	Optimization of resilience and stress distribution in porcelain veneers for the treatment of crown-fractured incisors	The International journal of periodontics & restorative dentistry	1999	Dental
51	Plant attribute diversity, resilience, and ecosystem function: The nature and significance of dominant and minor species	Ecosystems	1999	Ecological
52	Research on Resilience and Its Implications for Tobacco Prevention	Nicotine and Tobacco Research	1999	Human
53	Resilience among Urban African American Male Adolescents: A Study of the Protective Effects of Sociopolitical Control on Their Mental Health	American Journal of Community Psychology	1999	Human
54	Resilience and Success among Deaf High School Students: Three Case Studies	American Annals of the Deaf	1999	Human
55	Resilience concepts and findings: implications for family therapy	Journal of Family Therapy	1999	Psychological
56	Using resistance and resilience measurements for 'fitness' tests in ecosystem health	Journal of environmental management	1999	Ecoogical
57	Adversity, resilience and young people: the protective value of positive school and spare time experiences	Children & Society	2000	Human
58	Building Resilience in Literacy Learners		2000	Educational
59	Ecological resilience–in theory and application	Annual Review of Ecology and Systematics	2000	Ecological
60	Lives through time: an ideographic approach to the study of resilience	Bulletin of the Menninger Clinic	2000	Human; Social

#	Title	Periodical	Pub Year	Resilience Type
61	Modelling Loss of Resilience in Agroecosystems: Rangelands in Botswana	Environmental & Resource Economics	2000	Ecological; Economic
62	Social and ecological resilience: are they related?	Progress in Human Geography	2000	Social; Ecological
63	Testing the limits of social resilience in ant colonies	Behavioral Ecology and Sociobiology	2000	Social; Ecological
64	The construct of resilience: A critical evaluation and guidelines for future work	Child development	2000	Human
65	The construct of resilience: implications for interventions and social policies	Development and psychopathology	2000	Social
66	A contribution to the knowledge of resilience of forest ecosystems at higher altitudes of the Moravian-Silesian Beskids	Ekologia (Bratislava)/Ecology (Bratislava)	2001	Ecological
67	Challenges to the Definition of Resilience	Conference of the American Psychological Association, San Francisco, CA	2001	Psychological
68	Conceptualizing resilience in women older than 85: overcoming adversity from illness or loss	Journal of gerontological nursing	2001	Human
69	First-order reliability method for estimating reliability, vulnerability, and resilience	Water Resources Research	2001	Water; Ecological
70	From Metaphor to Measurement: Resilience of What to What?	Ecosystems	2001	Ecological
71	Loss and human resilience	Applied and Preventive Psychology	2001	Psychological
72	Modelling the resilience of Australian savanna systems to grazing impacts	Environment international	2001	Ecological
73	Resilience and social work practice: Three case studies	Families in Society-the Journal of Contemporary Human Services	2001	Human

#	Title	Periodical	Pub Year	Resilience Type
74	Resistance and Resilience of Alpine Lake Fauna to Fish Introductions	Ecological Monographs	2001	Ecological
75	Scale, ecosystem resilience and fire in shortgrass steppe		2001	Ecological
76	Spatial Resilience of Coral Reefs	Ecosystems	2001	Ecological; Spatial
77	Species Traits, Species Richness and the Resilience of Wetlands after Disturbance	Journal of Aquatic Plant Management	2001	Ecological
78	Disturbance and resilience in soil animal communities	European Journal of Soil Biology	2002	Ecological
79	Ecosystem adaptation: Do ecosystems maximize resilience?	Ecology	2002	Ecological
80	Ecosystem health: is resilience an accurate and sensitive index in a salt marsh	Proceedings of Ecological Society of America 87th Annual Meeting	2002	Ecological
81	Keeping ecological resilience afloat in cross-scale turbulence: an indigenous social movement navigates change in Indonesia		2002	Ecological
82	Mental health promotion through resilience and resiliency education	International journal of emergency mental health	2002	Human
83	Migration, remittances, livelihood trajectories, and social resilience	Ambio	2002	Social
84	Pollution and recovery of Lake Orta (Italy): Resilience at work?	Aquatic Ecosystem Health & Management	2002	Ecological
85	Promoting resilience in children and young people	Developing Practice	2002	Human
86	Resilience and Sustainable Development: Building Adaptive Capacityin a World of Transformations	Ambio	2002	Ecological

#	Title	Periodical	Pub Year	Resilience Type
87	Resilience in aquatic ecosystems - hysteresis, homeostasis, and health	Aquatic Ecosystem Health & Management	2002	Ecological
88	Resilience in Families and Communities: Latin American Contributions from the Psychology of Liberation	Family Journal	2002	Collective; Social
89	Resilience management in social-ecological systems: a working hypothesis for a participatory approach	Conservation Ecology	2002	Ecological
90	Satellite Evidence of Decreasing Resilience in Mediterranean Plant Communities after Recurrent Wildfires	Ecology	2002	Ecological
91	Building Farm Resilience: The Prospects and Challenges of Organic Farming	Journal of Sustainable Agriculture	2003	Ecological
92	Childhood stunting in relation to adolescent living environment and resilience: a follow up study in Lahore	Pakistan.J Ayub Med Coll (Abbottabad)	2003	Human
93	Development of a new resilience scale: the Connor-Davidson Resilience Scale (CD-RISC)	Depression and anxiety	2003	Psychological
94	Environmental determinants of resistance and resilience to coral bleaching: implications for marine protected area management	Conserv.Biol	2003	Ecological
95	Mobile link organisms and ecosystem functioning: Implications for ecosystem resilience and management	Ecosystems	2003	Ecological
96	Navigating social-ecological systems: Building resilience for complexity and change		2003	Social; Ecological
97	Psychological and social aspects of resilience: a synthesis of risks and resources	Dialogues in Clinical Neuroscience	2003	Psychological; Social

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98	Resilience and Adaptive Capacity: Key Components of Sustainable Social-Ecological Systems	Newsletter of the International Human Dimensions Programme on Global Environmental Change (IHDP)	2003	Social; Ecological
99	Resilience and successful aging. Comparison among low and high income older adults	Journal of gerontological nursing	2003	Human
100	Resilience in pre-contact Pacific Northwest social ecological systems	Conservation Ecology	2003	Social; Ecological
101	Resilience of ecosystems to disturbances		2003	Ecological
102	Resilience of Epilithic Algal Assemblages in Atmospherically and Experimentally Acidified Boreal Lakes	Ambio	2003	Ecological
103	Resilience to natural hazards: How useful is this concept?	Global Environmental Change Part B: Environmental Hazards	2003	Natural Disasters
104	Resilience: a concept for the psychological approach of human behaviour	Annals of General Hospital Psychiatry	2003	Human
105	Resistance, resilience, and patchiness of invertebrate assemblages in native tussock and pasture streams in New Zealand after a hydrological disturbance	Canadian Journal of Fisheries and Aquatic Sciences	2003	Ecological
106	Risk and Resilience in the Life Course: Implications for Interventions and Social Policies	Journal of Youth Studies	2003	Human
107	The quest for resilience	Harvard business review	2003	Business
108	The Value of Resilience as a Concept for Practice in Residential Settings	Scottish Journal of Residential Child Care	2003	Human

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109	Building resilience and a supportive environment: Child-centred approaches to HIV/AIDS (CCATH)	Int Conf AIDS	2004	Human
110	Concept development of family resilience: a study of Korean families with a chronically ill child	Journal of clinical nursing	2004	Family
111	Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions	Urban Ecosystems	2004	Ecological
112	Experimental Definition of Resilience for State-and-Transition Models	Society for Range Management Meeting Abstracts	2004	Ecological
113	Institutional responses to development pressures: Resilience of social-ecological systems in Himachal Pradesh, India	International Journal of Sustainable Development and World Ecology	2004	Social; Ecological
114	Network Resilience through Multi-Topology Routing	University of Wurzburg, Institute of Computer Science, Tech.Rep	2004	Network
115	Psychobiological Mechanisms of Resilience and Vulnerability: Implications for Successful Adaptation to Extreme Stress	American Journal of Psychiatry	2004	Human
116	Psychological resilience and positive emotional granularity: Examining the benefits of positive emotions on coping and health	Journal of personality	2004	Psychological
117	Psychological Resilience and the Well-Being of Widowed Women	Ageing International	2004	Psychological
118	Pupil resilience in the classroom: a teacher's framework	Emotional and Behavioural Difficulties	2004	Human

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119	Resilience and flood risk management	Water Policy	2004	Natural Disasters
120	Resilience in a Community Sample of Children of Alcoholics: Its Prevalence and Relation to Internalizing Symptomatology and Positive Affect	Journal of Applied Developmental Psychology	2004	Human
121	Resilience, Adaptability and Transformability in Social-ecological Systems	Ecology and Society	2004	Social; Ecological
122	The contribution of direct and indirect flows to the resilience of element cycles	Acta Oecologica	2004	Ecological
123	The Cost of Restoration as a Way of Defining Resilience: a Viability Approach Applied to a Model of Lake Eutrophication	Ecology and Society	2004	Ecological
124	Adolescent resilience: a framework for understanding healthy development in the face of risk	Annual Review of Public Health	2005	Human
125	An Exploratory Framework for the Empirical Measurement of Resilience	Ecosystems	2005	Ecological
126	APA's Resilience Initiative	Professional Psychology: Research and Practice	2005	Psychological
127	Conceptual clarifications in the study of resilience	American Psychologist	2005	Psychological
128	Environmental Variability in the Florida Keys: Impacts on Coral Reef Resilience and Health	American Geophysical Union, Fall Meeting 2005, abstract# OS23B-04	2005	Ecological
129	Evaluation, analysis, and enhancement of error resilience for reliable compression of VLSI test data	IEEE Transactions on Instrumentation and Measurement	2005	Electronic

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130	Fauna of Yosemite National Park lakes has low resistance but high resilience to fish introductions	Ecological Applications	2005	Ecological
131	Interpreting and Correcting Cross-scale Mismatches in Resilience Analysis: a Procedure and Examples from Australia's Rangelands	Ecology and Society	2005	Ecological
132	Notes on Lifelong Resilience: Perceptual and Personality Factors Implicit in the Creation of a Particular Adaptive Style	Psychoanalytic Psychology	2005	Psychological
133	Promoting community resilience in disasters: the role for schools, youth, and families		2005	Human
134	Psychological well-being, resilience, and social support expectancy: Junior high school students facing high school entrance examinations	Japanese Journal of Educational Psychology	2005	Psychological
135	Resilience as a Component of Ecological Health: Lessons From Stream Ecosystems	American Geophysical Union, Spring Meeting 2005, abstract# NB23A-03	2005	Ecological
136	Resilience of the Dominant Human Fecal Microbiota upon Short-Course Antibiotic Challenge	Journal of clinical microbiology	2005	Biological
137	Resilience: Going from Conventional to Adaptive Freshwater Management for Human and Ecosystem Compatibility		2005	Ecological
138	Social-ecological resilience to coastal disasters	Science	2005	Social; Ecological
139	Stress, Aging, and Resilience: Can Accrued Wear and Tear Be Slowed?	Canadian Psychology	2005	Human
140	Stress-resilience, illness, and coping: a person-focused investigation of young women athletes	Journal of Behavioral Medicine	2005	Human

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141	Supply chain resilience - Analysis of a distribution network model under changing scenarios		2005	Supply Chain
142	The phenomenon of resilience in crisis care mental health clinicians	International Journal of Mental Health Nursing	2005	Psychological
143	The Use of Discontinuities and Functional Groups to Assess Relative Resilience in Complex Systems	Ecosystems	2005	Ecological
144	Understanding and Fostering Family Resilience	Family Journal Counseling and Therapy for Couples and Families	2005	Family
145	Vulnerability or Resilience? Development in a Network Perspective		2005	Network
146	A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions	Proceedings of the 37th conference on Winter simulation	2006	Network
147	A multiple-levels-of-analysis perspective on resilience: implications for the developing brain, neural plasticity, and preventive interventions	Annals of the New York Academy of Sciences	2006	Human
148	Access and resilience: Analyzing the construction of social resilience to the threat of water scarcity	Ecology and Society	2006	Ecological; Social
149	Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes	Frontiers in Ecology and the Environment	2006	Ecological
150	Building Resilience and Adaptation to Manage Arctic Change	Ambio	2006	Ecological

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151	Can forest management based on natural disturbances maintain ecological resilience?	Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere	2006	Ecological
152	Conceptualizing and Measuring Economic Resilience		2006	Economic
153	Developing an Agenda for Translational Studies of Resilience and Vulnerability Following Trauma Exposure	Annals of the New York Academy of Sciences	2006	Human
154	Exploring Resilience in Social-ecological Systems: Comparative Studies and Theory Development		2006	Ecological; Social
155	Firm size diversity, functional richness, and resilience	Environment and Development Economics	2006	Ecological
156	Implications of resilience concepts for scientific understanding	Annals of the New York Academy of Sciences	2006	Human
157	Knowledge, learning and the evolution of conservation practice for social-ecological system resilience	Human Ecology	2006	Social; Ecological
158	On the Concept of Resilience (Preliminary Paper #356)		2006	Physical; Biological; Personality; Social; Cultural
159	Overview of the Resilience Concept	100th Anniversary Earthquake Conference	2006	Seismic; Natural Disasters

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160	Population and community resilience in multitrophic communities	Ecology	2006	Ecological
161	Psychological "resilience" and its correlates in chronic pain: Findings from a national community sample	Pain	2006	Psychological
162	Resilience and sustainable development	Environment and Development Economics	2006	Ecological
163	Resilience as an attribute of the developmental system: comments on the papers of Professors Masten & Wachs	Annals of the New York Academy of Sciences	2006	Human
164	Resilience Engineering: New directions for measuring and maintaining safety in complex systems		2006	Engineering
165	Resilience is associated with better recovery in Chinese people diagnosed with coronary heart disease	Psychology & Health	2006	Personal; Psychological
166	Resilience Under Military Operational Stress: Can Leaders Influence Hardiness?	Military Psychology	2006	Psychological
167	Resilience: determinants, measurement, and treatment responsiveness	CNS spectrums	2006	Human
168	The Mekong Program on Water, Environment and Resilience (M-POWER)	Mountain Research and Development	2006	Human; Ecological
169	Cultural understandings of resilience: roots for wings in the development of affective resources for resilience	Child and adolescent psychiatric clinics of North America	2007	Human
170	Data mining of resilience indicators	IIE Transactions	2007	Economic

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171	Genetically informative designs in the study of resilience in developmental psychopathology	Child and adolescent psychiatric clinics of North America	2007	Psychological
172	Is attachment style a source of resilience against health inequalities at work?	Social Science & Medicine	2007	Human
173	Mountain hazards and the resilience of social-ecological systems: lessons learned in India and Canada	Natural Hazards	2007	Social; Ecological
174	Resilience and transitions from dementia caregiving	The journals of gerontology.Series B, Psychological sciences and social sciences	2007	Human
175	Resilience in landscape exploitation systems	Ecological Modelling	2007	Ecological
176	Resilience: research evidence and conceptual considerations for posttraumatic stress disorder	Depression and anxiety	2007	Psychological
177	Resistance and resilience of zinc tolerant nitrifying communities is unaffected in long-term zinc contaminated soils	Soil Biology and Biochemistry	2007	Biological
178	Understanding uncertainty and reducing vulnerability: lessons from resilience thinking	Natural Hazards	2007	Natural Disasters; Human; Environmental